Westinghouse – Cambridge – Georgia Tech – INL – Morehouse – PoliMi – VirginiaTech – U. of Tennessee – U. of Michigan – U. of Idaho – SNOC –

I^2S–LWR

Integral Inherently Safe Light Water Reactor (I^2S-LWR) Concept

Razvoj koncepta integralnog lakovodnog reaktora s inherentnim sigurnosnim karakteristikama

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February 10, 2014

Outline

- Georgia Institute of Technology (Georgia Tech) and Nuclear and Radiological Engineering (NRE) Program
- Nuclear Power in US and Worldwide
- Development trends:
  - New construction in USA
  - SMRs and “Safety-by-Design”
  - High-temperature high-efficiency reactors
- Next generation LWRs:
  Integral Inherently Safe Light Water Reactor – I^2S-LWR
- Concluding remarks
- Q&A

Introductory Remarks on Nuclear Power in USA and Worldwide

Worldwide use of nuclear power

- 2012: 435 reactors, 370.0 GWe (NN 3/2012)
- 2013: 433 reactors, 371.5 GWe (NN 3/2013)
- About 1/6-th world electricity
- Over 60 new reactors in 14 countries under construction (WNA, 2/2013)
- Major source of electricity in several countries

NUCLEAR POWER UNITS BY NATION

POWER REACTORS BY TYPE, WORLDWIDE

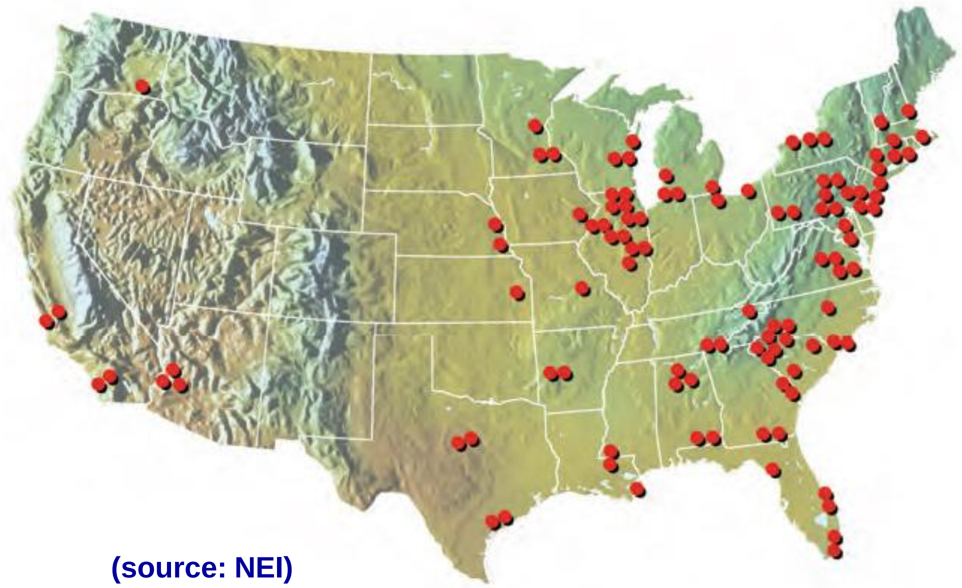
Reactor Type	# Units (in operation)	Net MWe (in operation)	# Units (forthcoming)	Net MWe (forthcoming)	# Units (total)	Net MWe (total)
Pressurized light-water reactors (PWR)	267	246 555.1	89	93 014	356	339 569.1
Boiling light-water reactors (BWR)	84	78 320.6	6	8 056	90	86 376.6
Gas-cooled reactors, all models	17	8 732	1	200	18	8 932
Heavy-water reactors, all models	51	25 610	8	5 112	59	30 722
Graphite-moderated reactors, all models	15	10 219	0	0	15	10 219
Liquid-metal-cooled reactors, all models	1	560	4	1 516	5	2 076
Totals	**435**	**369 996.7**	**108**	**107 898**	**543**	**477 894.7**

March 2012 NUCLEAR NEWS 79

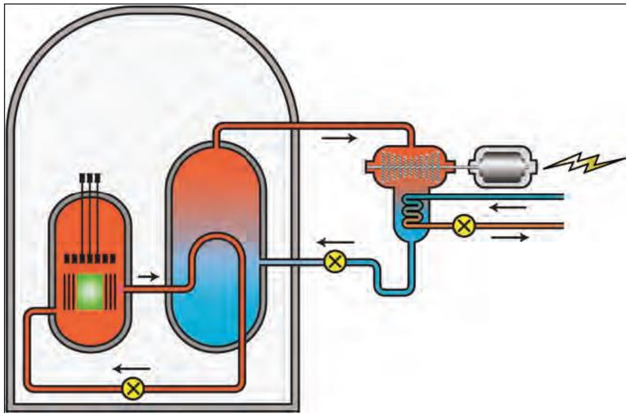
(source: ANS, Nucl. News 3/2012)

Nuclear power plants in the U.S.

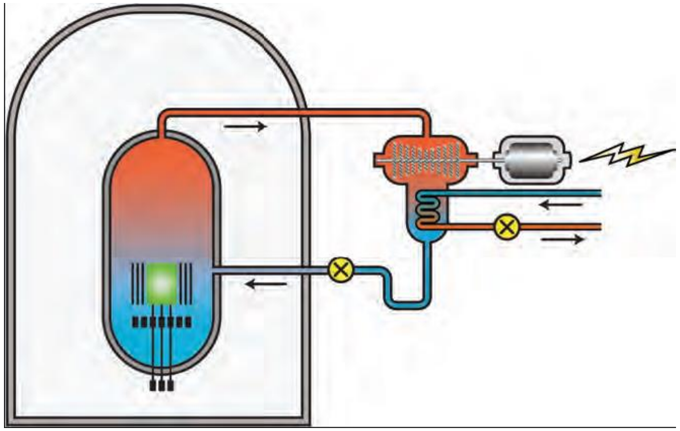
- 100 operating reactors in 31 states
- Close to 20% electricity produced
- 65 PWRs, 35 BWRs
- ~102 GWe



(source: NEI)



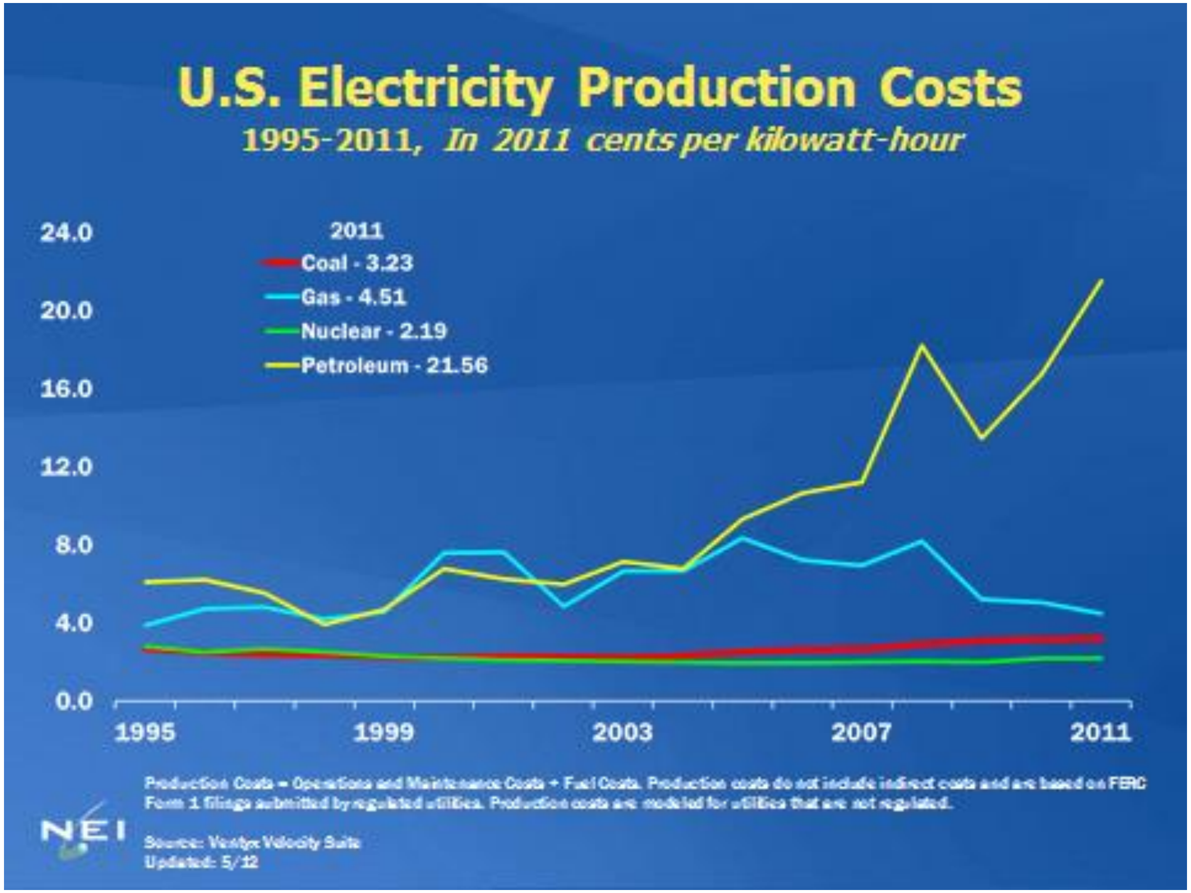
Pressurized Water Reactor (PWR)



Boiling Water Reactor (BWR)

Nuclear Power Plants – Most Expensive Electricity?

Energy production cost

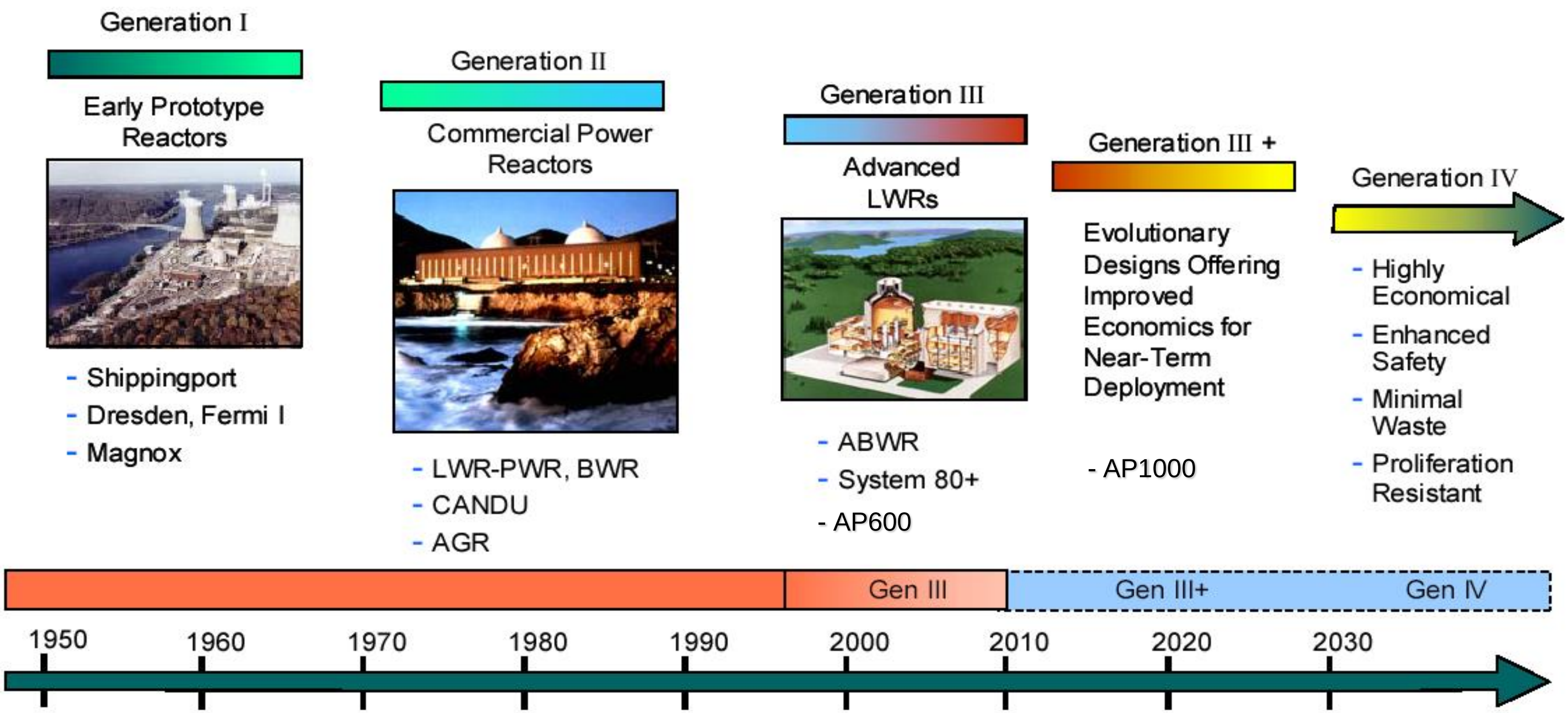


Nuclear power has low electricity production cost
(lowest-cost source of electricity over the past 10+ years;
it will be initially higher but still competitive for the newly constructed NPPs)

(Source: NEI)

Nuclear Power –
What is New in USA?

Nuclear power plants – past/present/future



Nuclear power – What is new in the US?

- New Gen-III+ build in US

- New/advanced designs
  - Gen-IV
  - SMRs
  - Other **(I²S-LWR)**

- Impact of The Great East Japan Earthquake (Fukushima)
- Push for "Accident Tolerant Fuel (ATF)" [fuel with enhanced accident tolerance…]

- Nuclear Waste – Long term considerations
  - Yucca Mountain (intended site of deep geological nuclear waste repository)
  - Interim Storage
  - Blue Ribbon Commission on America's Nuclear Future – Final Report

- New/old fuel cycle options
  - Thorium fuel

New construction in the U.S.

- 4 new units (AP1000) under construction in USA: 2 in Georgia (Vogtle 3 and 4) and 2 in South Carolina (V.C. Summer 2 and 3); each unit 1,170 MWe

Aerial photograph of Vogtle 3 and 4 construction site. Unit 3 is located at left and top of photo and Unit 4 to the right and bottom. Heavy lift derrick crane foundation in center. August 11, 2011

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TVA: 2 projects to complete

- Watts Bar 2, PWR (1,180 MWe)
- Bellefonte 1, AL (1,260 MWe), project started in 1974, suspended in 1988, 8/2011 approved, targeting 2018-2020

New construction in the U.S.

- 2 new units (AP1000) under construction in Georgia, Vogtle 3 and 4 (2x1,170 MWe)
- Vogtle 3 and 4 Construction Photos _ Georgia Power Company.pdf

New/advanced designs

- New/advanced designs
  - “Gen-IV” (Generation IV nuclear power plants) – 6 types

- New/advanced designs pursued at GT NRE

  - SMR (Small Modular Reactors), up to several hundred MWe
    Reduces the required investment from several billion $ to <$1B
    Extremely high interest recently

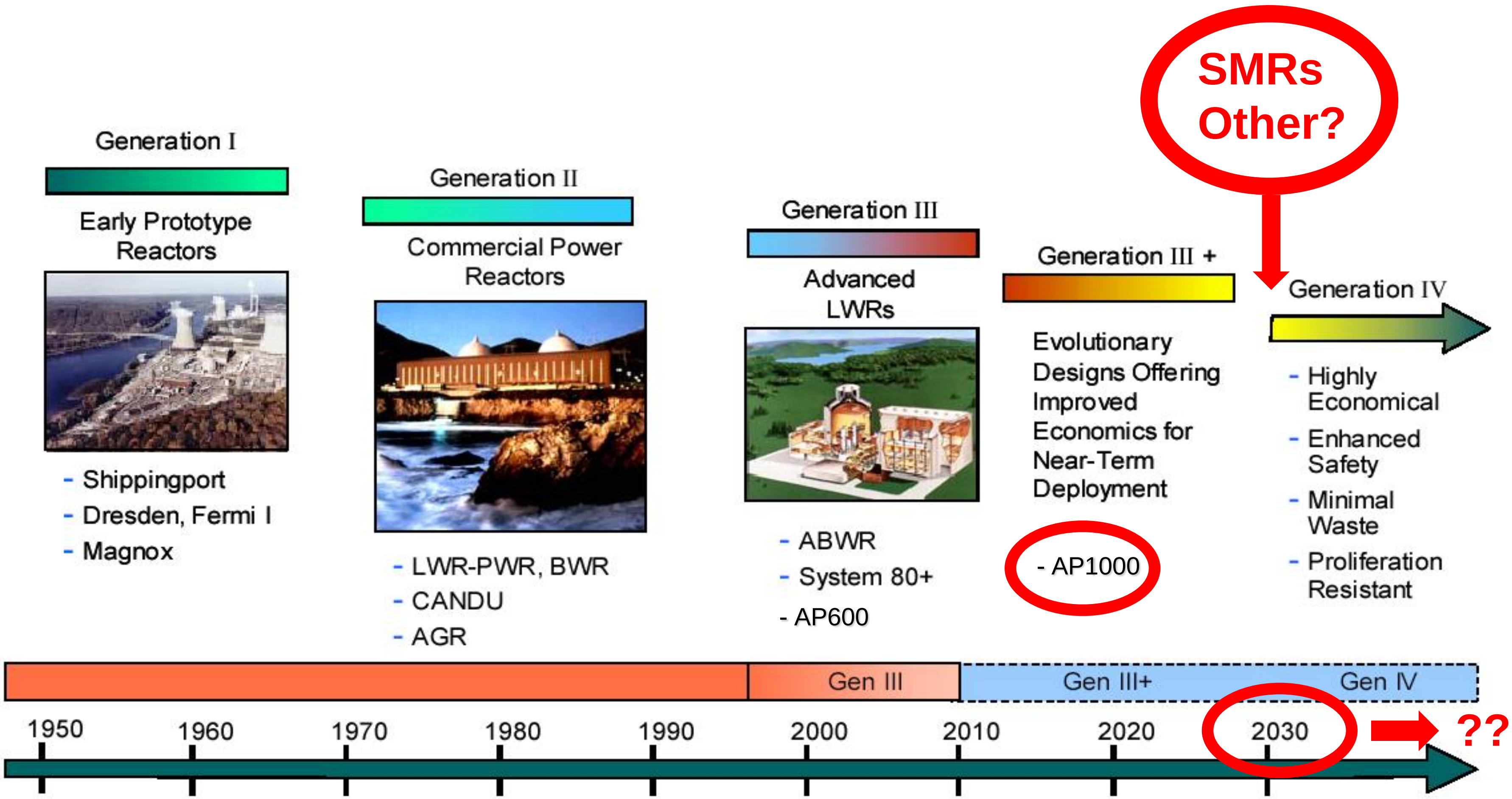
  - I^2S-LWR
    Inherent safety features

  - Liquid-salt cooled reactors (LSCR), ORNL
    High temperature, high efficiency, low reject heat, low pressure

  - Hybrid systems
    - high temperature nuclear + energy storage for process heat
    - Nuclear + Renewables (NuRenew)

  - Fusion-fission hybrid (Dr. W. Stacey)

Nuclear power plants – past/present/future



Fukushima?
Safety?

State-of-the-art: Safe enough?

- Gen. III+ Advanced Passively Safe Nuclear Power Plants
- Safety systems operate based on laws of nature (gravity, natural circulation), thus don’t require external power, and much less likely to fail than active systems

- Is it safe enough?
- Can it be safer?

Personal perspective:

- ALWRs (and Gen-II LWRs) - extremely safe for all planned/foreseen events
- Inherent safety may (significantly?) improve response to unforeseen events (Fukushima-type scenario)

Inherent safety - examples

Small power reactors

- Large surface-to-power ratio
- Decay heat removal by conduction

Integral primary circuit configuration

- All primary circuit components within the reactor vessel
- Eliminates large external piping
- Since it does not exist, cannot break it
- No possibility for LB-LOCA

SMR
Small Modular Reactors

SMRs – Summary and Personal Perspective

- **Attractive safety** (in most cases promoted through integral configuration)
- Emphasis on **modularity and transportability**
- **Power limited to a few hundred MWe**
- **Economic competitiveness "yet to be demonstrated"**
  - "Economy of scale" impact overused as counter-argument (neglects that SMRs may use design features not accessible to large reactor)
  - Licensing cost is a real issue (but it may be overcome)

Personal perspective

- SMRs can be economical
- SMRs offer a viable option for certain markets
- One size does not fit all; certain markets favor/prefer larger units

Integral Inherently Safe Light Water Reactor (I^2S-LWR)

DOE NEUP IRP

U.S. DOE – U.S. Department of Energy

NEUP – Nuclear Engineering University Programs

IRP – Integrated Research Project

Only one Integrated Research Project awarded each year for a new reactor concept

DOE NEUP IRP: (Nuclear Engineering University Program – Integrated Research Project)

Integral Inherently Safe Light Water Reactor (I^2S-LWR) Concept

IRP – DOE's flagship research program in nuclear engineering for universities (only 1 to 3 awarded annually)

FY13 IRP solicitation requirements:
- Large PWR for US market - economics
- Inherent safety beyond Gen-III+

Multi-institutional, multi-disciplinary team:

Lead: Georgia Tech

B. Petrovic (PI), NRE/ME/MSE faculty

Ten partnering organizations:
- U. of Michigan, U. of Tennessee, Virginia Tech, U. of Idaho, Morehouse
- National Lab: INL
- Industry: Westinghouse
- Utility: Southern Nuclear
- International: Politecnico di Milano, Italy; U. of Cambridge, UK
- Pending: **University of Zagreb**, Florida Institute of Technology

	Team Members	Co-PIs/Co-Is
Lead	Georgia Tech (GT)	B. Petrovic (PI) F. Rahnema (Co-PI) C. Deo, S. Garimella, P. Singh, G. Sjoden (Co-Is)
Acade-mia	University of Idaho (U-Id)	I. Charit (Co-PI)
	University of Michigan (U-Mich)	A. Manera (Co-PI) T. Downar, J. Lee (Co-Is)
	Morehouse College (MC)	L. Muldrow (Co-PI)
	University of Tennessee (UTK)	B. Upadhyaya, W. Hines (Co-PIs)
	Virginia Tech (VT)	A. Haghighat (Co-PI), Y. Liu (Co-I)
Industry	Westinghouse Electric Company (WEC)	P. Ferroni (Co-PI) F. Franceschini, M. Memmott (Co-Is)
	Southern Nuclear (SNOC)	R. Cocherell (Co-PI)
Nat'l Lab	Idaho National Laboratory (INL)	A. Ougouag (Co-PI), G. Griffith (Co-I)
Int'l	Politecnico di Milano, Milan, Italy (PoliMi)	M. Ricotti (Co-PI)
	University of Cambridge, Cambridge, UK (U-Cambridge)	G. Parks (Co-PI)
Consultant		H. Garkisch

I^2S-LWR concept – Top level requirements

	Requirement	Target	Comment
APPLICATION-DRIVEN REQUIREMENTS			
Power	>910 MWe	1,000 MWe	For markets preferring large plants
Electricity production efficiency	>32%	35%	Competitiveness; reduced reject heat
Design lifetime	60 years	100 years	Competitiveness; economics, sustainability
Reactor pressure vessel	Same size as or smaller than current large PWRs		Manufacturability
FUEL-RELATED REQUIREMENTS			
Fuel/cladding system	Enhanced accident tolerance*		Post-Fukushima considerations
Fuel enrichment	Viable reloading with <5% enriched fuel	Improved fuel cycle with 5-8% enriched fuel	Option to use existing infrastructure for <5% enrichment
Refueling	Multi-batch, refueling interval 12 months or longer	Options for 12-18-24 months refueling	Offer longer cycles when required by utilities
SAFETY AND SECURITY			
Security, safeguards and proliferation resistance	As in current LWRs or better		
Safety indicators	CDF $<3x10^{-7}$ LERF $<3x10^{-8}$	CDF $<1x10^{-7}$ LERF $<1x10^{-8}$	Improve safety indicators relative to current Gen-III+ passive plants
Safety philosophy/systems	Inherent safety features Full passive safety High level of passivity		Eliminate accident initiators Eliminated need for offsite power in accidents
Grace period	At least 1-week	Indefinite for high percentage of considered scenarios	Resistance to LOOP and Fukushima-type scenarios
Decay heat removal	Passive system with air as the ultimate heat sink		Resistance to LOOP and Fukushima-type scenarios
Seismic design	Single compact building design	Seismic isolators	Allows siting at many locations
Other natural events	Robust design		Address unforeseen events
Monitoring	Enhanced, in normal and off-normal conditions		Improve normal operation; Address unforeseen events
Spent fuel pool safety	Monitoring Passive cooling		Address Fukushima issues with SFP
Used nuclear fuel management	On-site, for the life of the plant		Remove reliance on repository availability at certain date
DEPLOYMENT REQUIREMENTS			
Economics	Competitive with current LWRs		
Deployment	Near-term: 5% enriched fuel Option: use of oxide fuel	Long-term option: up to 8% enriched silicide fuel	Path to accelerated deployment
Operational flexibility	2-batch and 3-batch, ≥12-month cycle	5% and 8% 12-18-24 months cycle	Diverse market needs
Operational flexibility		Load follow with MSHIM	Reduced effluents (environmental)
D&D	Easily returned to green site		Sustainability and public acceptance

I^2S-LWR Concept Overview

I^2S-LWR approach to advanced, safe and economical nuclear power plant (extending SMR safety concept to large plants)

Advanced, passively safe, large loop LWRs

Demonstrated economics

+

Integral configuration SMRs

Credible

Inherent safety features

→

I^2S-LWR

Large (GWe-class) LWR

Economics

Inherent safety features

Addresses Fukushima concerns

↑

Fully passive DHRS

Extended to indefinite coping time

Enhanced accident tolerance fuel

Seismic isolators (compact design)

I²S-LWR concept - design objectives – what and how?

- Economics
  - Large (1 GWe-class)
    - » Compact core
    - » Compact integral HX
- Inherent safety features
  - LWR of integral design

- Fukushima concerns and lessons learnt
  - Indefinite passive decay heat removal
    - » Natural circulation
    - » Rejection to ambient air
- Fuel with enhanced accident tolerance
  - Silicide or nitride (high conductivity)
  - Advanced steel cladding (reduced oxidation at high temperatures)
- Enhanced seismic resistance
  - Seismic isolators

Main challenges (i.e., why not already done?)

Compared to current PWRs:

- Integral configuration → compact core
- Compact core → higher power density core
- Yet, aiming at more accident tolerant fuel
- Requires novel fuel/clad design → require major testing and licensing efforts

- Primary HX inside the vessel
- SMR power in such configuration limited to a few hundred MWe
- Requires novel design of several key components
  - Primary HX
  - …

I²S-LWR approach to advanced, safe and economical nuclear power plant (extending SMR safety concept to large plants)

Advanced, passively safe, large loop LWRs

Demonstrated economics

+

Integral configuration SMRs

Credible

Inherent safety features

I²S-LWR

Large (GWe-class) LWR

Economics

Inherent safety features

Addresses Fukushima concerns

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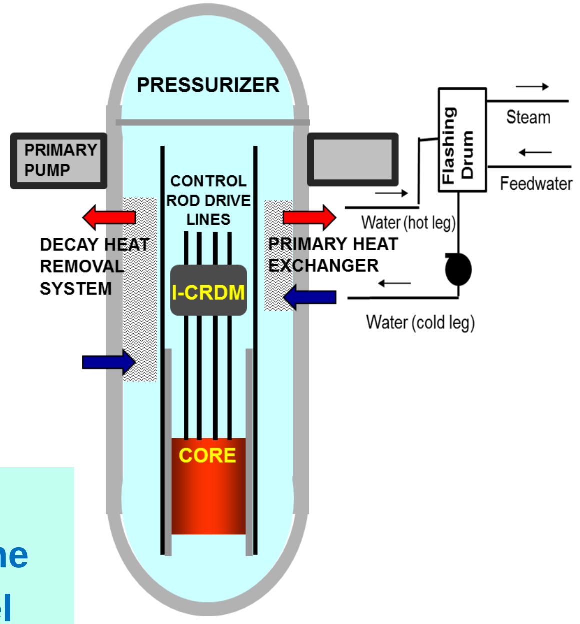
Seismic isolators (compact design)



Key enabling technologies

Technologies developed for SMRs:

- Integral layout
- Integral primary components

I2S-LWR specific, novel technologies:

- High power density fuel/clad system (silicide fuel)
- High power density (micro-channel type) primary HX mC-PHX)
- Steam Generation System (mC-PXH + Flashing Drum)

Additional design features/challenges (a.k.a. the devil is in the “details”)

- Reactor pressure vessel size
- High power density core (flow, vibrations, …)
- Feasibility of compact HX for nuclear application and this power level (likely feasible, but is it practical/economical?)
- Licensing of a new fuel form/design
- Demonstration of the novel decay heat removal concept
- Integrating/harmonizing all components and systems

Enabling Technologies

Key enabling technologies

Technologies developed for SMRs

- Integral layout
- Integral primary components

I^2S-LWR specific

- High power density fuel/clad system
- High power density primary HX
- Innovative steam generation system (SGG)

Rationale and selected options for fuel/cladding materials and geometry configuration

- Fuel
  - High-conductivity fuel
  - High HM load

- Cladding
  - Reduced oxidation rate

- Primary choice: Silicide (U_3Si_2 + advanced FeCrAl ODS)

Fuel Pellet Materials

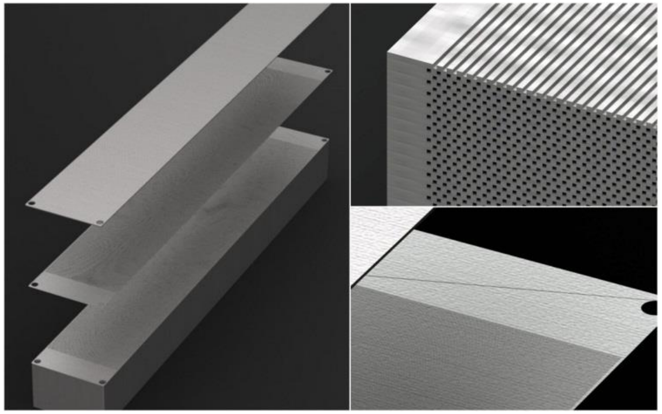
- Higher U loading of U_3Si_2 vs. UO_2 enables acceptable cycle length at higher specific power and improves fuel management
- Better thermal conductivity lowers T and stored fuel energy
- **Swelling = ?**

Fuel	U_3Si_2	UO_2
Theoretical density (g/cm^3)	12.2	10.96
HM Theoretical density (g/cm^3)	11.3	9.66
Thermal conductivity (unirradiated) (W/m K)	9-20 (300-1200°C)	5-2 (300-2000°C)
Specific heat J/kg K	230-320 (300-1200°C)	280-440 (300-2000°C)
Melting point °C	1665	2840

Innovative steam generation system (SGG)

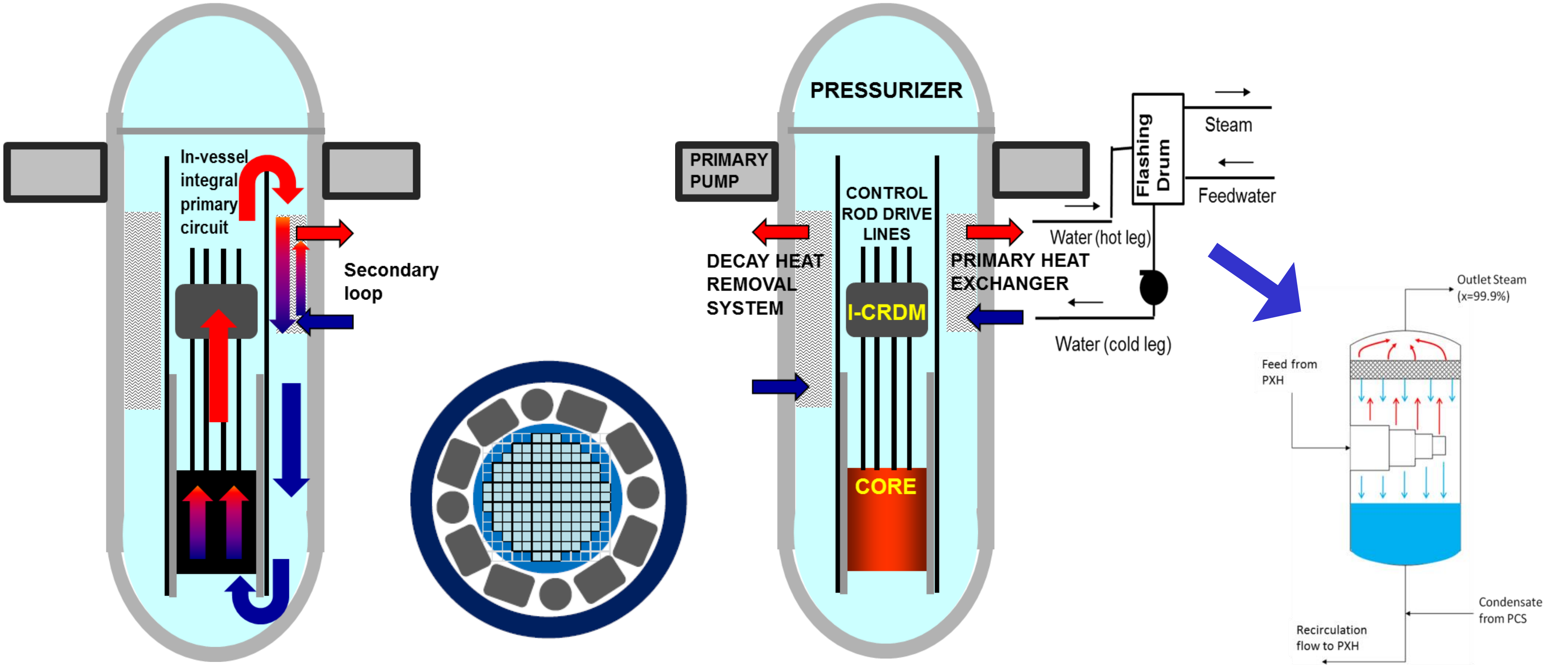
- Integral compact primary HX
  - Microchannel HX
  - High power density

- Combined with external steam drum



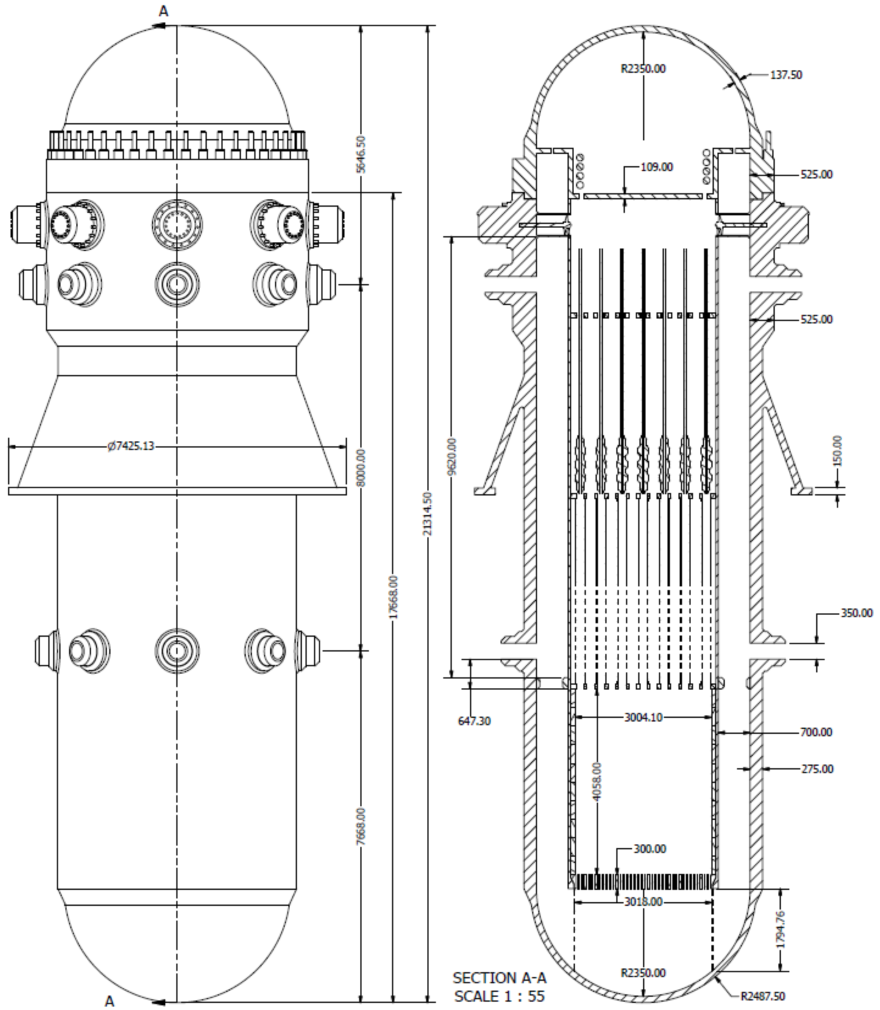
I2S-LWR Layout

I^{2}S-LWR Reactor Layout
Integral Configuration



Integral configuration:
- Primary coolant circulates within RPV only
- All primary circuit components (except main pumps) located within the RPV
- 4 SGG subsystems (2 paired modules each): Primary heat exchangers (inside RPV) and flashing drums (outside RPV, inside containment)
- 4 full passive DHRS

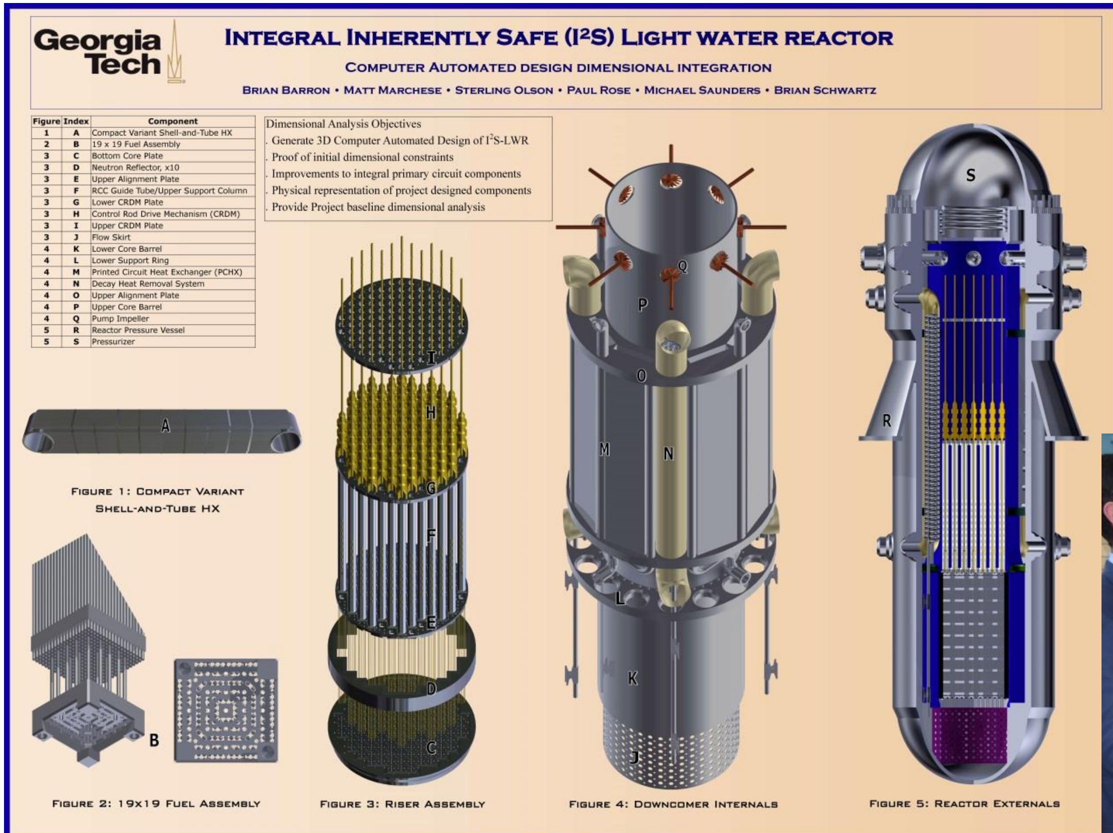
I²S-LWR Reactor Layout
Integral Configuration

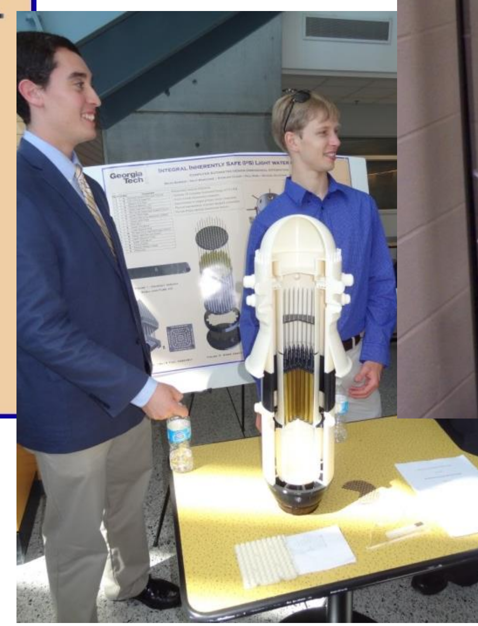


3-D printed mockup 1:30 scale

Examples of a Student Senior Design Project: I²S-LWR Integral vessel layout, 3D CAD model

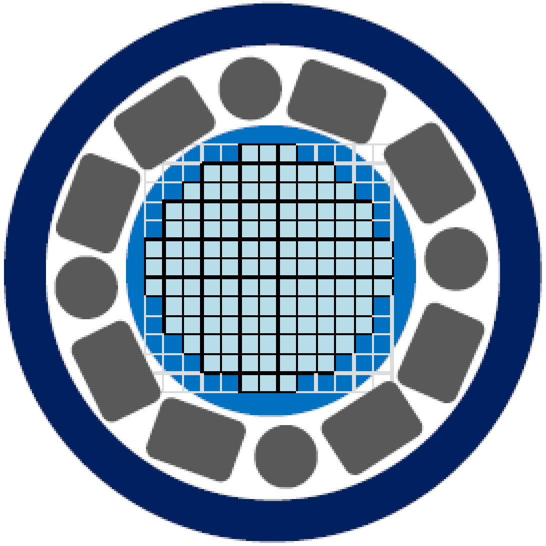
Devised layout, developed 3D CAD model, printed in 1:30 scale (80 cm tall)

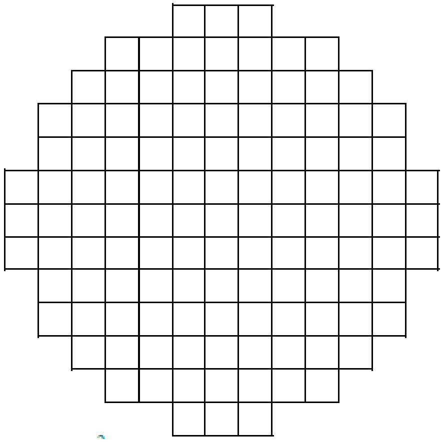




Core layout and fuel assembly design

- 121 assemblies core configuration, steel radial reflector
- 12 ft active fuel height
- Similar to 2-loop cores but with ~40% higher power rating
- 19x19 assembly, 0.360” fuel rod OD, p/d=1.325





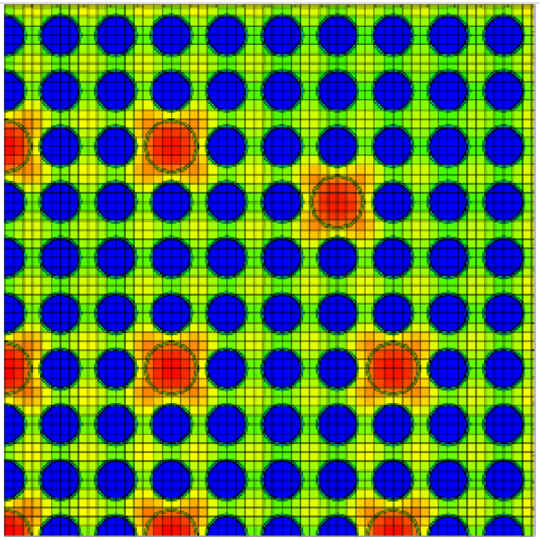
Lattice type	19×19, square
Fuel type	U_3Si_2
Cladding material	Advanced SS
Fuel rods per assembly	336
Fuel rod outer diameter (mm)	9.144
Cladding thickness (mm)	0.406
Pellet-clad gap width (mm)	0.152
Pellet outer diameter (mm)	8.026
Pellet inner void diameter (mm)	2.540
Fuel rod pitch (mm)	12.106
Assembly pitch (mm)	231

Core Concept (5% enrich)

Scoping study on fuel assembly level

- UO_2 (17x17) or U_3Si_2 (19x19) fuels
- SS and Zirc-4 Clad
- Evaluated Fuel Cycle Impact on selections
- Included soluble boron and IFBA coatings
- Tentative core design:
  - 19x19 assembly with U_3Si_2 fuel
  - 2850 MWth

Geometry Parameter	Value
Rod Diameter [cm]	0.9144
Inner Clad Radius [cm]	0.41656
Fuel Radius [cm]	0.40132
Pitch:Diameter Ratio	1.323
Assembly Pitch [cm]	231
Hydraulic-Diameter [cm]	1.124



…also 5-8% enrichment analyzed: longer cycle (>2 years)

Fuel Management Schemes for I²S-LWR

3-batch core with 40 Feed/Reload

					2X	2X	2X					
			2X	2X	Fd	Fd	Fd	2X	2X			
		2X	Fd	Fd	Fd	1X	Fd	Fd	Fd	2X		
	2X	Fd	1X	1X	1X	2X	1X	1X	1X	Fd	2X	
	2X	Fd	1X	1X	1X	Fd	1X	1X	1X	Fd	2X	
2X	Fd	Fd	1X	1X	2X	1X	2X	1X	1X	Fd	Fd	2X
2X	Fd	1X	2X	Fd	1X	3X	1X	Fd	2X	1X	Fd	2X
2X	Fd	Fd	1X	1X	2X	1X	2X	1X	1X	Fd	Fd	2X
	2X	Fd	1X	1X	1X	Fd	1X	1X	1X	Fd	2X	
	2X	Fd	1X	1X	1X	2X	1X	1X	1X	Fd	2X	
		2X	Fd	Fd	Fd	1X	Fd	Fd	Fd	2X		
			2X	2X	Fd	Fd	Fd	2X	2X			
					2X	2X	2X					

2-batch core with 60 Feed/Reload

					1X	1X	1X					
			1X	1X	Fd	Fd	Fd	1X	1X			
		1X	Fd	Fd	Fd	Fd	Fd	Fd	Fd	1X		
	1X	Fd	Fd	1X	1X	Fd	1X	1X	Fd	Fd	1X	
	1X	Fd	1X	Fd	1X	1X	1X	Fd	1X	Fd	1X	
1X	Fd	Fd	1X	1X	Fd	Fd	Fd	1X	1X	Fd	Fd	1X
1X	Fd	Fd	Fd	1X	Fd	2X	Fd	1X	Fd	Fd	Fd	1X
1X	Fd	Fd	1X	1X	Fd	Fd	Fd	1X	1X	Fd	Fd	1X
	1X	Fd	1X	Fd	1X	1X	1X	Fd	1X	Fd	1X	
	1X	Fd	Fd	1X	1X	Fd	1X	1X	Fd	Fd	1X	
		1X	Fd	Fd	Fd	Fd	Fd	Fd	Fd	1X		
			1X	1X	Fd	Fd	Fd	1X	1X			
					1X	1X	1X					

- Full 3-D depletion/reshuffling analysis to equilibrium cycle
- 3-batch /40 Feed-> 3 irradiation cycles before discharge (better fuel use)
- 2-batch /60 Feed -> 2 irradiation cycles before discharge (longer cycle)
- Higher BU fuel assemblies on the periphery (VLLLP)

Fuel cycle

- Westinghouse evaluated a number of options:
  - » 17x17 and 19x19
  - » 5% and 8%
  - » 12-18-24 months refueling interval

- Viable options:
  - » up to 5% enriched, 12/18-month refueling
  - » up to 8% enriched, 12/18/24-month refueling

- FCC
  - Seems within acceptable range

Fuel/cladding system
Economics justification of I^2S-LWR

New fuel/clad system is enabling technology, aiming to:

- Enable high power density core
- Enable more compact NPP footprint
- Enhance safety

Resulting in economic advantages and disadvantages:

- Neutronics: FCC increased by 15-20%
- More compact NPP layout: capital cost reduced by ?%
- Inherent safety features: some safety systems potentially eliminated, capital cost reduced by ?%

Thus, the trade-off is:

- Reduced capital cost (front-loaded, main portion of COE)
- Increased subsequent FCC

Safety goals and philosophy

MULTIPLE LINES OF DEFENSE

First line of defense – inherent safety features (eliminate/limit event initiators/precursors)

- Integral primary circuit eliminates occurrence of LBLOCA/IMLOCA and CR ejection
- Seismic insulator eliminate/limit the impact of seismic events
- Partial burying of containment and underground placement of SFP eliminate/limit external events

Second line of defense - prevention

- All safety systems are passive with a high degree of passivity and deterministically address DBAs (prevent core damage)

Third line of defense - mitigation

- Integral configuration with small penetrations limit loss of RPV inventory
- Fuel with enhanced accident tolerance extend grace period
- Passive DHRs extend grace period (potentially indefinitely)
- DPRA-guided design utilizes passive and active systems

Fourth line of defense - protection

- Containment vessel cooling by air or other medium in natural circulation regime

Safety goals and philosophy

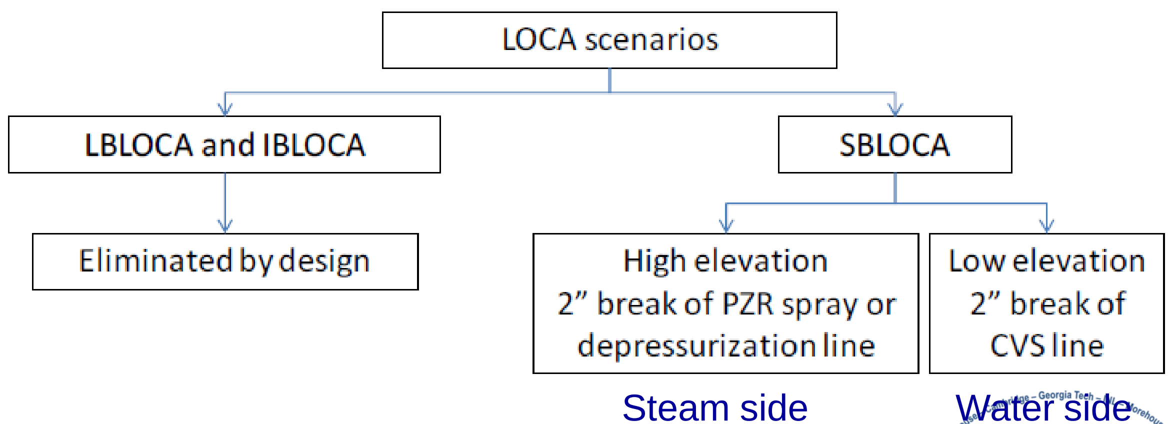
- As high level of passivity as possible

Degree of passivity:

Elements of the passive system	A	B	C	D
Structures (Barriers, pressure proof)	X	X	X	X
Working fluids		X	X	X
Moving mechanical parts			X	X
Stored operating power				X
External activation signal				X

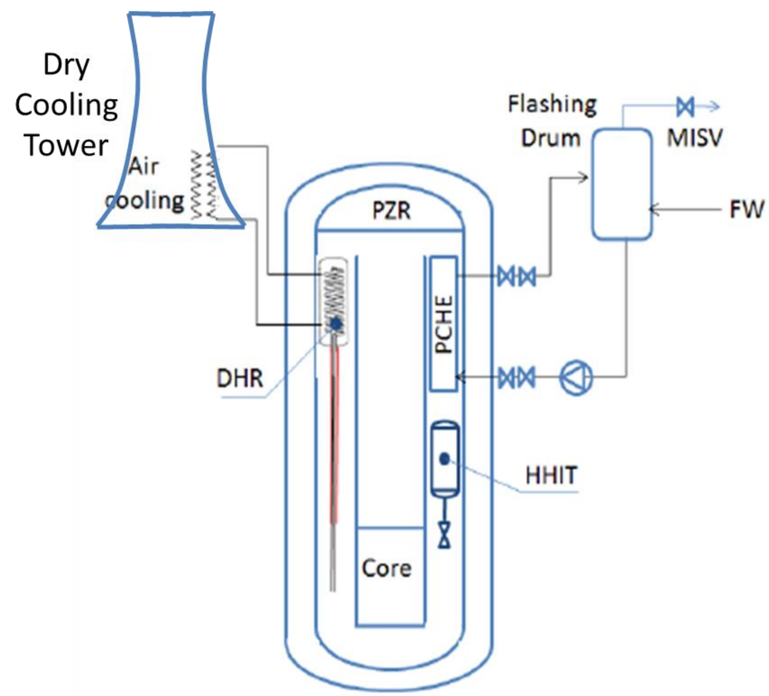
Categories of passive safety systems [IAEA, 1991]

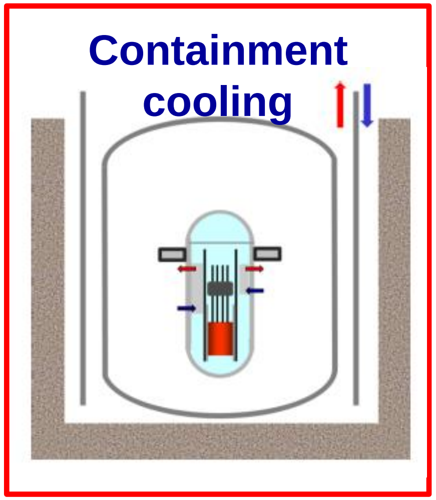
- Eliminate accident initiators as far as achievable
- Limit loss of inventory during LOCAs



Safety Systems

- Passive DHRS (Decay Heat Removal System)
- PHX (mC-HX) as passive heat removal system
- HHIT (High Head Injection Tanks)
- Passive containment cooling

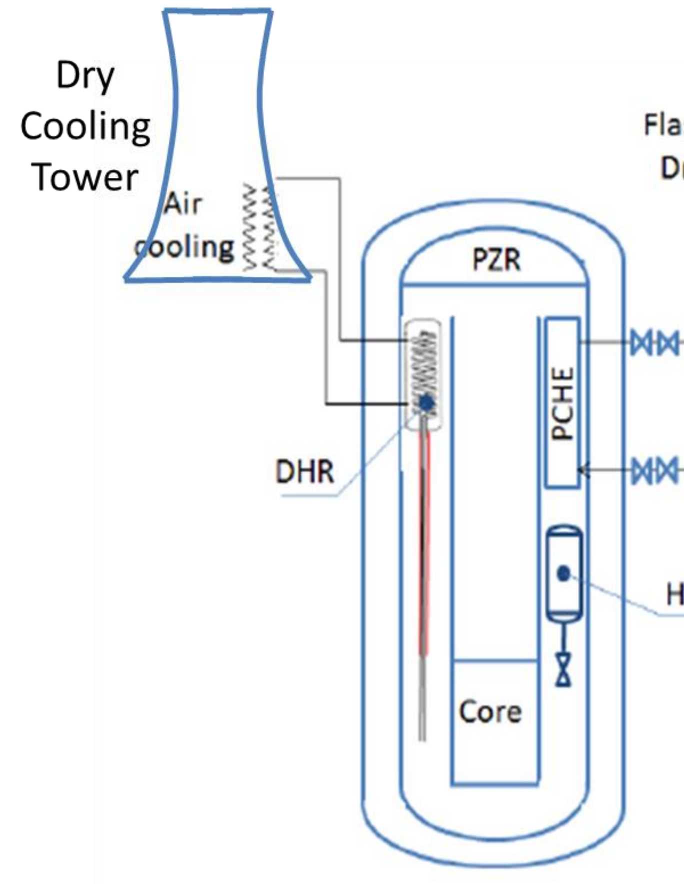




Passive Decay Heat Removal System

Goal: long term self-sustained decay heat removal capabilities with no need for intervention in case of an accident, including loss of external power

- Passive, natural circulation
- Ultimate heat sink – ambient air
- Four units, sized for 3 of 4
- Target: indefinite heat removal



Comparison to current large loop PWR

Similar:

- Core geometry as 2-loop PWR (121 fuel assemblies)
- Fuel assembly similar to 17x17 PWR fuel assembly
- Core internals and control rods
- Secondary and BOP
- Pumps

Different

CORE:
- Higher power density (10-30% higher)
- Different fuel form (silicide, …)
- Enrichment potentially increased (up to 8%)
- Different cladding materials (advanced DS steel)
- Potentially different fuel geometry
- [radial reflector]

INTEGRAL PRIMARY CIRCUIT:
- Larger reactor vessel (RV)
- PHE (primary heat exchanger) inside RV
- CRDM inside RV
- PZR integrated in RV

COMPONENTS/SYSTEMS:
- Compact PHE (micro-channel PHE)
- DHRS (decay heat removal system)
  - Natural circulation
  - Ambient air ultimate heat sink
- Seismic isolators

SAFETY:
- Passive → inherent (features)

Summary

- New I^2S-LWR concept aims to extend inherent safety features of SMRs to larger power level reactors
  - Large (~1,000 MWe) PWR
  - Integral configuration
  - Inherent safety features
  - Novel fuel design, components, etc.

- Multi-disciplinary, multi-organization project

- Great opportunity for students to participate in the cutting edge research with involvement of industry and national lab
  (Example: GT - senior design class, 45 students in 2013; ~30 expected in 2014)
  Significant leveraging of DOE funding

- Exciting project – developing potentially the next generation of PWR

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I^{2}S–LWR

Thank you for your attention!