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Small and Medium Sized Reactors

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Advanced Small and Medium Sized Reactors – Design Status and Trends, Deployment Opportunities, and Challenges

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Definitions/ Developments in Member States

Small Reactor: < 300 MW(e)
Medium Sized Reactor: <700 MW(e)

- **This year, of the 436 NPPs operated worldwide 134 are with SMRs; of the 45 NPPs under construction 10 are with SMRs**
- **In 2009, not less than 40 concepts and designs of advanced Small and Medium Sized Reactors (SMRs) are analyzed or developed in** *Argentina, China, India, Japan, the Republic of Korea, Russian Federation, South Africa, USA, and several other IAEA member states*

Definitions (IAEA-TECDOC-1451, May 2005; IAEA-TECDOC-1485, March 2006; IAEA-TECDOC-1536, January 2007)

Small and Medium Sized Reactors:

- **Reactors with conventional refuelling schemes (partial core refuelling in batches, on-line refuelling, pebble bed transport)**
- **Small reactors without on-site refuelling (SRWOR)**

SCOPE OF INNOVATIVE SMRs UNDER DEVELOPMENT

"Status of Innovative SMR Designs 2005: Reactors with Conventional Refuelling Schemes" (IAEA-TECDOC-1485, March 2006)

"Status of Small Reactor Designs Without On-Site Refuelling" (IAEA-TECDOC-1536, January 2007)

26 inputs from 11 member states

- ***Water Cooled(13)***
- ***Gas Cooled (6)***
- ***Liquid Metal Cooled (6)***
- ***Non-conventional (1)***

30 inputs from 6 Member States

Water Cooled (12)

Gas Cooled (1)

Liquid Metal Cooled (14)

Non-conventional (3)

Incentives for SMRs – Near Term

Today, the progress of SMRs is largely defined by their ability to address the needs of those users that for whatever reason cannot benefit from large NPP deployments

- ***Countries with small electricity demand/ small electricity grids < 10,000 MW(e) peak load***

- ***Countries with limited investment capability (attractive investment profile through incremental capacity increase)***

- ***Settlements and energy intensive industrial sites in remote off-grid locations (permanent frost, islands, remote draught areas, etc.)***

Small or Medium Sized Reactor Does not Mean a Low Capacity Nuclear Power Station

- Several SMRs can be built at a single site; twin units are possible
- Many of innovative SMRs provide for power station configurations with 2, 4, or more NPPs or reactor modules .

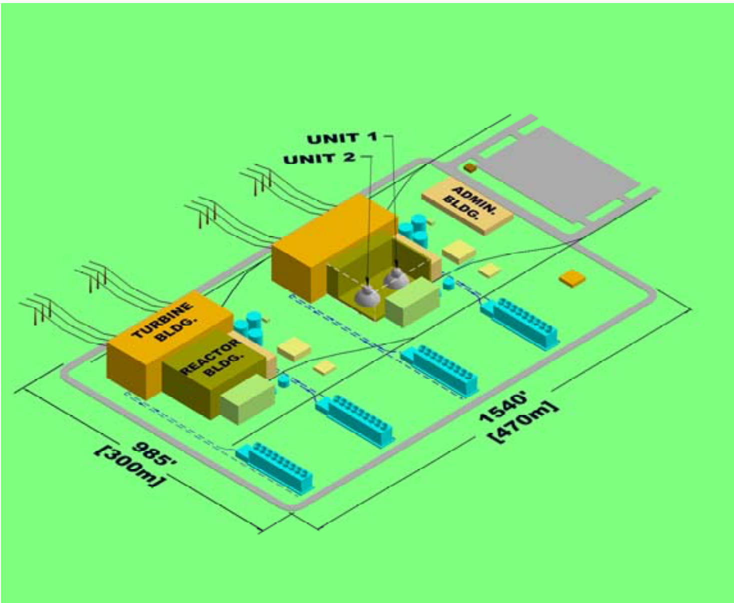


FIG. II-10. Perspective view of IRIS multiple twin-unit site layout.

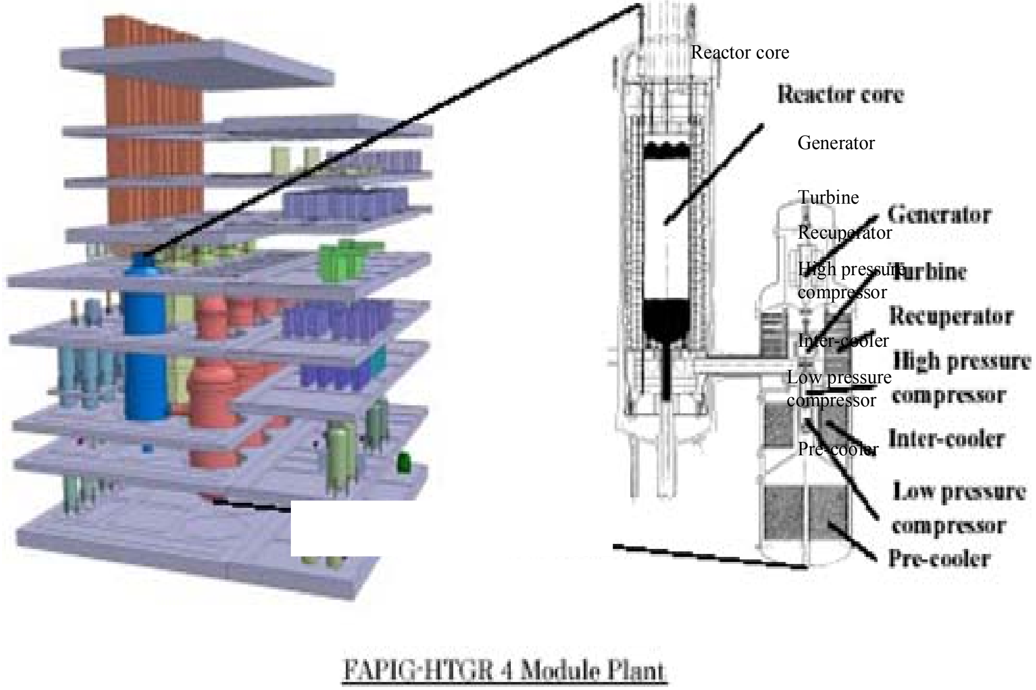


Fig. XVIII-1. Schematic view of the FAPIG-HTGR 4-module plant.

SMRs - Options for Immediate Deployment

Few options are available:

- ***CANDU6/ EC6 AECL (Canada)***

- ***PHWR-220 – being built in India; PHWR-540 (NPCIL, India)***

- ***Chinese PWRs of 325 MW(e) (China) – being built in Pakistan; and 610 MW(e) – being built in China***

SMRs – Recently Deployed/ Under Construction

- ***PHWR/ 692 MW(e) (Siemens Design, 1980s) – Under construction in Argentina (Atucha-2, Buenos Aires, 2010/10/01)***

- ***CANDU-6/ 650 MW(e) (AECL, Canada) – Chernavoda, Romania, 2008/08/07***

- ***CNP-600/ 610 MW(e) (PWR, China) – Two units under construction (Quinshan 2-3 and 2-4, 2010/12/28 and 2011/09/28)***

- ***PWR/ 300 MW(e) (China) – Under construction (Punjab, Pakistan, 2011/05/31)***

- ***PHWR-220/ 202 MW(e) (NPCIL, India) – Three units under construction 2007-2009 (KAIGA-4, 2009/11/30; RAJASTHAN-5 2009; RAJASTHAN-6, 2009/06/39)***

- ***PFBR-500/ 470 MW(e) (IGCAR, India) – Under construction in India (TAMIL NADU)***

- ***Floating NPP with two KLT-40S reactors/ 2x35 MW(e) (Rosenergoatom, Russia) – under construction in St. Petersburg (Russia) - 2010***

SMRs - Options for Near-Term Deployment

Reactors with Conventional Refuelling Schemes

PWRs with integrated design of primary circuit

- **IRIS - Westinghouse (USA) + Intl. Team**
- **CAREM – CNEA, Argentina**
- **SMART – KAERI, the Republic of Korea, and several others**

PWRs – marine reactor derivatives

- **KLT-40S *(Floating NPP)* – Rosenergoatom, Russia**
- **VBER-300 *(Land based NPP)* – OKBM + Government of Kazakhstan, Rosatom**

Advanced Light Boiling Water Cooled Heavy Water Moderated Reactors, Pressure Tube Vertical Type

- **AHWR (Designed specifically for *U233-Pu-Th fuel*) – BARC, India**

High Temperature Gas Cooled Reactors

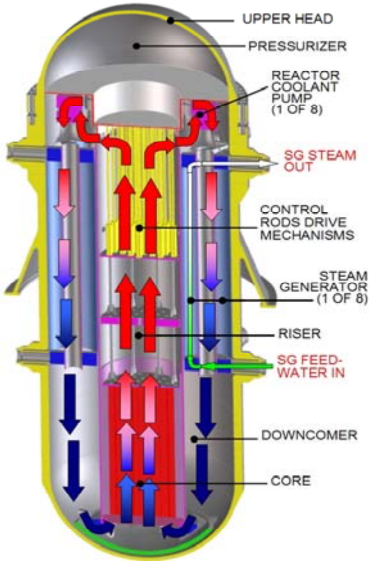
- **HTR-PM – INET, China**
- **PBMR – PBMR Pty, Ltd., South Africa**

Small Reactors without On-site Refuelling

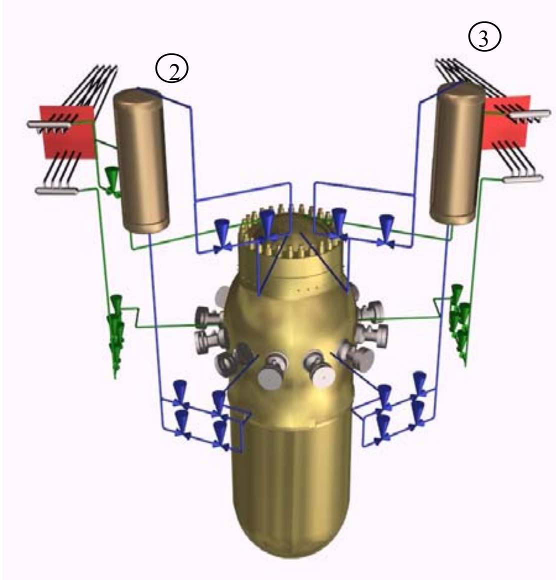
- **ABV *(Floating NPP)* – OKBM, Russia; *NuScale - NuScale, USA***

SMRs - Options for Near-Term Deployment

	W(e)/W(th)	Twin-units	Co-generation
IRIS Westinghouse	335/ 1000 per unit	Yes	Yes, flexible
SMART KAERI	90 / 330		40,000 t of potable water per day
CAREM CNEA	300/ 900		Yes
Floating NPP 2 x KLT-40S	70/ 300	Two reactors on barge	Yes, district heating or potable water
VBER-300 Russia-Kazakstan	295/ 850	Yes	Yes, district heating or potable water
AHWR BARC	300 MW(e)		Yes, potable water
HTR-PM INET	250 MW(e) per module	Two-module plant 500 MW(e)	TBD at later stages
PBMR PBMR Pty	165/ 400	4- and 8 module plants	Yes, process steam
ABV OKBM	11 MW(e) per module	Two-module plants	Yes, district heating or potable water
NuScale NuScale (USA)	45/ 150 per module	12- module plant	



(a)



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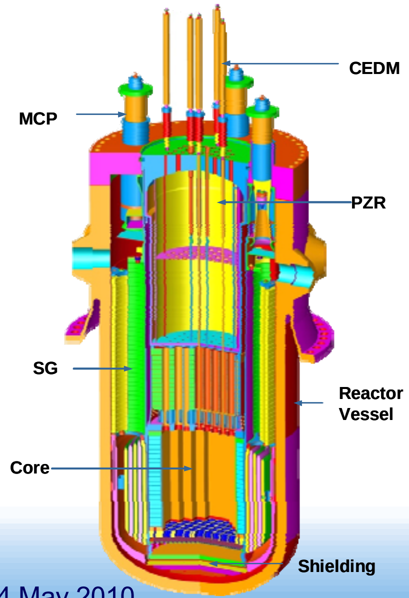


(c)

Reactor Types/ Distinct Groups (Examples)

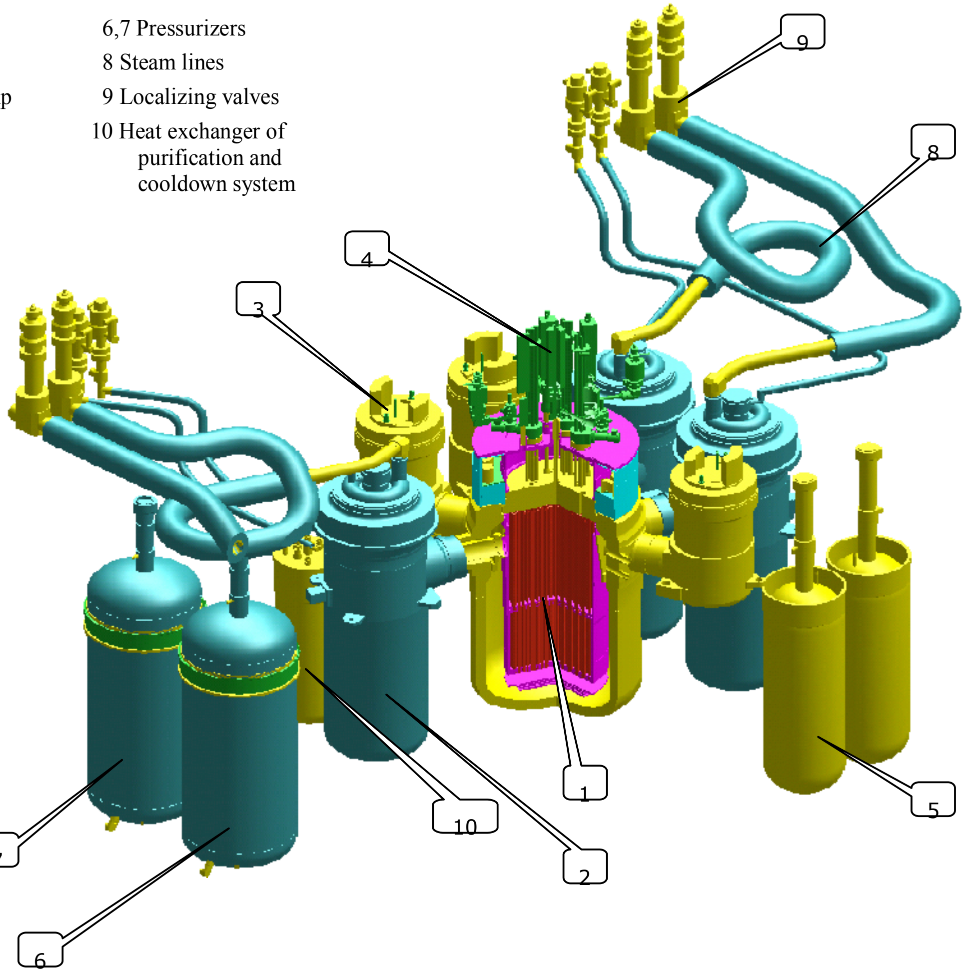
Pressurized Water Reactors/ Integral Design PWRs

- **(a) IRIS – Westinghouse, USA**
- **(b) CAREM – CNEA, Argentina**
- **(c) SMART – KAERI, Republic of Korea**

Reactor Types/ Distinct Groups (Examples)

Pressurized Water Reactors/ Marine Reactor Derivatives

1 Reactor
2 Steam generator
3 Main circulating pump
4 CPS drives
5 ECCS accumulator
6,7 Pressurizers
8 Steam lines
9 Localizing valves
10 Heat exchanger of purification and cooldown system



Modular layout of the KLT-40S reactor plant (OKBM, Russian Federation).

PWRs – Marine Reactor Derivatives – KLT-40S (Russia)

- **The KLT-40S is a modular reactor unit developed for a pilot floating nuclear cogeneration plant (PATES, in Russian), currently under construction in Sankt-Peterburg, the Russian Federation.**
- **Thermal power per unit– 150 MW(th)**
- **PATES – two units, 300 MW(th), 70 MW(e)**
- **Targets: Construction started; pilot plant deployment - 2012**

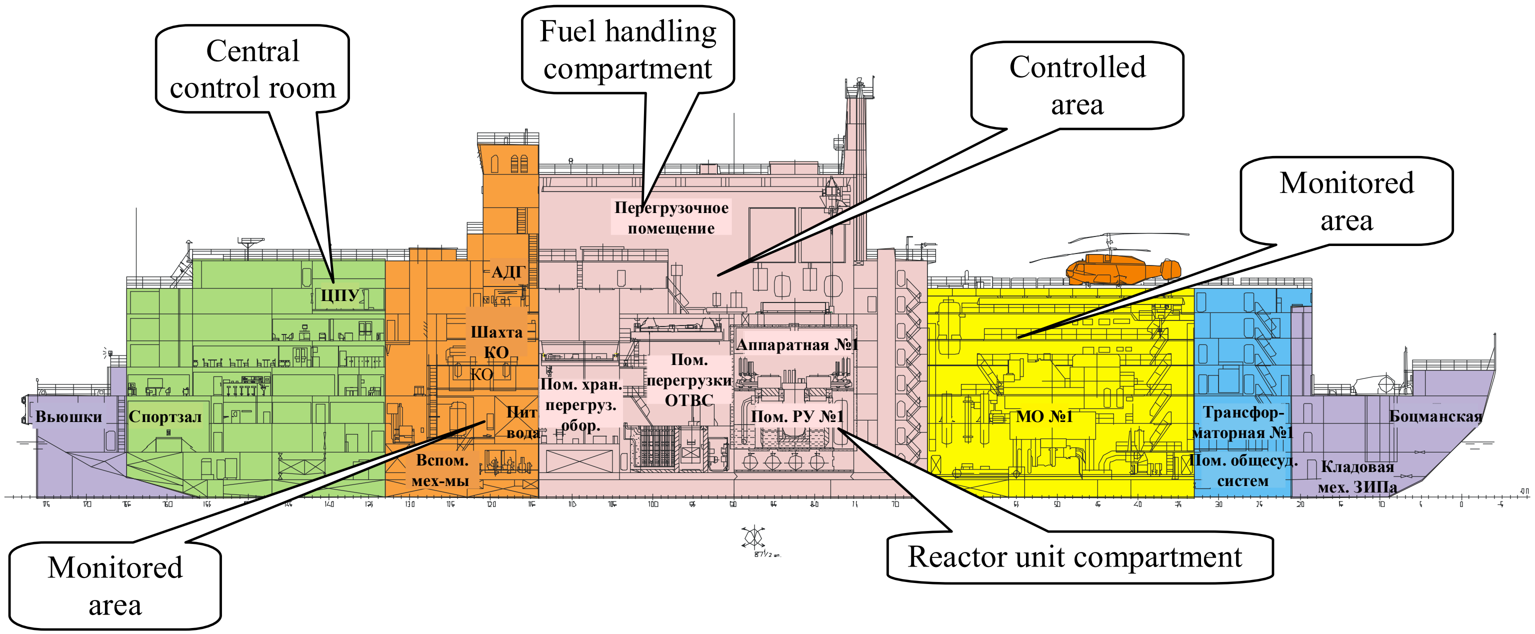
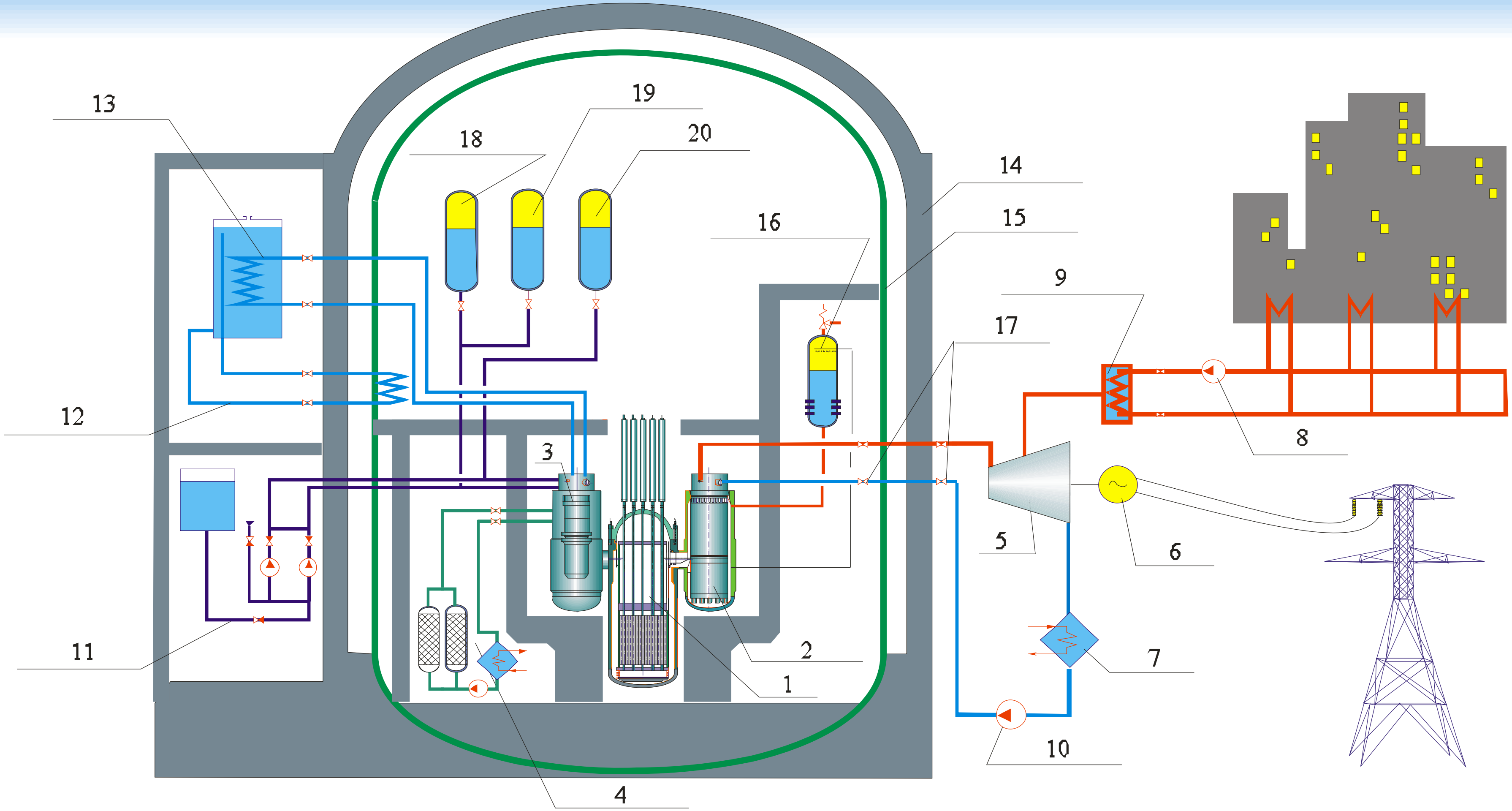


FIG. I-2. Floating power unit with two KLT-40S nuclear installations.

PWRs – Marine Reactor Derivatives – VBER-300 (Russia, Kazakhstan)



1-Reactor
2-Steam generator
3-Main circulating pump
4-Primary
5-Turbine
6-Generator
7-Condenser
8-Circuit pump
9-Circuit heat exchanger
10-Feedwater pump
11-Water and boron solution makeup system
12-Protective enclosure pressure drop system
13-Emergency heat removal system
14-Containment
15-Steel protective enclosure
16-Steam pressurizer
17-Stop valves
18-Hydraulic accumulator
19-Secondary stage ECCS tank
20 Boron solution passive supply system

Reactor Types/ Distinct Groups (Examples)
High Temperature Gas Cooled Reactors/ Direct Gas Turbine Brayton Cycle

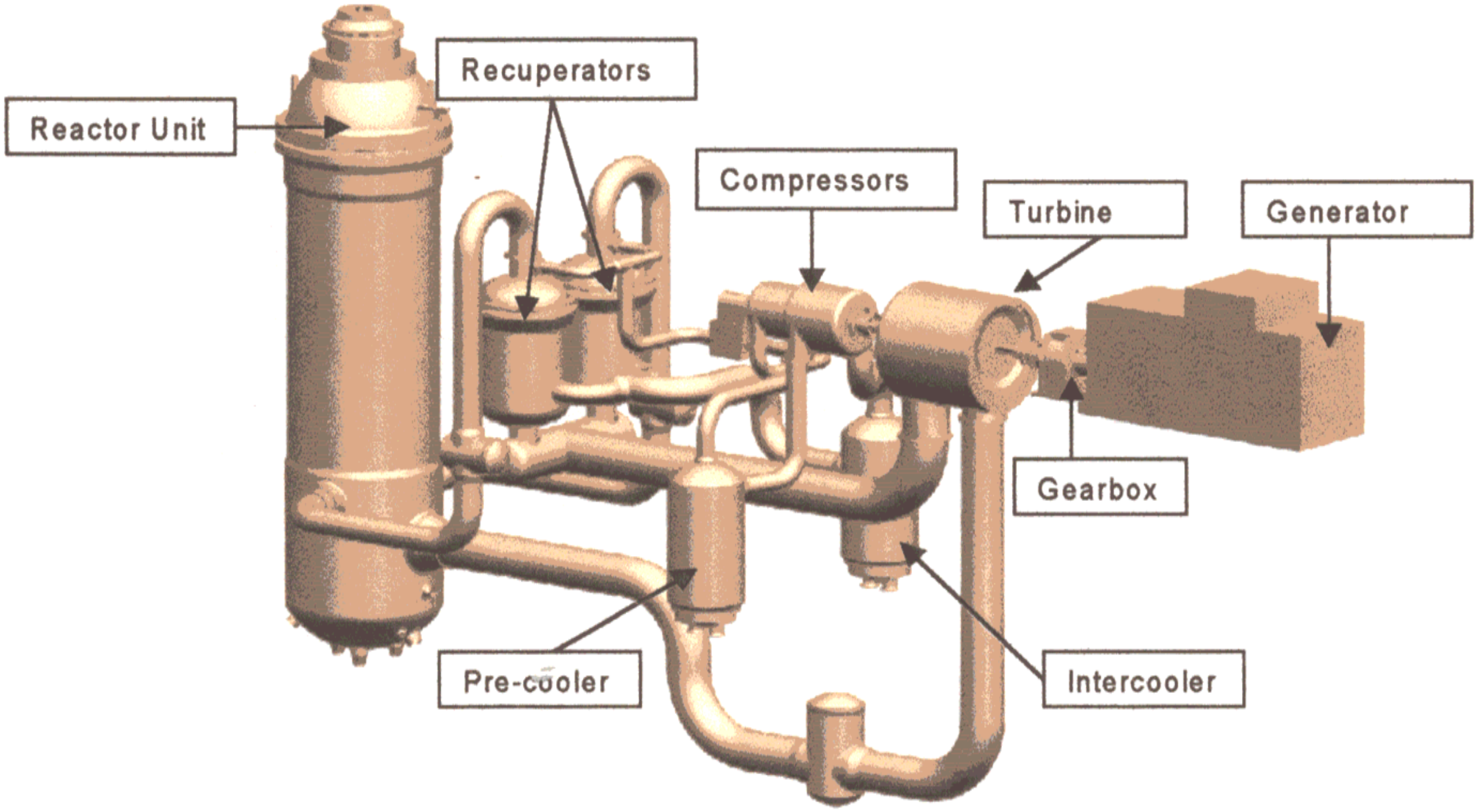
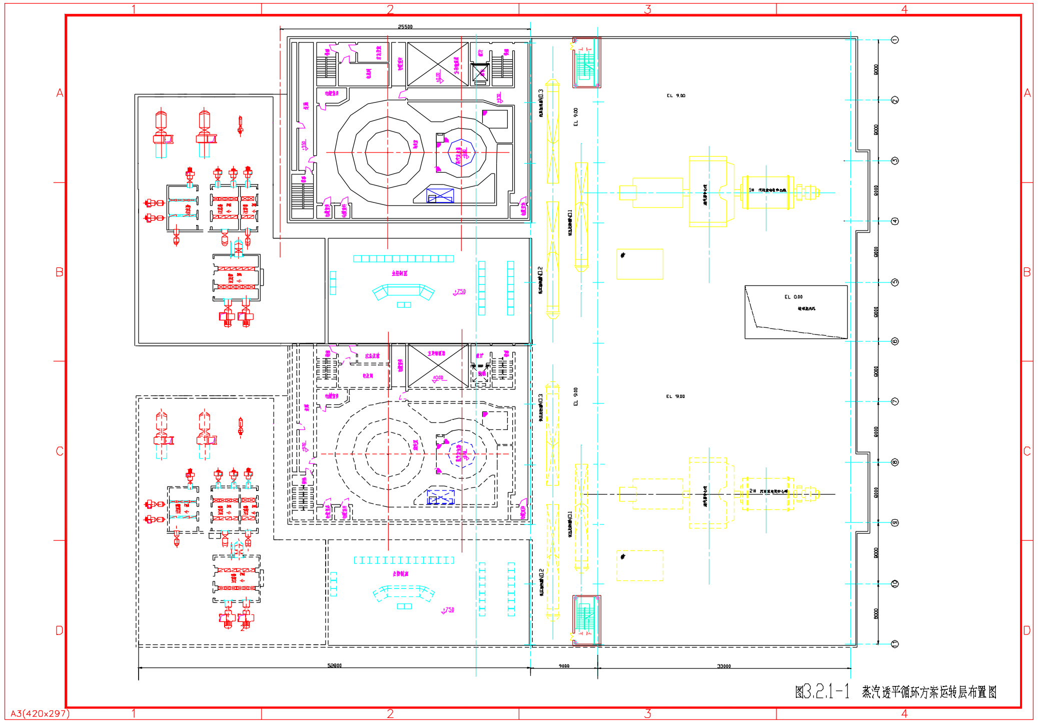


FIG. XIV-2. Conceptual layout of the PBMR primary system.

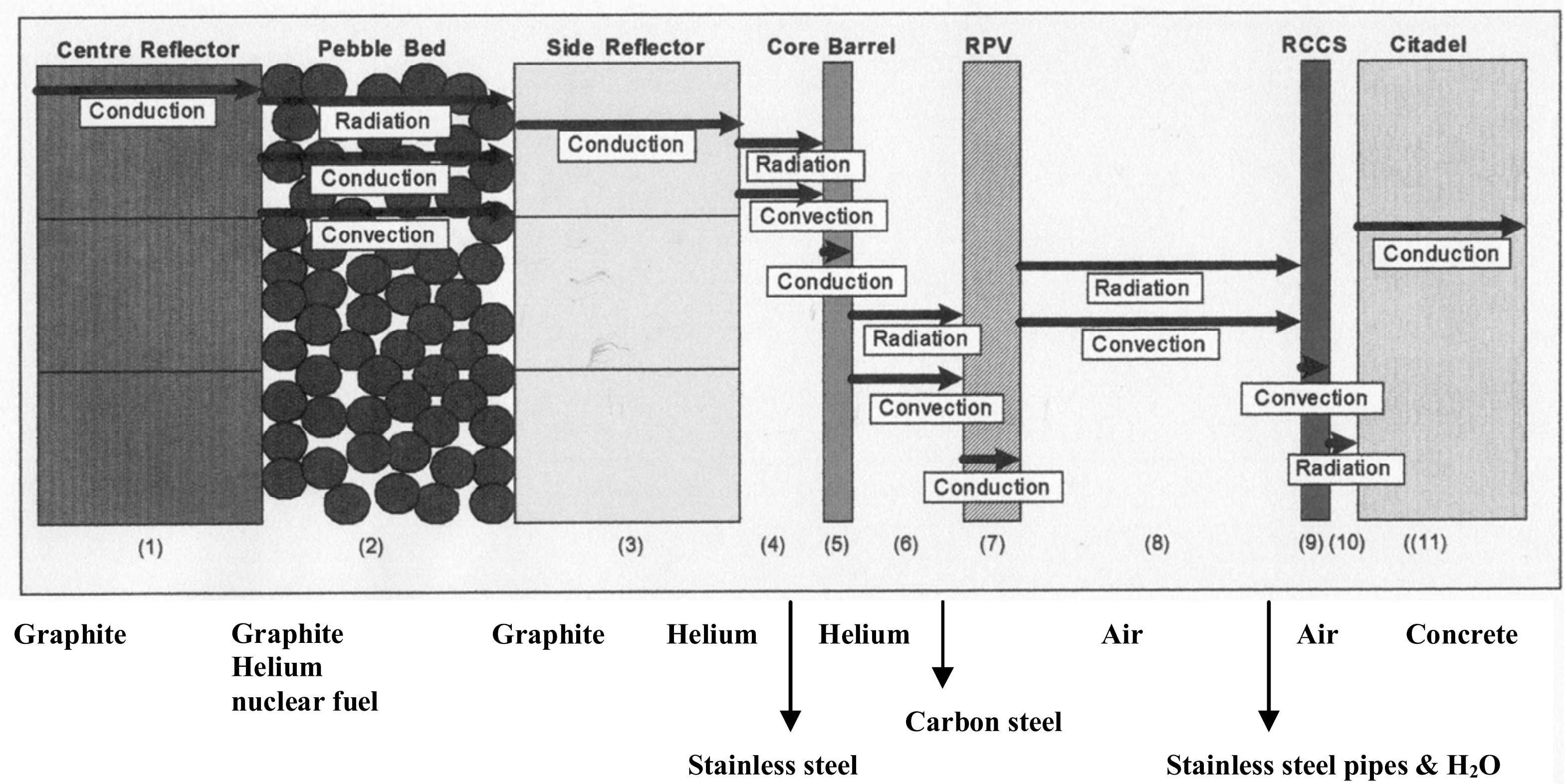
High Temperature Gas Cooled Reactors – HTR-PM (INET, China)

- High Temperature Gas Cooled Reactor – Pebble Bed Module (HTR–PM)
- Indirect cycle modular HTGR plant, which is designed by the Institute of Nuclear and New Energy Technology (INET), Tsinghua University of China.
- 250 MW electrical output per module.
- Targets: Construction related actions started in 2009, Licensing in progress



Reactor Types/ Distinct Groups (Examples)

High Temperature Gas Cooled Reactors/ Pebble Bed Fuel



Passive heat removal paths of PBMR (PBMR (Pty), Ltd., South Africa)

Reactor Types/ Distinct Groups (Examples)
High Temperature Gas Cooled Reactors/ Pin-in-block fuel

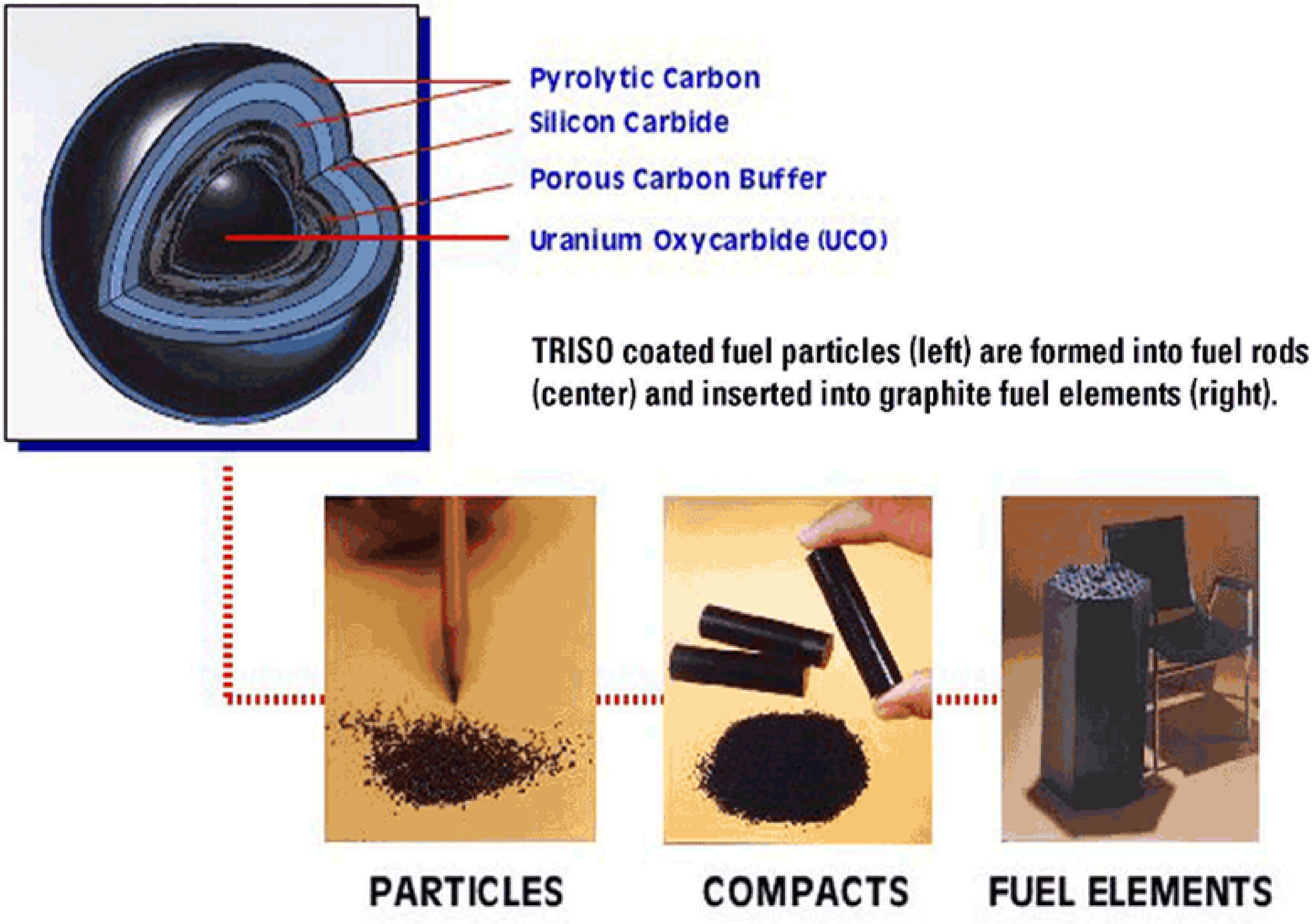


FIG. XV-11. GT–MHR fuel element.

INCENTIVES FOR SMRs -IN THE LONGER TERM

➢***Utilities and merchant plants for non-electric energy services worldwide*** ***(similar to aircraft, car and other mature industries)***

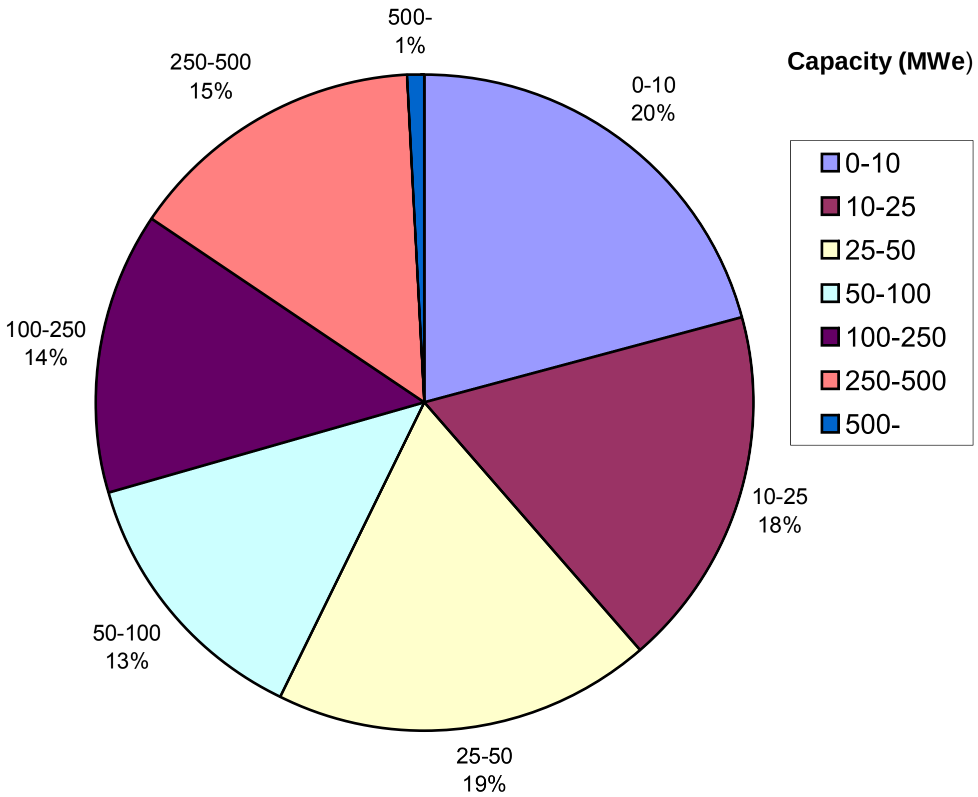
Primary energy (in developed countries) is utilized in three roughly equal fractions [*]:

✓***A third is used to generate electricity;***
✓***A third is used in the transportation sector;***
✓***A third is used for domestic and industrial heating.***

[*] World Energy Book 2005, World Energy Council: http://www.worldenergybook.com/

Incentives for SMRs – In the Longer-Term

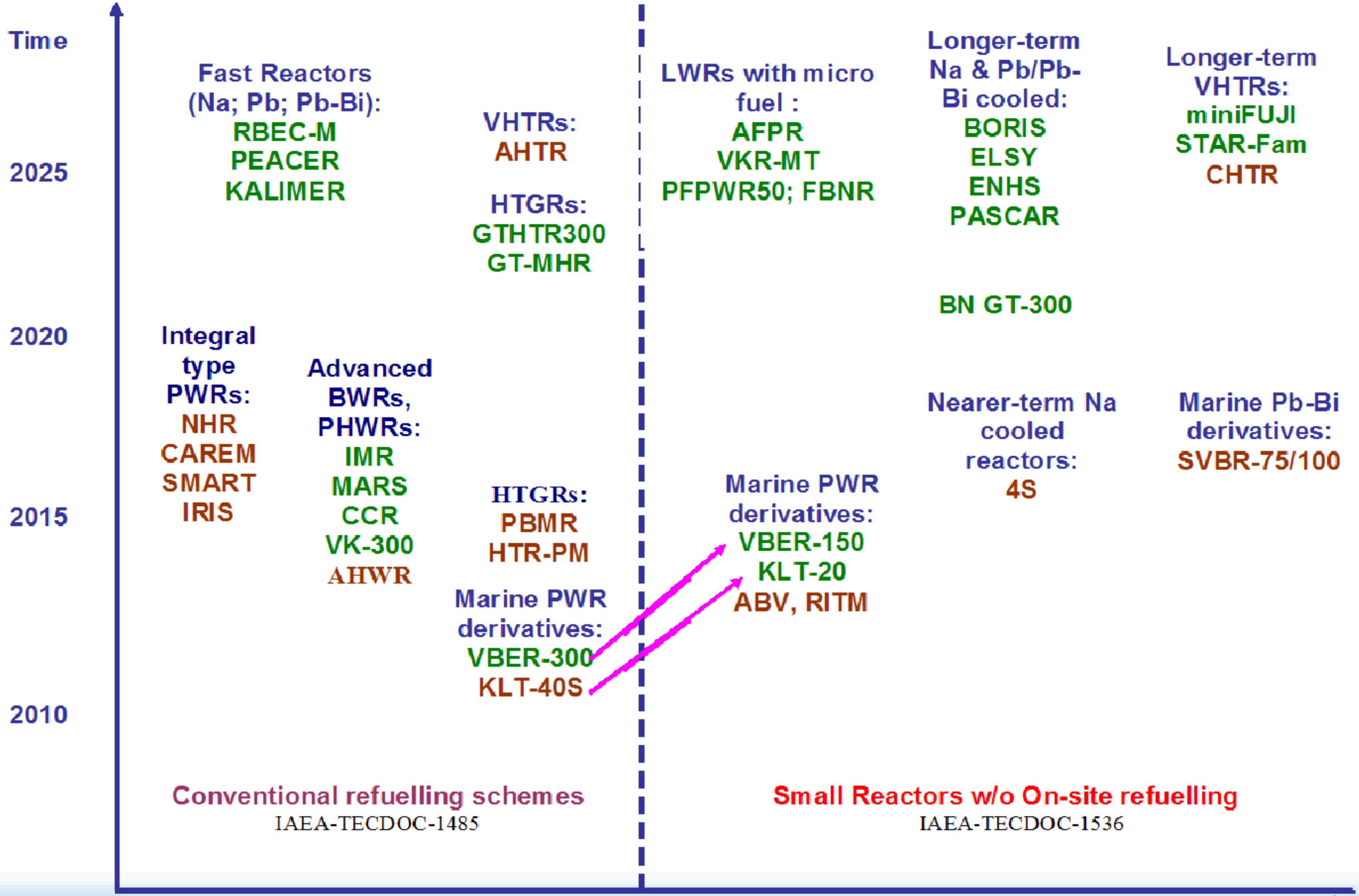
Looking into the future:



Distribution of units capacity (MWe) in Mexico (2003)
Selected capacity is 32208.24 MWe
(43,726.74 MW in total, by the end of December 31, 2003. CFE in Mexico)

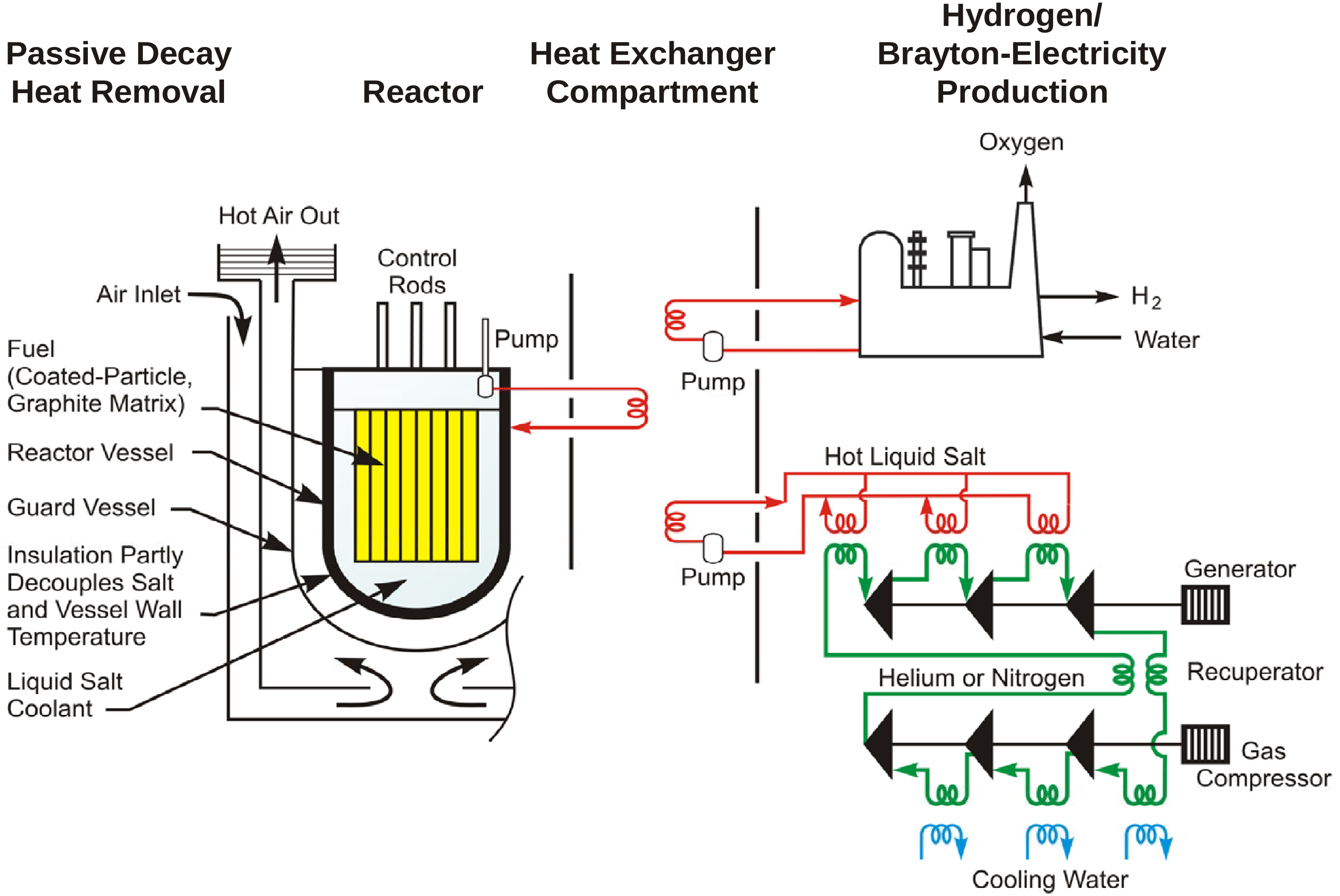
FIG. 10. Distribution of power plant sizes in Mexico.

Deployment potential of innovative SMRs



Reactor Types/ Distinct Groups (Examples)

Non-conventional Very High Temperature Reactor/ AHTR (ORNL and MIT, USA)



Definitions (IAEA-TECDOC-1536, January 2007)

- **Small Reactors Without On-Site Refuelling (SRWOR) are reactors designed for infrequent replacement of well-contained fuel cassette(s) in a manner that impedes clandestine diversion of nuclear fuel material**

- **Small reactors without on-site refuelling could be:**

  (a) Factory fabricated and fuelled transportable reactors or

  (b) Reactors with once-at-a-time core reloading on the site performed by an external team that brings in and takes away the core load and the refuelling equipment

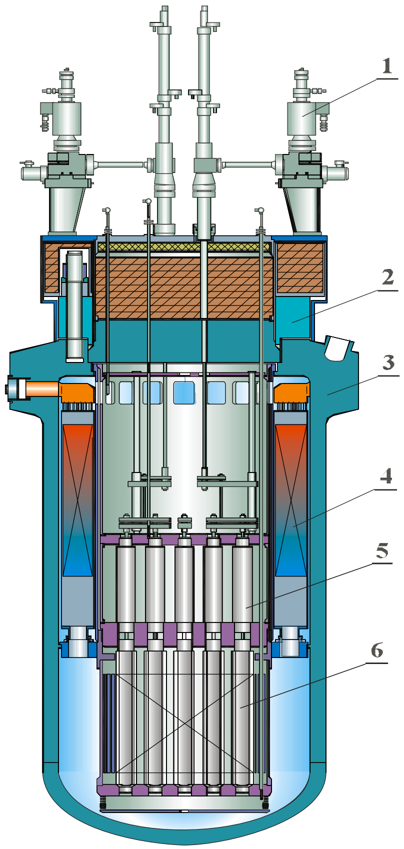
- **SRWOR incorporate increased refuelling interval (from 5 to 30+ years) consistent with plant economy and considerations of energy security**

SRWORs – Design Approaches

- **Design approaches to ensure long-life core operation include:**
  - ***Reduced core power density;***
  - ***Burnable absorbers (in thermal reactors);***
  - ***High conversion ratio in the core (in fast reactors)***
  - ***Refuelling performed without opening the reactor vessel cover***
- **The majority but not all SRWORs would end up at the same or less values of fuel burn-up and irradiation on the structures, although achieved over a longer period than in conventional reactors**

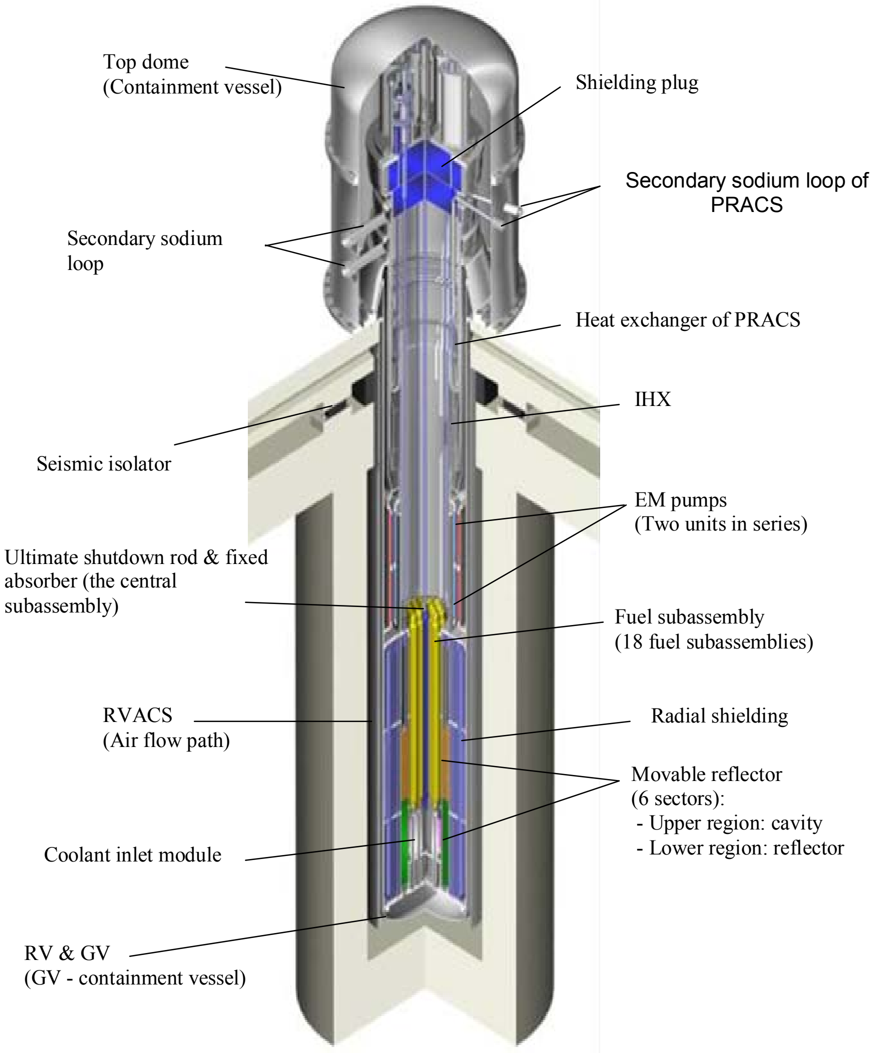
Small Marine-Derivative PWR without On-site Refuelling – ABV (Russia)

- **Designed by OKBM (Russia)**
- **11 MW(e) per module**
- **Operating experience – available**
- **Design – Licensed in most of its parts**
- **Targets: Floating NPPs around 2014-2015**



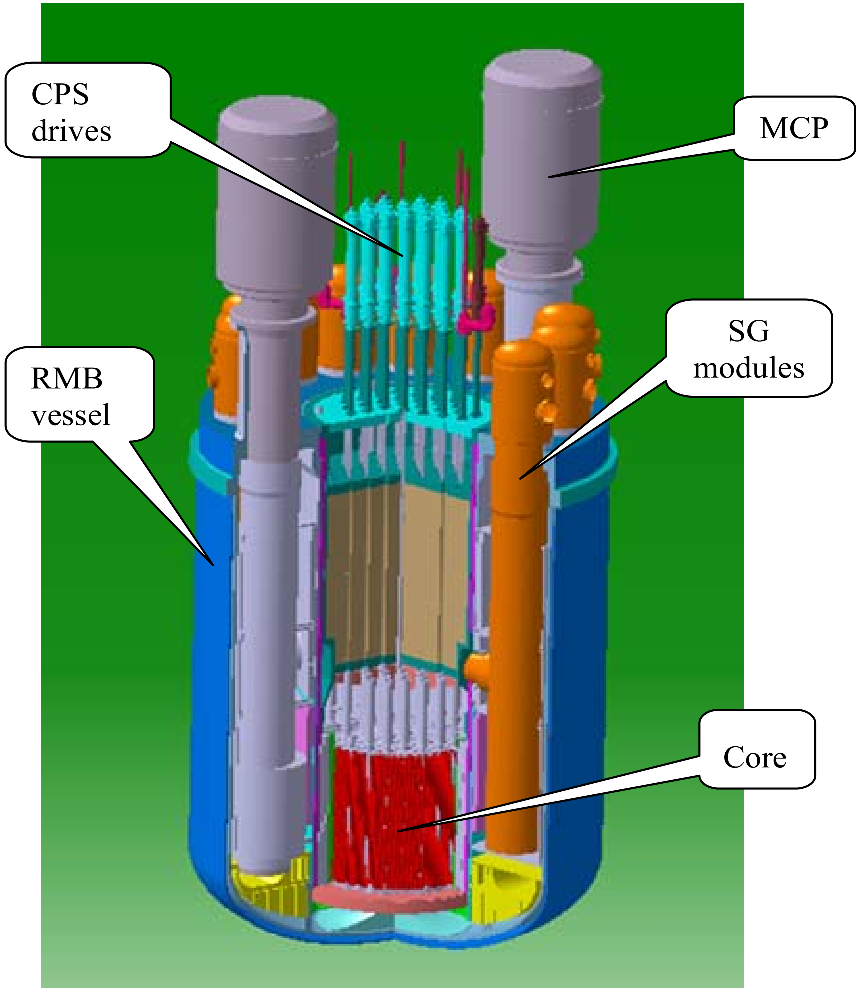
1 – CPS drive	2 – Reactor cover	3 – Reactor vessel
4 – Steam generator	5 – Block of protective tubes	6 – Core

Reactor Types/ Distinct Groups (Examples)
Sodium Cooled Fast Reactors/ SRWOR



4S sodium cooled reactor with a 30-year refuelling interval for a 10 MW(e) plant (Toshiba – CRIEPI, Japan)

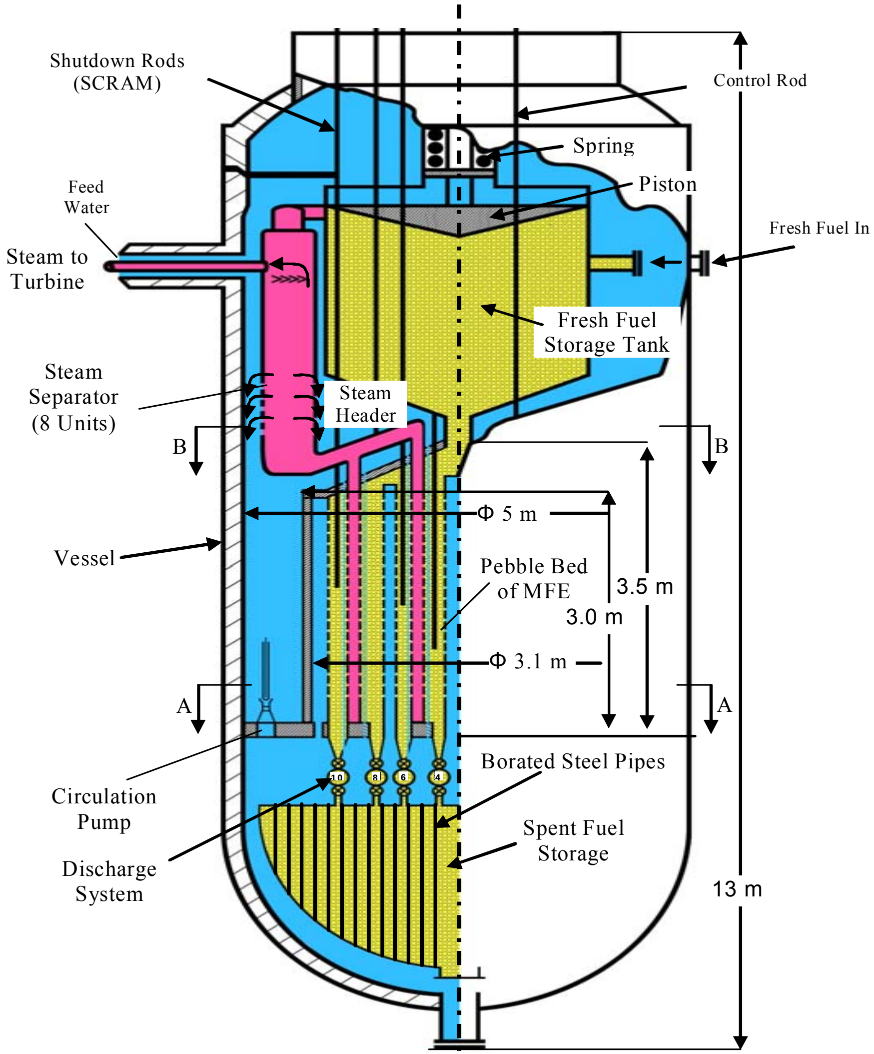
Reactor Types/ Distinct Groups (Examples)
Lead-Bismuth Cooled Reactors/ SRWOR

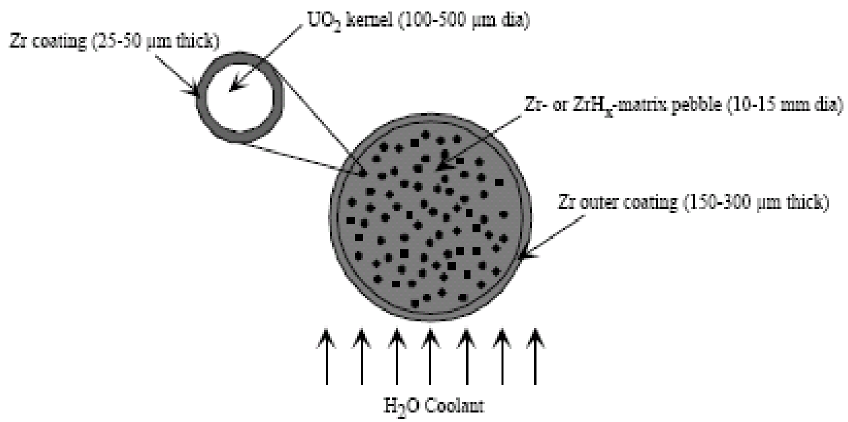


Pb-Bi cooled SVBR 100 reactor of 100 MW(e) with 6-9 EFPY refuelling interval (IPPE-“Gidropress”, Russia)

Reactor Types/ Distinct Groups (Examples)

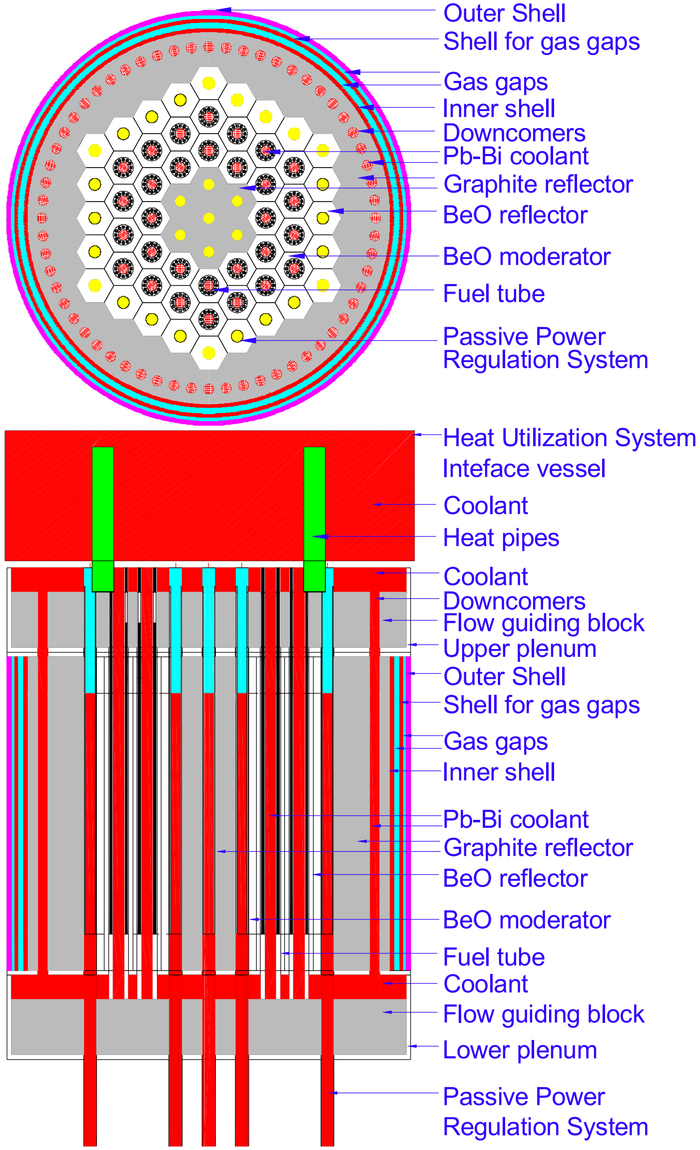
Non-conventional Water Cooled SRWOR/ AFPR-100 (PNL, USA)





Reactor Types/ Distinct Groups (Examples)

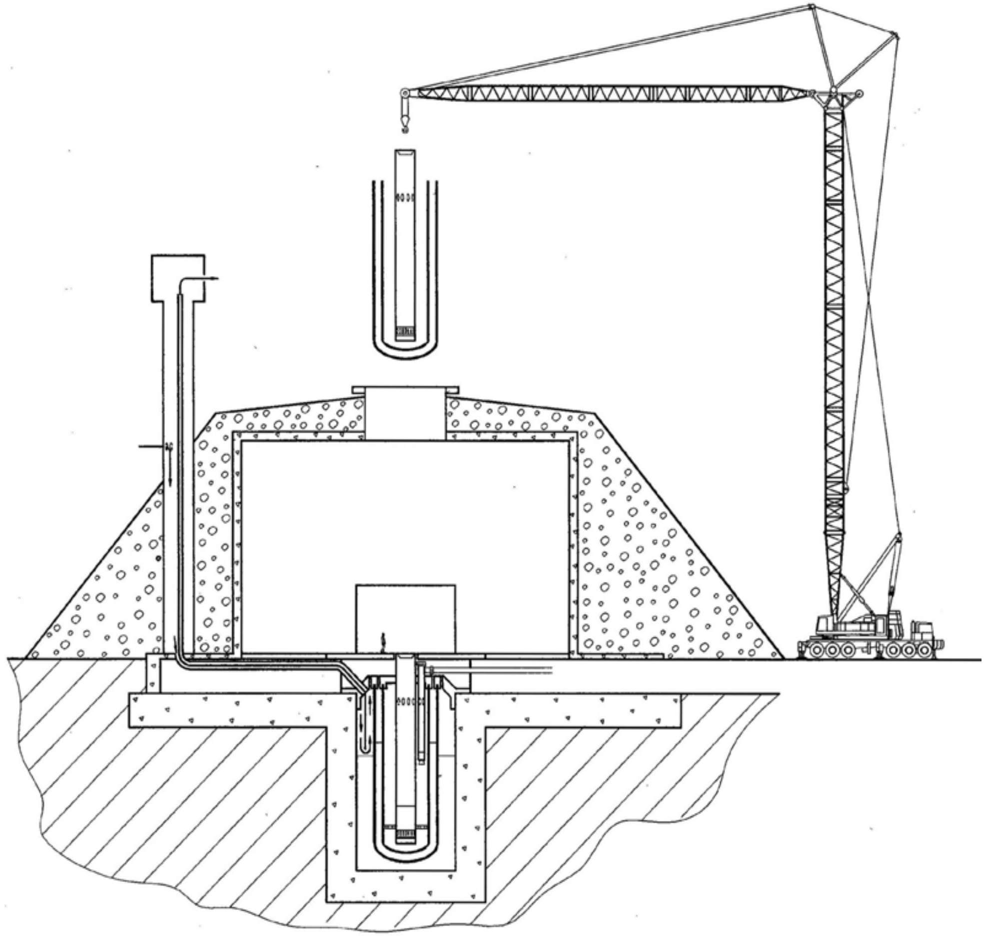
Non-conventional Very High Temperature SRWOR/ CHTR (BARC, India)



SRWORs - Special Features

Parameter	Range
Electrical power rating	From 2.5 to 300 MW(e), the majority is less than 100 MW(e)
Common fuel cycle support strategy: • Long refuelling interval and outsourced front and back end fuel cycle services • No refuelling equipment and fresh or spent fuel storages on the site	Implemented by one of the following options: • *Return floating plant to a factory* • *Return transportable land-based reactor module or plant to a factory* • *Whole core cassette refuelling* • *Sub-assembly cassette refuelling* • *In-situ pebble bed recharging*

SRWORs – Rapid Site Assembly example



Rapid site assembly of STAR-H2 reactor (ANL, USA)

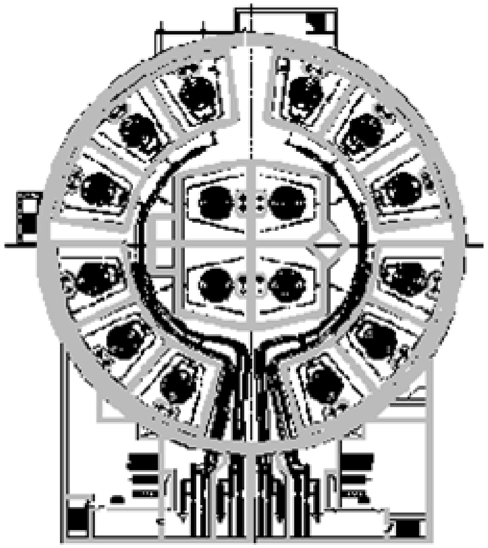
SRWORs – Design Status

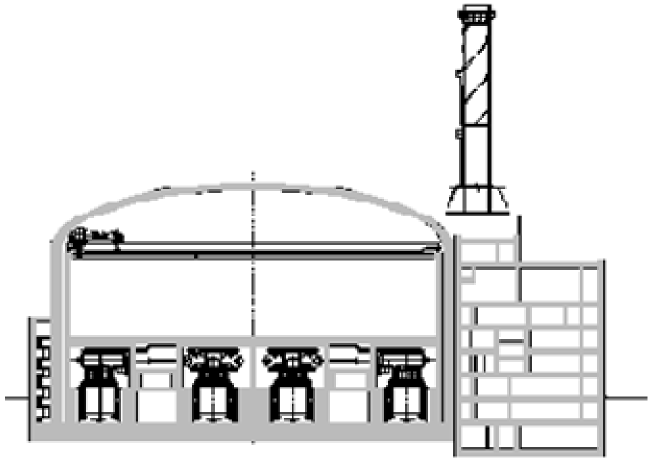
Development Approach	Time Scale to First Deployment*	Examples
Adaptation of proven designs by historical industrial consortia	5 - 6 years	*Derivatives of Russian icebreaker (water-cooled) and submarine reactors (water or Pb-Bi cooled)*
Size reductions using already commercialized fuels, coolants and components	Up to 10 years	•*Small oxide-fuelled PWRs* •*Small Na-cooled fast reactors*
Designs in conventional temperature ranges using new fuels, coolants, and structural materials	10 – 20 years	•*TRISO- or CERMET-fuelled water reactors* •*Nitride-fuelled Pb-Bi Reactors*
High temperature designs including hydrogen production	15 – 25 years	•*Pb, molten salt or gas cooled reactors at 700°C to 1000°C using nitride or TRISO fuel*

***First deployment – except for the first row of the table – will generally mean deployment of a prototype.**

Definition

Small reactor does not necessarily mean low-output NPP





Clustered modular nuclear steam supply system SVBR-1600 with 16 SVBR-100 modules (IPPE-“Gidropress”, Russian Federation)

HYPERION Concept

- ***Few technical details known***

- ***Technical concept originates from Los-Alamos National Laboratory USA***

- ***Intellectual property owned by a small private company***

- ***Aggressive PR campaign to raise funds***

Paper by Otis G. Peterson and Robert H. Kimpland, titled "Compact, Self-Regulating Nuclear Power Source" (Pacific Basin 2008)

DESIGN DATA:

- **Power:** *Few tens of MW(th), e.g., 25 MW(e)*
- **Core Diameter:** *0.5 - 2 m*
- **Core Height:** *0.5 - 2 m*
- **Operation Temperature:** *N/A*
- **Fuel:** *UHx, decomposeable x=1…3, Phase Stability 800 – 900 ^oC, Low enriched Uranium*
- **Fuel form:** *Fixed Pebble Bed, tiny particles, size not specified, flat surface at the top*
- **Heat removal:** *Heat Pipes, Na vapour, No pumps*
- **Power conversion:** *N/A, Non-electrical applications and co-generation foreseen*
- **Reactivity control:** *Passive, Doppler + Decomposition at increased temperature & Association at reduced temperature, No Control rods*

DESIGN DATA (CONTINUED):

❖**Start-up:** **Pumping very certain amount of hydrogen from outside**

❖**Shut down:** **Removing hydrogen from the core**

❖**Core temperature trap:** **Storage media (Depleted U) around the core kept at constant temperature (Three US Patents)**

❖**Reactor module layout:** **Core and storage media in several leak tight vessels**

❖**Plant layout :** **Underground reactor module, Surface Conversion system**

❖**Mode of power operation:** **Base Load and easy Load Following – Core temperature does not depend on removed power**

❖**Mode of supply:** **Factory-fabricated and fuelled reactor, long refuelling interval possible**

❖**Mode of deployment:** **Individual separate plants, No multi-modular plants**

❖**Fuel reprocessing:** **Metallic fuel reprocessing, H removed by heating**

HYPERION Concept

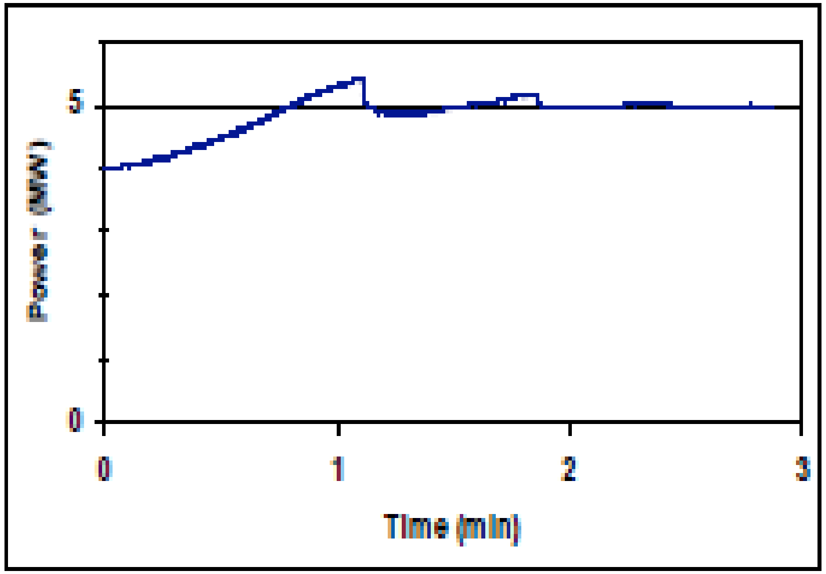


Figure 2. Power changes produce damped oscillations.

VALIDATION AND TESTING:

- **Core issue: Predictable performance of the uranium hydride fuel under changing temperatures and ambient hydrogen pressures**

- **“Uranium hydride was demonstrated to be a successful reactor fuel very early in the nuclear era” (around 1960) although “the hydride was cast in blocks using a polymetric binder to prevent the hydrogen from escaping”. “This binding of the fuel precluded any observation of the self-regulation characteristics inherent to the material”**
- ***Reliability of Storage media temperature maintenance system***
- ***Reliability of Start-up system***
- ***Fission gas release with hydrogen***
- ***Demonstration of operability and operation.***
- ***Etc., Etc.***

New Concepts of SRWORs

TRAVELLING WAVE REACTOR

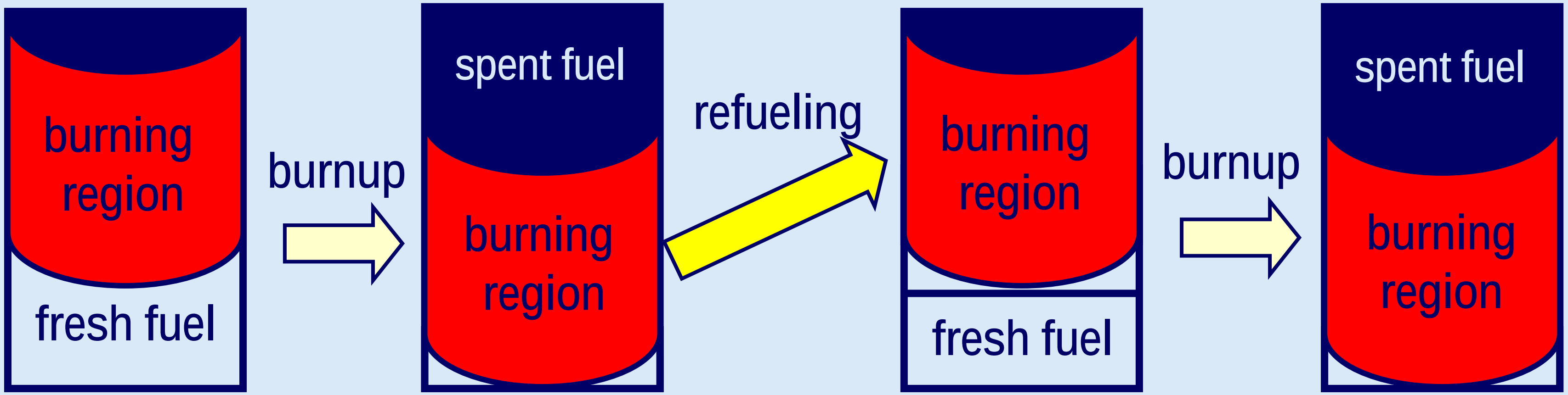
- ***Similar to CANDLE Concept of the TokyoTech (Japan)***

- ***Intellectual property owned by a private company TERRAPOWER-INTELLECTUAL VENTURES (USA)***

- ***Invited to Cooperate in IAEA Activities***

CANDLE

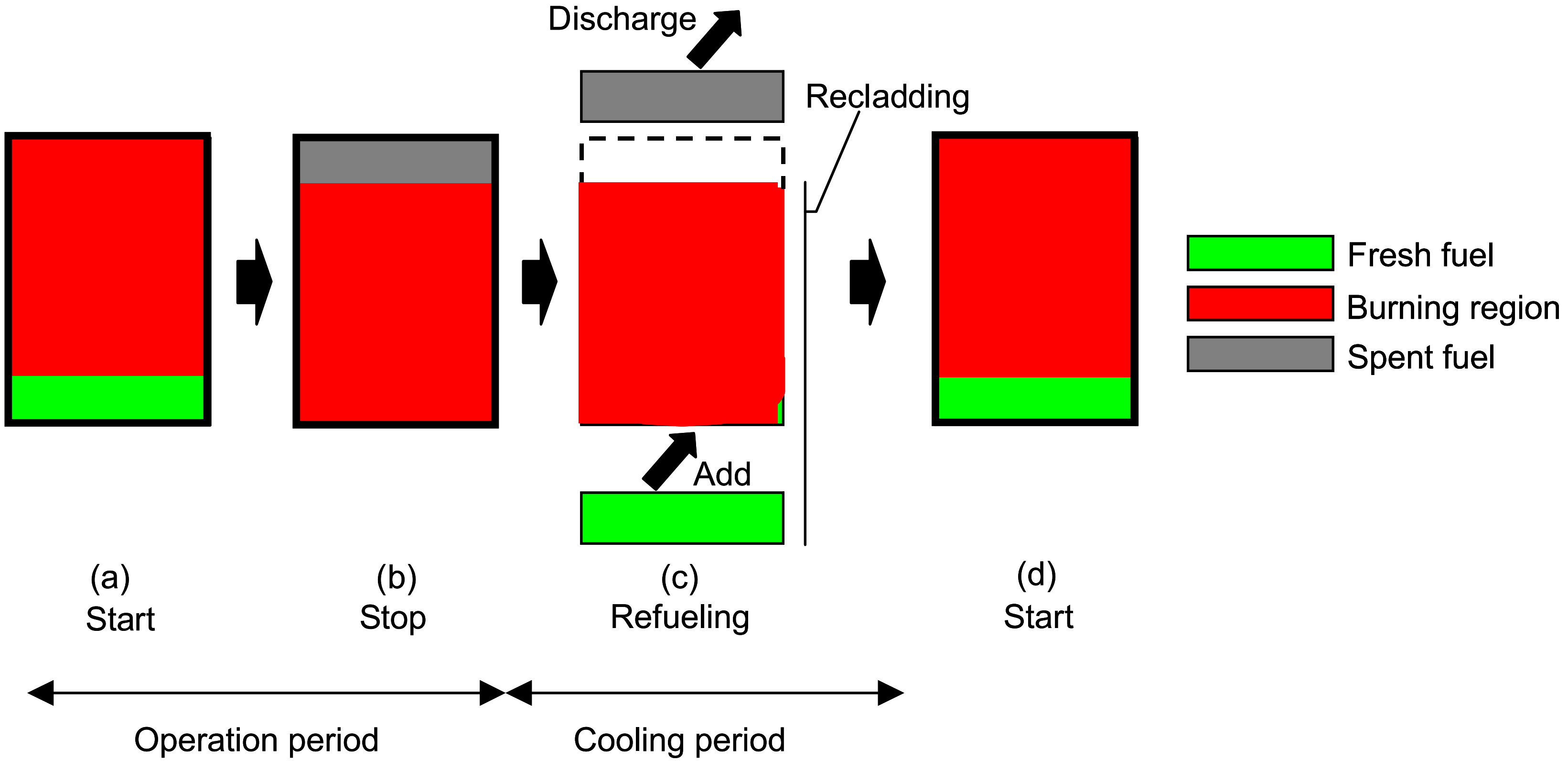
Constant Axial Shape of Neutron Flux,
Nuclide Densities and Power Shape
During Life of Energy Production



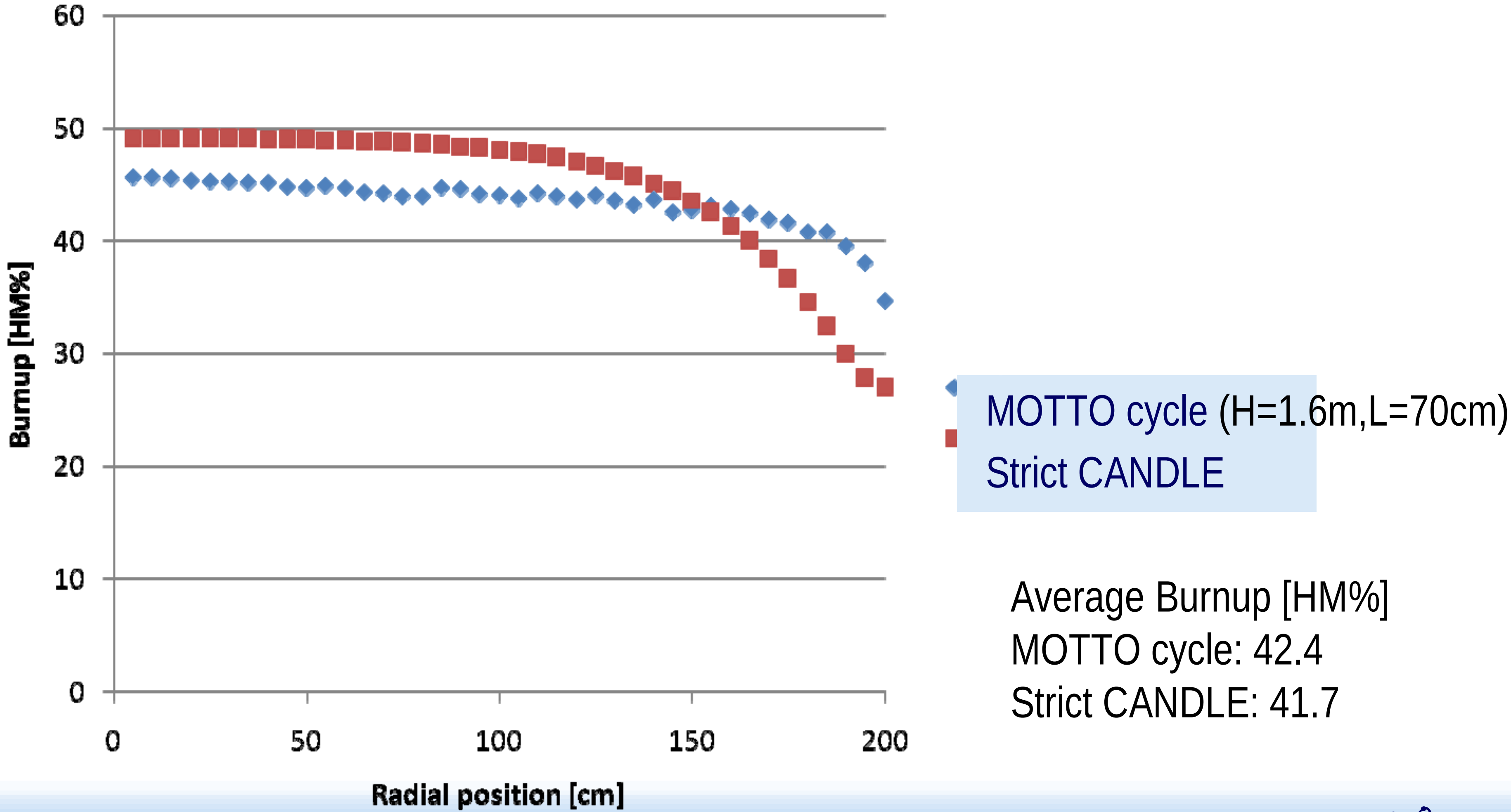
where

- Solid fuels are fixed in the reactor core. (same as the conventional reactors)
- No burnup control mechanism (such as control rod, movable reflector)

Recladding process employed in CANDLE burn-up



Discharged fuel burn-up for different radial position



Average Burnup [HM%]
MOTTO cycle: 42.4
Strict CANDLE: 41.7

Attractive Common Features of SMRs

➢ ***Option of incremental capacity increase, flexible and just-in-time capacity addition***

➢ ***Potentially, smaller emergency planning zone and proximity to the users***

➢ ***A variety of flexible and effective non-electrical application options (i.e., co-generation)***

➢ ***For small reactors without on-site refuelling: long refuelling interval and reduced obligations of the user for spent fuel and waste management***

Project "Common Technologies and Issues for SMRs"

P&B 2008-2009: 1.1.5.4 Recurrent Project, Ranking 1

Objective:

- To facilitate the development of key enabling technologies and the resolution of enabling infrastructure issues common to future SMRs of various types

Expected outcome:

- Increased international cooperation for the development of key enabling technologies and the resolution of enabling infrastructure issues common to future SMRs of various types

Project "Common Technologies and Issues for SMRs"

Deliverables

✓INTERNATIONAL ATOMIC ENERGY AGENCY, Innovative Small and Medium Sized Reactors: Design Features, Safety Approaches, and R&D Trends, IAEA-TECDOC-1451, Vienna (May 2005)

✓INTERNATIONAL ATOMIC ENERGY AGENCY, Advanced Nuclear Plant Design Options to Cope with External Events, IAEA-TECDOC-1487, Vienna (February 2006);

✓INTERNATIONAL ATOMIC ENERGY AGENCY, Status of Innovative Small and Medium Sized Reactor Designs 2005: Reactors with Conventional Refuelling Schemes, IAEA-TECDOC-1485, Vienna (March 2006)

✓INTERNATIONAL ATOMIC ENERGY AGENCY, Status of Small Reactor Designs without On-site Refuelling, IAEA-TECDOC-1536, Vienna (March 2007)

✓Appendix 4 of the IAEA Nuclear Technology Review 2007, titled "Progress in Design and Technology development for Innovative SMRs",

✓INTERNATIONAL ATOMIC ENERGY AGENCY, Design Features to Achieve Defence in Depth in Small and Medium Sized Reactors, NUCLEAR ENERGY SERIES REPORT NP-T-2.2 (2009)

✓INTERNATIONAL ATOMIC ENERGY AGENCY, Approaches to Assess Competitiveness of SMRs, NUCLEAR ENERGY SERIES REPORT (Final Editing, to be Published in 2009)

✓INTERNATIONAL ATOMIC ENERGY AGENCY, Final Report of a CRP on Small Reactors Without On-site Refuelling, IAEA-TECDOC (Drafting, to be Published in 2010)

✓SMR Inputs for Updateable Electronic Database of Advanced Reactor Designs – In Progress, More Than 30 Designers Preparing Their Inputs

Economics and Investments

There is no case when a single small plant needs to be compared to a single large plant:

- ***Either a single SMR goes where there is no option to accommodate a large NPP (and then the competition are non-nuclear options available there)***

Addressed explicitly in the activities on energy planning by IAEA/NE/PESS

- ***A series of SMRs is considered against fewer larger plants of the same total capacity***

Economics and Investments – Deployment in Series

Economics – Conventional Approach:

G4-ECONS Model: angelique.servin@oecd.org

LUEC = LCC +[(FUEL+O&M+D&D)/E]

LUEC – Levelized Unit Electricity Cost

LCC – Levelized Cost of Capital

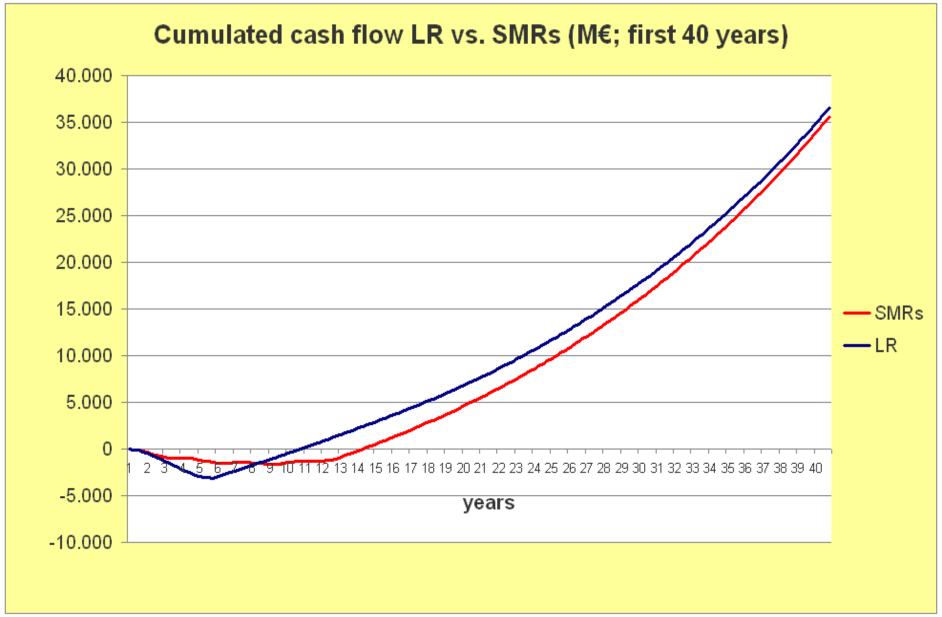
E – Average annual electricity production MWh

Assumption: Constant annual expenditures and production

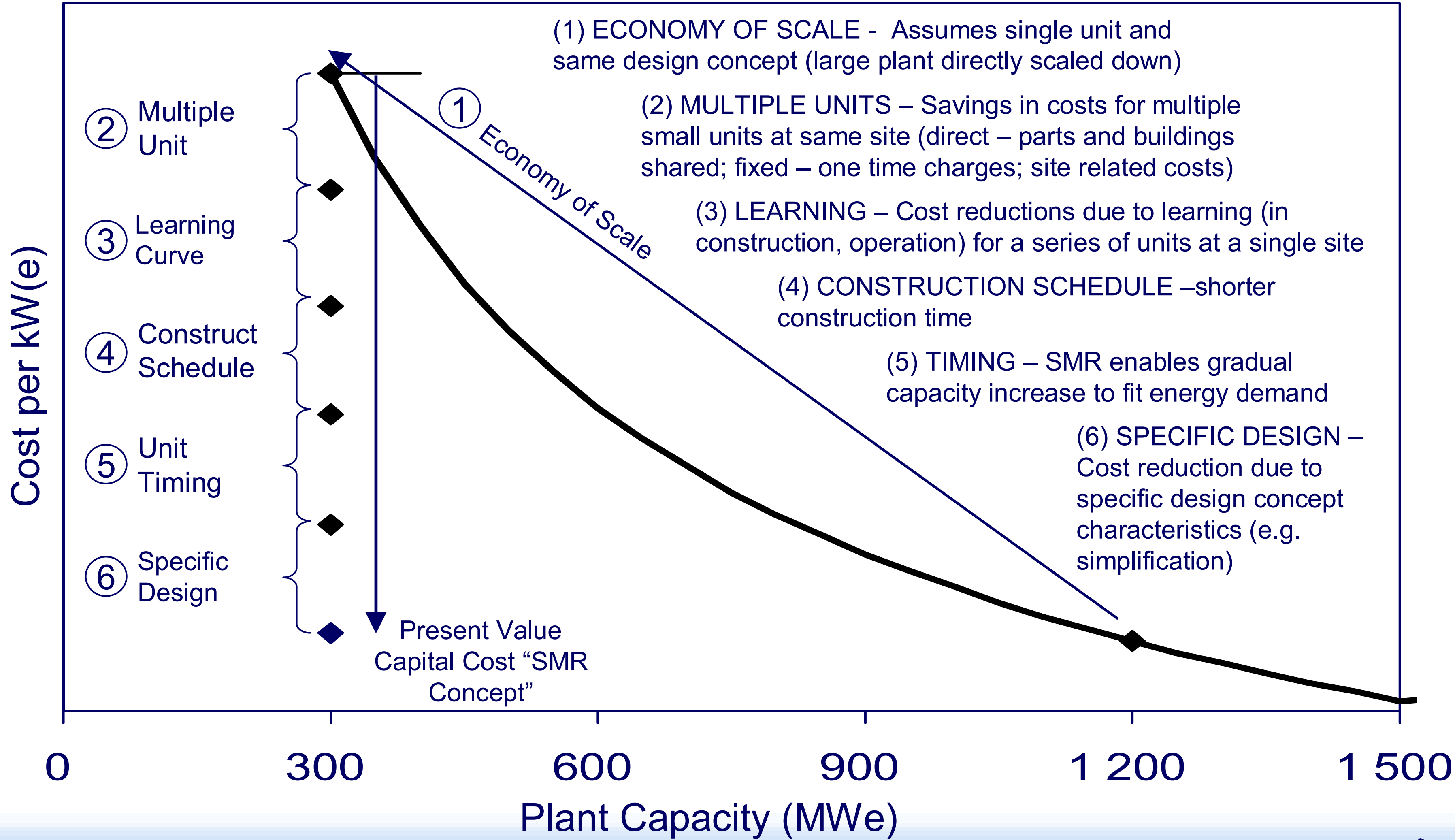
Investments and Revenues for Deployment in Series:

Important Factors:

- ✓ ***Time-Dependent Expenditure and Production***
- ✓ ***Uncertainties and Sensitivities***



Present Value Capital Cost (PVCC) Model – Westinghouse, USA



Economics Taking Into Account PVCC – A Simple Case Study
Present Value Capital Cost (PVCC) Model – Westinghouse, USA

Table 1. Assumptions for the test case.

SMR to large reactor capacity ratio	1:4
Scaled large reactor cost	Based entirely on large reactor design scaled to 1:4 ratio
SMR unit timing	Every 9 months
Discount rate	5% per year

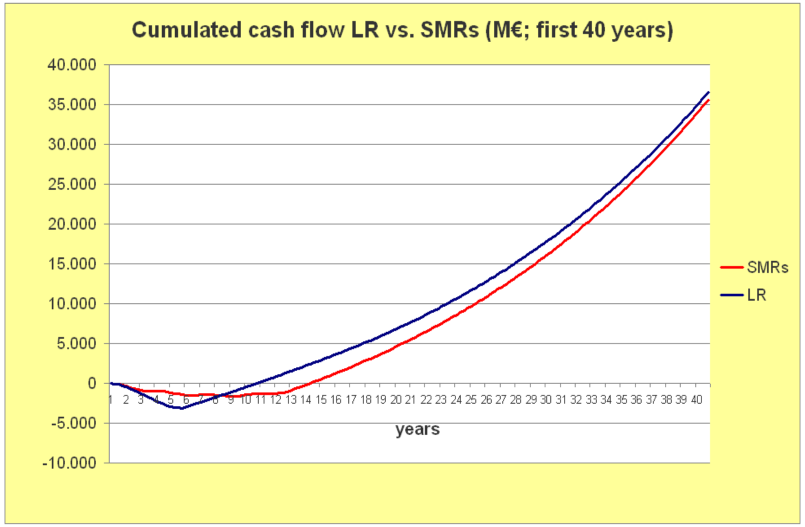
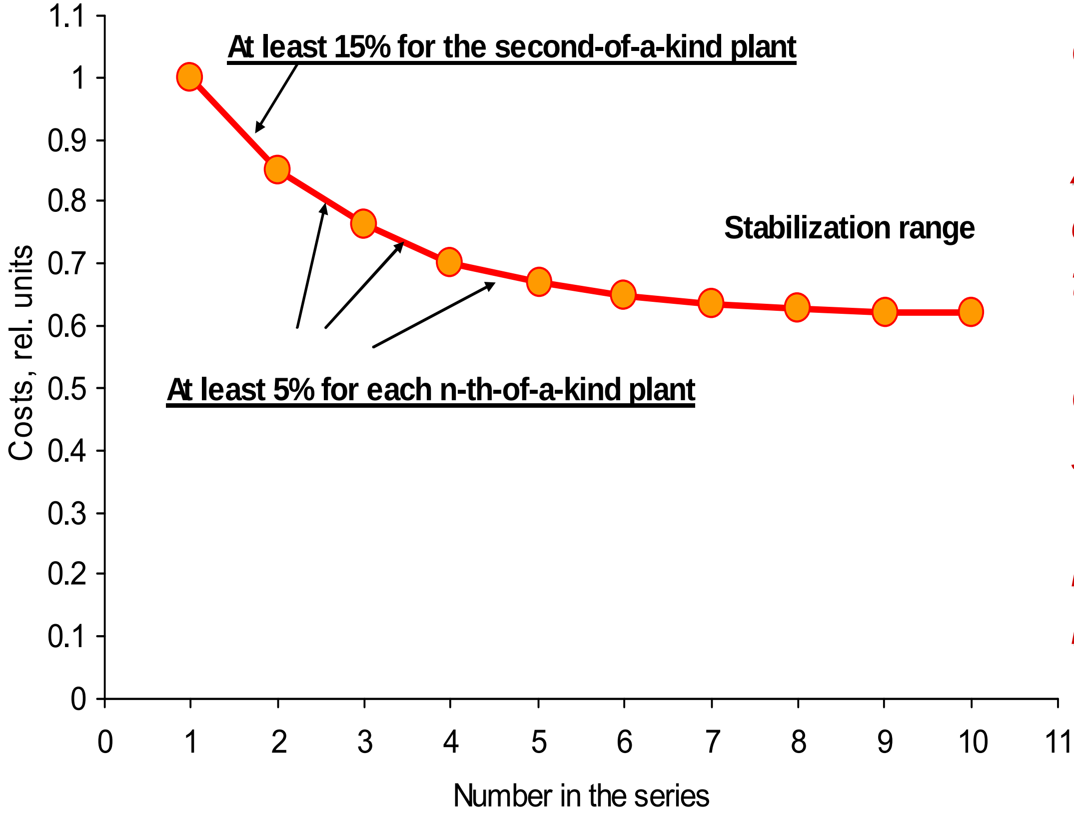


Table 2. Results of SMR capital cost factor model.

Capital cost factor	*Capital cost factor ratio (Four SMRs versus single large reactor, see Table 1)*		
	Overnight capital cost	*Total capital investment cost*	*Present value capital cost*
(1) Economy of scale	1.74	1.74	1.74
(2) + (3) Multiple units plus Learning	0.78	0.78	0.78
(4) Construction schedule	N/A	0.95	0.95
(5) Unit timing	N/A	N/A	0.94
(6) Design specific factor	0.85	0.85	0.85
Cumulative Total	*1.16*	*1.09*	*1.04*

The initial 74% economy of scale penalty is largely offset by capital cost improvement factors!

Learning Curve – Capital Cost Reduction; Example (OKBM, Russia)



➢ **_Learning Curve Applicability:_**

Only valid within a country

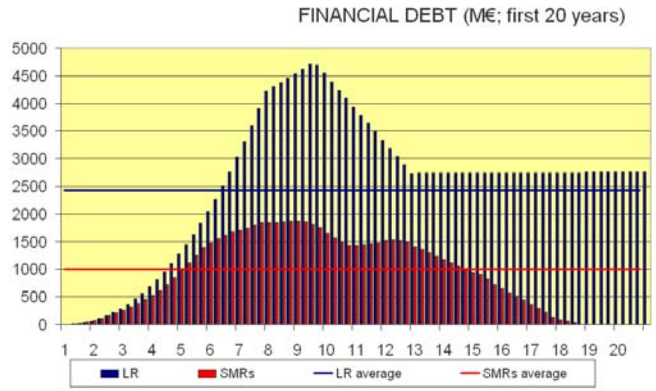
Assumes no substantial changes to regulations over time

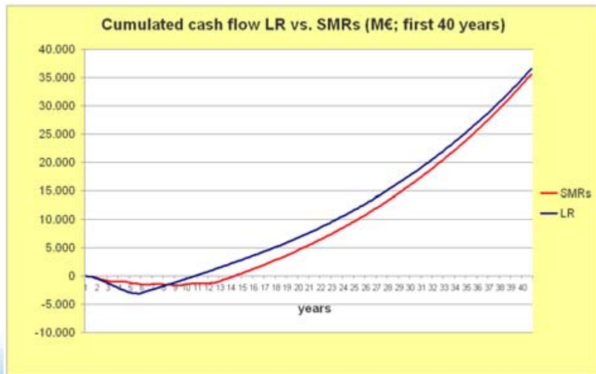
Cannot be extrapolated to new sites with new reactors

Depends on continuity in reactor build-up

The benefits of Investment Scalability - Case Study By Politecnico Di Milano (Italy)

- Incremental capacity reduces the required front end investment and the Capital-at-Risk
- Lower Interest During Construction compensates higher overnight costs:
  - ***Lower Total Capital Investment cost of SMRs vs. Large Reactors***
- Capital structure is more balanced and risk of default is lower
- SMRs may bear a higher financial leverage during construction.
- SMRs are able to absorb construction delay without heavy financial shock
- Profitability is comparable between LR and SMRs in terms of NPV and IRR
- Trade-off: excessively staggered construction delays full site power availability to the grid and lowers NPV of the project (by shifting cash inflows onwards).





G4-ECONS + PVCC Approach – Case Study by BATAN (Indonesia)

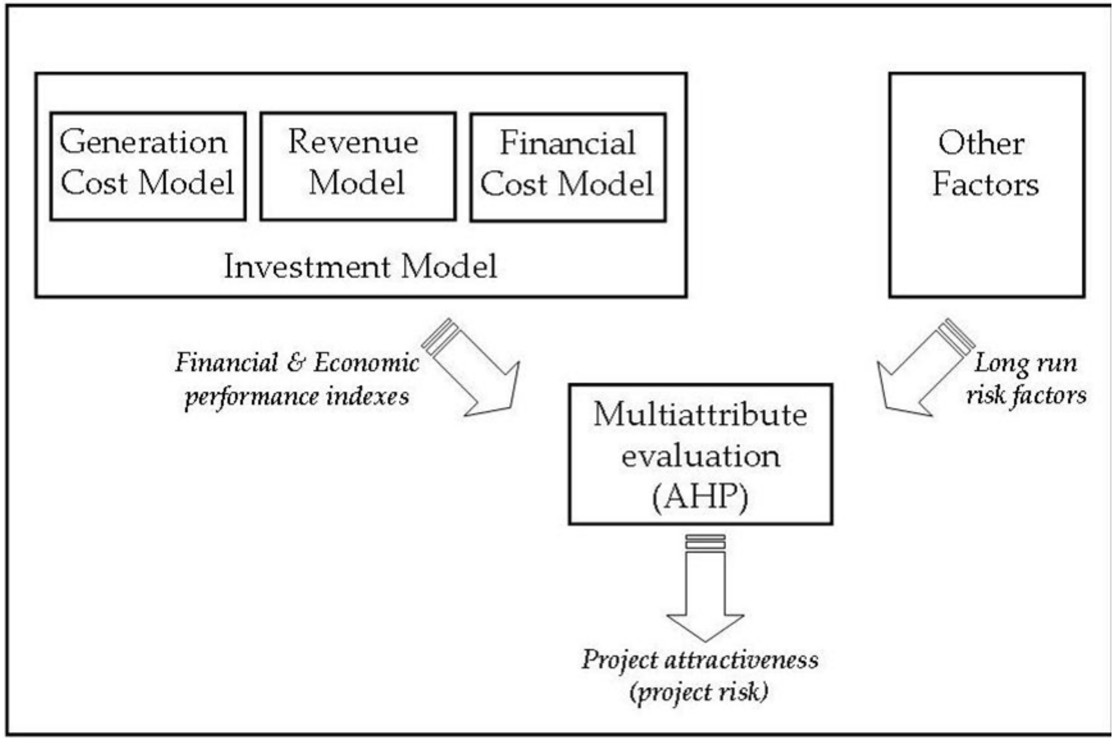
Table 1. Technical and economic parameters of MIT PBMR and PWR, year 2008

Description	Units	MIT PBMR 12 x 110 MWe	PWR 1 x 1300 MWe
Year Adjust	year	1	1
Hours in a Day	hours	24	24
Days in a Year	days	365	365
Reactor Net Electrical Capacity	MWe	1320	1300
Reactor Average Capacity Factor over Life	%	90	90
Thermodynamic Efficiency (net)	%	46	33
Plant Economic and Operational Life	years	40	40
Years to Construct	years	5	6
Real discount rate for Interest during Construction & Amortization	%	10%	10%

G4-ECONS + PVCC Approach – Case Study by BATAN (Indonesia)

Table 12. LUEC and LUPC (Desalination) of MIT PBMR and PWR

Description of LUEC and LUPC	**MIT PBMR (1 x 110 MWe)**		**MIT PBMR (12 x 110 MWe) w PVCC factors**		**MIT PBMR (12 x 110 MWe) w/o PVCC factors**		**PWR (1 x 1300 MWe)**	
	Electricity (mills$/kWh)	Desalination ($/m3 H2O)	Electricity (mills $/kWh)	Desalination ($/m3 H2O)	Electricity (mills $/kWh)	Desalination ($/m3 H2O)	Electricity (mills$/kWh)	Desalination ($/m3 H2O)
Capital (Including Financing)	58.15	0.078	46.61	0.063	58.15	0.078	44.01	-
Operations Cost	7.15	-	7.28	-	7.52	-	9.63	-
Fuel Cycle - Front End	6.50	-	6.50	-	6.50	-	7.44	-
Fuel Cycle - Back End	1.20	-	1.20	-	1.20	-	1.23	-
Non-energy options plus capital replacement component of unit cost	-	0.083	-	0.067	-	0.083	-	-
Energy component of unit cost	-	0.764	-	0.647	-	0.771	-	-
TOTAL of LUEC and LUPC	**73.74**	**0.925**	**61.66**	**0.777**	**73.43**	**0.932**	**62.38**	-



Framework of a general model for investment evaluation (POLIMI, Italy)

NEW MODELS AND SOFTWARE

•A variety of methods and tools required to conduct comparative economic assessments of SMRs versus larger reactors already exist in member states or are available from international organizations.

•In addition to this, the IAEA coordinates the development of an open model for the analysis of SMR economic and investment opportunities, which targets bringing together all currently available state-of-the-art models for generation costs, revenues, financial costs, and external factors and risks, while "keeping the door open" for any new approach or development once it becomes available.

•The open model is being developed for a specific task of comparing the deployments of SMRs versus larger reactors in liberalized energy markets.

•LUEC will be an important figure of merit in this model; however, provisions would be made to ensure that LEUC is calculated taking into account time-dependent expenditure and production profiles and changing interest rates.

•In addition models to calculate investment profiles and revenues will be included. Finally, an approach to take into account other factors potentially affecting the competitiveness of SMRs, such as energy supply security, proliferation-resistance, political posture, etc. will be developed.

✓**INTERNATIONAL ATOMIC ENERGY AGENCY, Approaches to Assess Competitiveness of SMRs, NUCLEAR ENERGY SERIES REPORT (Final Editing, to be Published in 2009)**

IAEA Technical Meeting To Coordinate Case Studies on SMR Competitiveness – 23-26 June 2004, Vienna, Austria – The Door Is Still Open!

We already have 17 participants from *Argentina, Croatia, India, Indonesia, Italy, Japan, the Republic of Korea, Lithuania, and the United States of America*

SAFETY

TO BE RATED SAFE, BOTH LARGE AND SMALL REACTORS SHOULD MEET SAFETY REGULATIONS CURRENTLY IN FORCE. HOWEVER, THE CONDITIONS OF SAFE OPERATION OF LARGER AND SMALLER PLANTS COULD BE DIFFERENT

- ***For smaller reactors these conditions may include emergency planning zone (EPZ) reduced against that needed for a large reactor***

- ***Reduced EPZ allows NPP location closer to the user, which could be a process heat application plant or a consumer of heat, potable water, etc.***

SAFETY

Current Safety Approach:

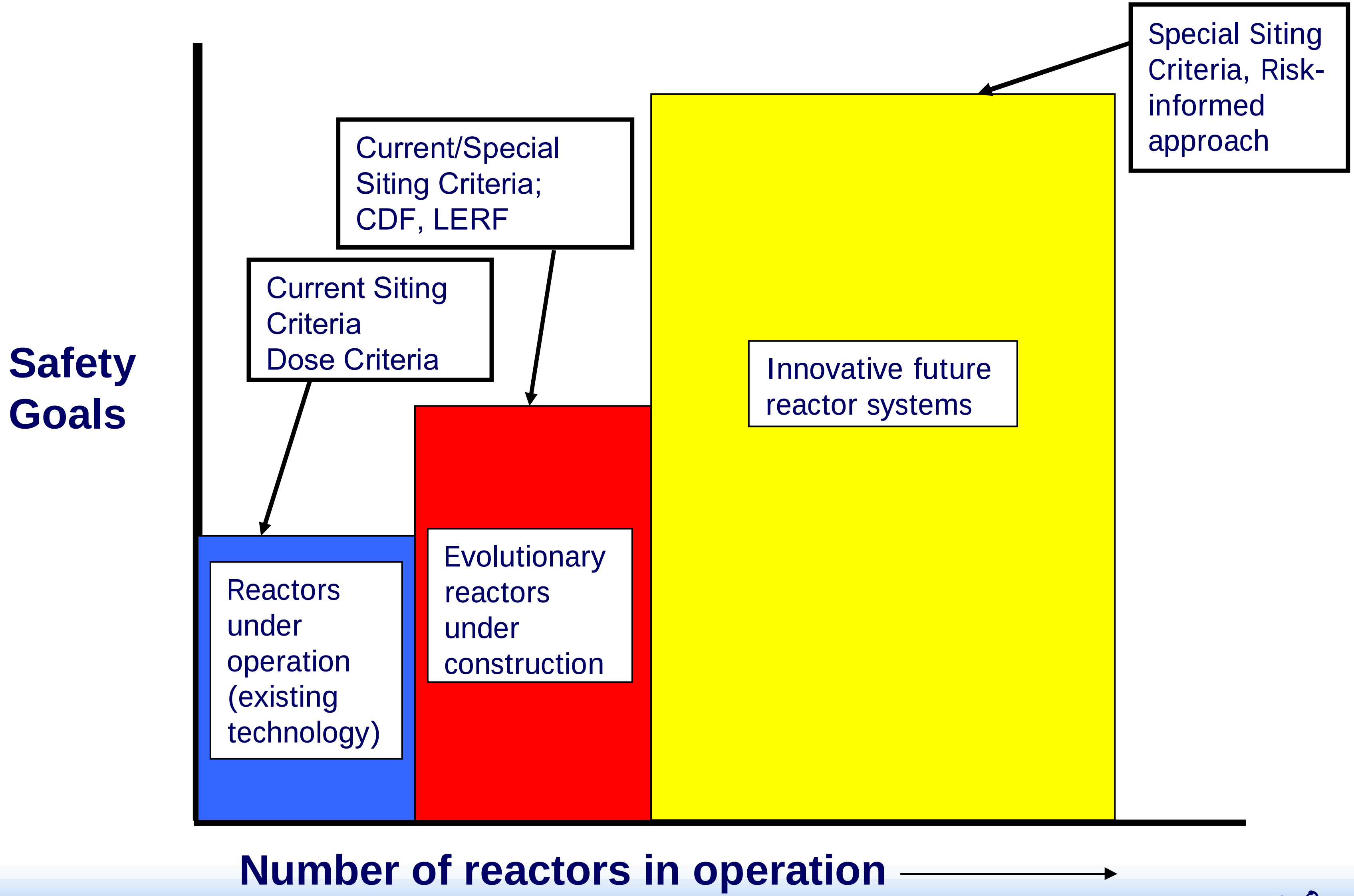
IAEA Safety Standard NS-R-1 "Safety of the Nuclear Power Plants: Design Requirements"

Main 'pillars':

- **Qualitative Safety Objectives** *of the general nuclear safety, the radiation safety, and the technical safety;*
- **Fundamental Safety Functions,** *which are the confinement of radioactive material, control of reactivity, and the removal of heat from the core;*
- *The application of* **Defence in Depth,** *which requires several levels of protection to be provided* **(multiple barriers to the release of radioactive materials + safety systems to ensure safe shutdown of the reactor)**
- *The application of* **Probabilistic Safety Assessment** *techniques, which complements deterministic methods*

SAFETY

Level of safety goals should, logically, increase with the size of the nuclear power programme (BARC, India)



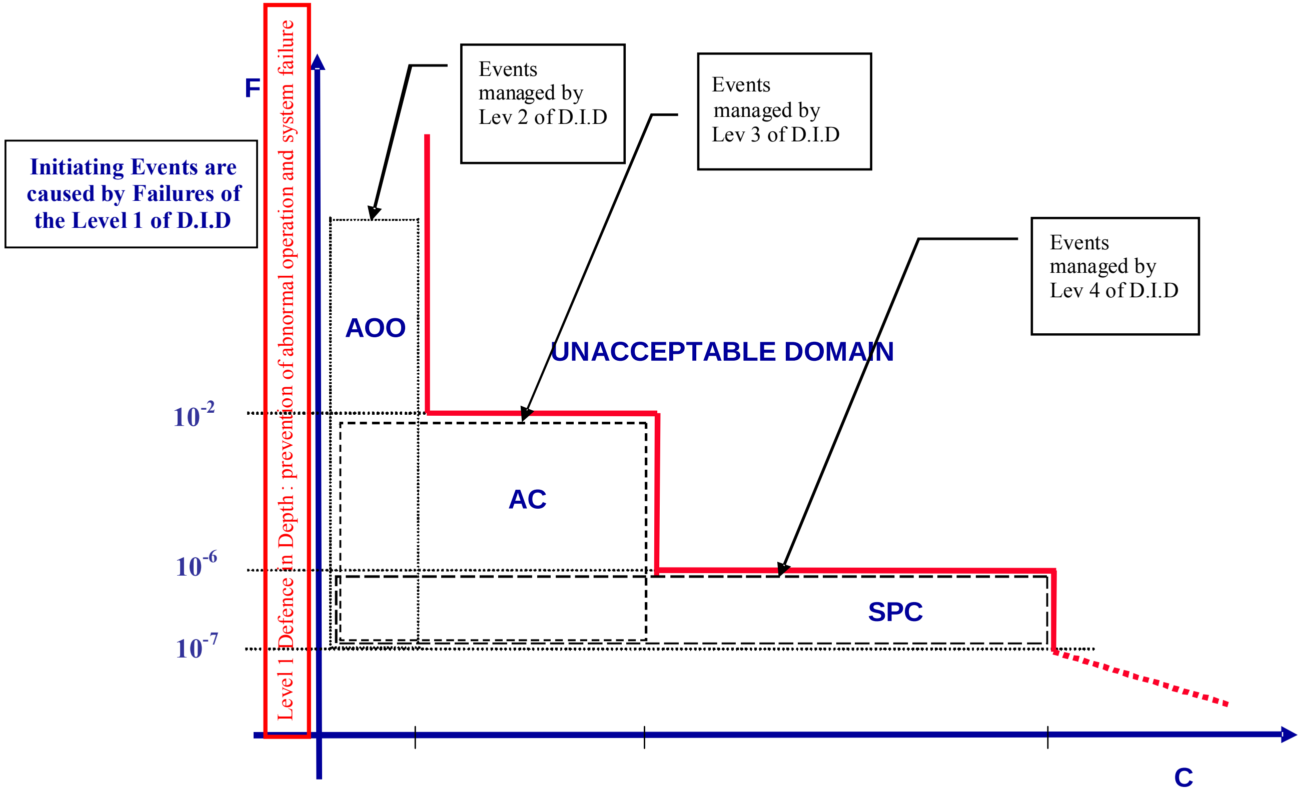
SAFETY

Proposal for a Technology-Neutral Safety Approach for New Reactor Designs (IAEA-TECDOC-1570, September 2007)

Main 'pillars':

- **Quantitative Safety Goals**, *correlated with each level of Defence in Depth;*
- **Fundamental Safety Functions**
- **Defence in Depth (generalized),** *which includes probabilistic considerations*

SAFETY APPROACH (*IAEA-TECDOC-1570)*

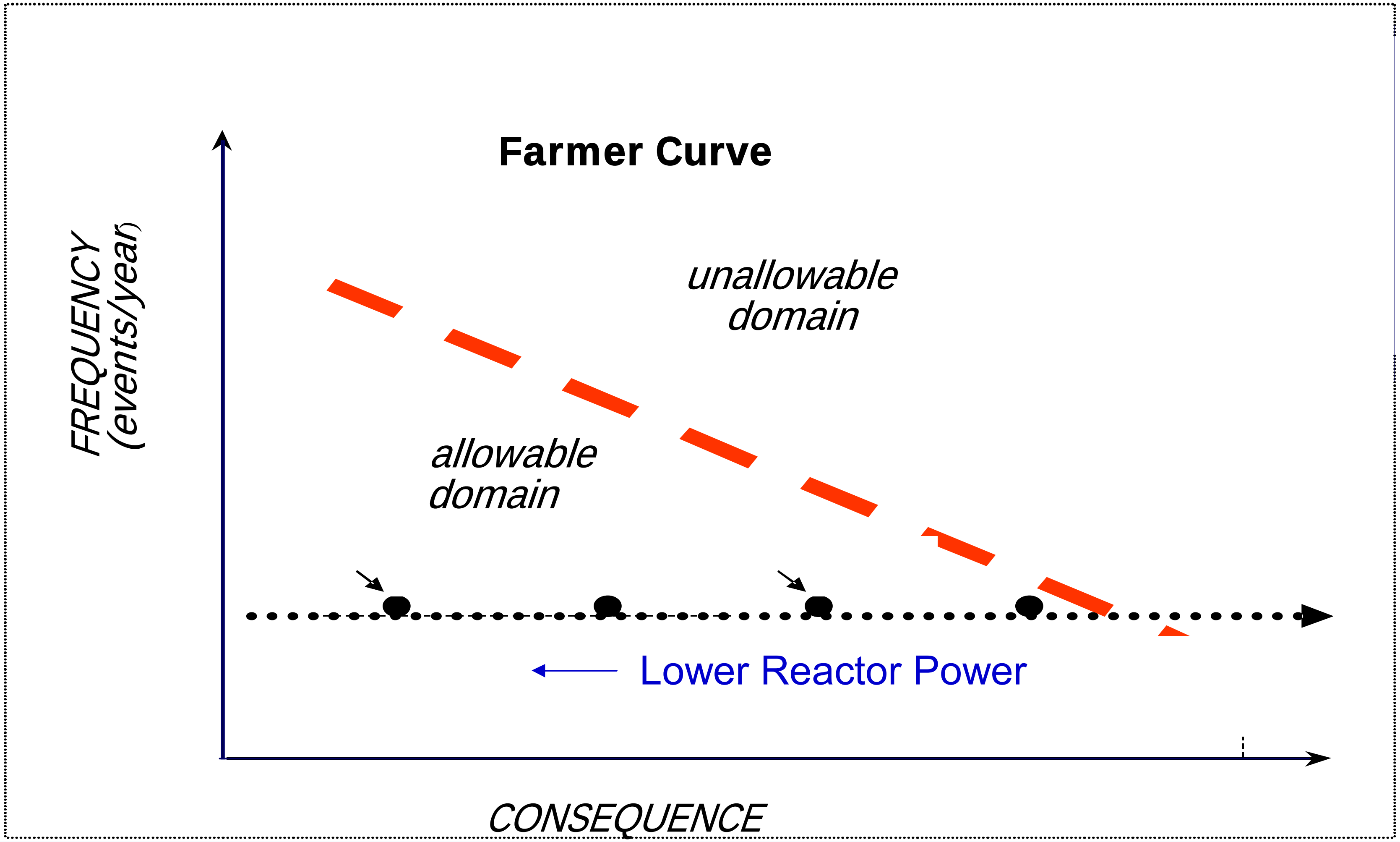


AOO – abnormal operation occurrences
F – frequency C – consequences

AC – accidental conditions
SPC – severe plant conditions

FIG. 2. Quantitative Safety Goal and Correlation of Levels of Defence

SAFETY
The role of passive safety features and reactor power



Safety

Source Term – the amount and isotopic composition of material released (or postulated to be released) from a facility

Used in modelling releases of radionuclides to the environment, particularly in the context of accidents at nuclear installations…

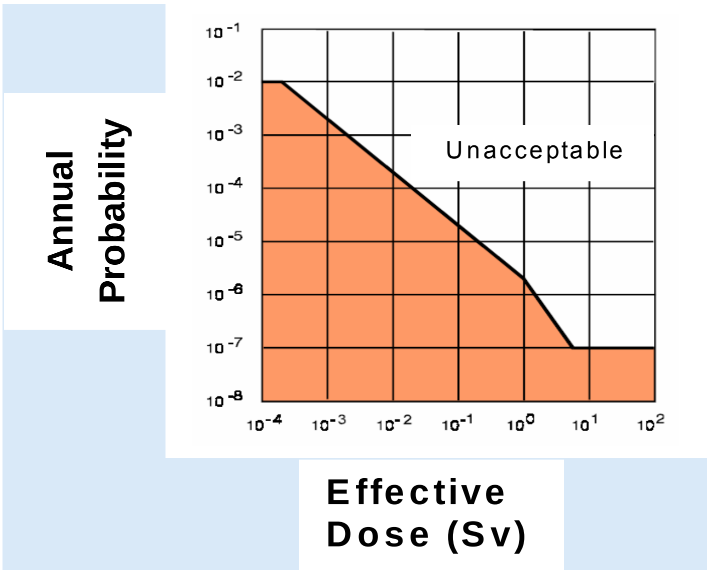
Smaller reactors may have smaller source terms owing to:

- *Smaller fuel inventory;*
- *Smaller stored non-nuclear energy*
- *Smaller cumulative decay heat rate*
- *Larger margins to fuel failure owing to smaller power density*
- *Smaller number of accident initiators provided by design*

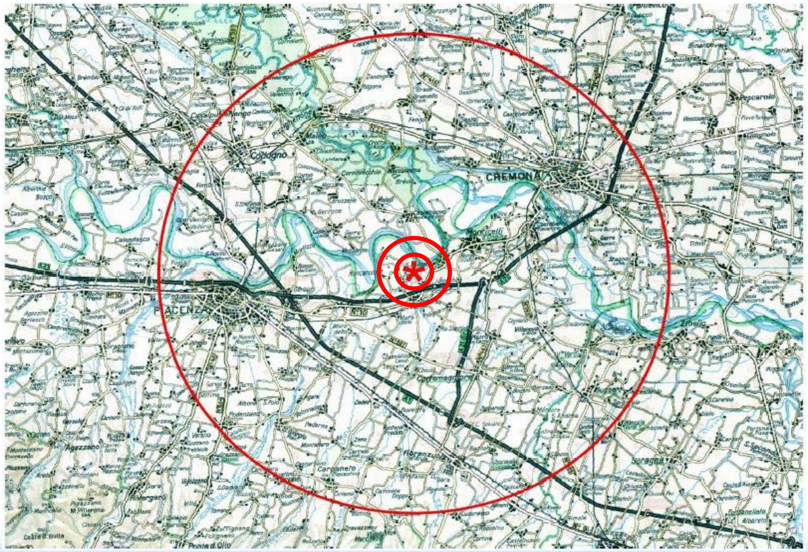
- **Benefits of the smaller source-term could be recognized in full when a technology-neutral and risk informed approach is established**
- **Smaller source terms of SMRs could help justify their licensing with a reduced or eliminated emergency planning zone (EPZ)**

Risk-Informed Approaches

Argentina's regulations (severe accidents)

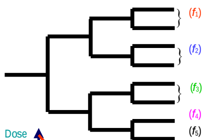


Risk-informed Methodology To Justify Reduced EPZ Requirements Has Been Developed within IAEA CRP "Small Reactors without On-site Refuelling" (2004-2009)

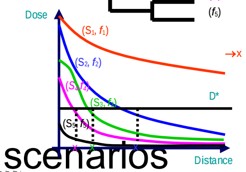


EPZ Redefinition Methodology

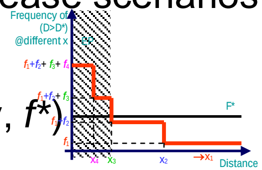
- Step1
  PRA accident sequences re-categorization
  and release scenario definition



- Step2
  Deterministic dose vs distance evaluation for relevant release scenarios



- Step3 (Limiting dose, D*)
- Step4 (Limiting frequency, f^*)
- Step5 (EPZ definition)



SAFETY

The enveloping design strategy for most of SMR concepts is to:

➢ ***Eliminate or de-rate as many accident initiators and/ or prevent or de-rate as many accident consequences as possible by design, and***

➢***Then, to deal with the remaining accidents/ consequences using reasonable combinations of active and passive safety systems and consequence prevention measures.***

THIS STRATEGY IS TYPICAL OF MANY ADVANCED REACTOR DESIGNS, SPECIFICALLY, GENERATION IV DESIGNS, IRRESPECTIVE OF THEIR SIZE

❖**TO ENABLE RISK-INFORMED APPROACH IN REACTOR DESIGN AND LICENSING, RELIABILITY OF PASSIVE SAFETY SYSTEMS NEEDS TO BE ASSESSED AND QUANTIFIED**

❖**THEN, BOTH ACTIVE AND PASSIVE SAFETY SYSTEMS COULD BE TREATED EQUALLY IN A PSA**

IAEA Regular Budget Activity

1.1.5.4/11: CRP "Development of Methodologies for the Assessment of Passive Safety System Performance in Advanced Reactors";
in Conjunction with Technical Working Groups on Advanced Reactors and Safety Assessment Section of the NS

The objective is *to determine a common analysis-and-test method for reliability assessment of passive safety system performance.*

Such a method would facilitate application of risk-informed approaches in design optimization and safety qualification of the future advanced reactors, contributing to their enhanced safety levels and improved economics.

CRP "Development of Methodologies for the Assessment of Passive Safety System Performance in Advanced Reactors"

- **First Research Coordination Meeting Convened on 31 March - 3 April 2009 in Vienna, Austria**
- **Detailed Work Plan and Schedule for the Next Year Defined**
- **The Participants Are:**

CNEA (Argentina)
BARC (India)
IGCAR (India)
CEA (France)
ENEA (Italy)
University of Pisa (Italy)
EDO "Gidropress" (Russia)
Idaho State University (USA)

+ Observers from Japan and Sweden

Current Approach (Deterministic) – There Are Success Stories (AP1000, VVER-1000, KLT-40S, SWR 1000) & Issues

- ***Separate Effect Tests***
- ***Codes & Validation of Codes***
- ***Integral Tests***
- ***Scaling***
- ***Capacity and Uncertainty***

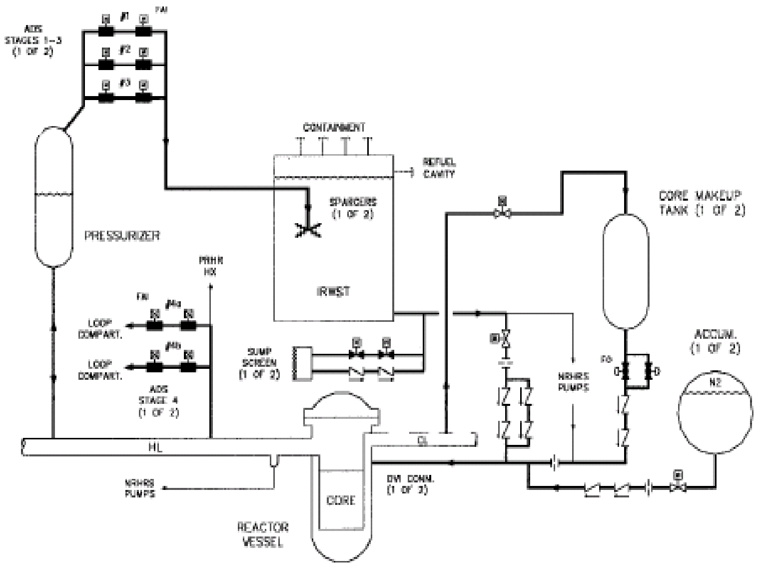


FIG. 4.10-5. AP1000 Passive core cooling system

- ***Risk Increase Factors Owing to Failure of Passive Systems***
- ***External and Internal Events and their Combinations, etc.***
- ***How to Quantify Passive Safety System Reliability to Treat Passive Systems in PSA?***

SAFETY
Reliability of Passive Safety Systems

➢**Passive systems should, by definition, be able to carry out their mission with minimum or no reliance on external sources of energy and should operate only on the basis of fundamental natural physical laws, such as gravity.**

➢**It may be stipulated that a passive system may fail to fulfil its mission because of a consequence of the following two failures:**

- Component failure: Classical failure of a component or components (passive or active) of the passive system;

- Phenomenological failure: Deviation from expected behaviour due to physical phenomena, e.g., related to thermal hydraulics or due to different boundary or initial conditions.

➢**The reliability of components of a passive system can be evaluated by means of well-proven classical methods.**

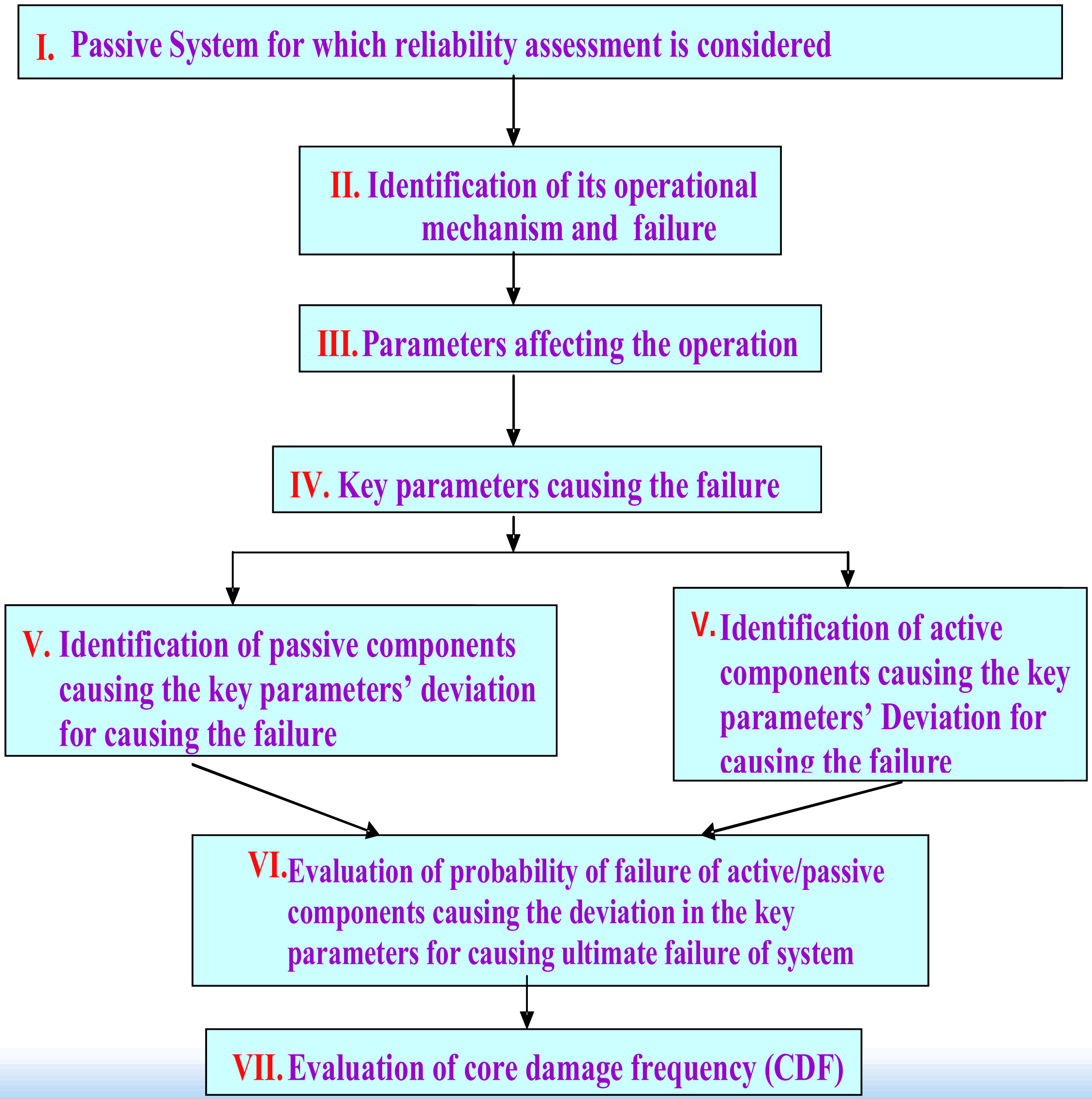
SAFETY
Reliability of Passive Safety Systems

➢ **Lack of data on some phenomena, missing operating experience over the wide range of conditions, and the smaller driving forces make the reliability evaluation of passive system phenomena a challenging one.**

➢ ***For evaluating the failure probability of passive systems, the methodology may move from the classical methods used for Probabilistic Risk Analysis (PRA) and consider, in addition to real components (valves, pumps, instrumentation, etc), virtual components, that represent the natural mechanism upon which the system operation is based (natural circulation, gravity, internal stored energy, etc.).***

SAFETY

Flowchart of a Generic Reliability Assessment Methodology for Passive Safety Systems – BARC (India)



SAFETY
Reliability of Passive Safety Systems

- **The contribution of real components can be easily assessed by resorting to the reliability databases available, whereas for evaluating the virtual component contribution *(process condition related)* it is necessary to develop a procedure that allows such assessment despite the lack of failure data.**

- **Such procedures have been elaborated by several research teams worldwide.**

- ***Several approaches suggest assigning probability density functions to process parameters.***

- ***One alternative approach suggests the use of tests to reveal the conditions under which virtual component fails***

CRP "Development of Methodologies for the Assessment of Passive Safety System Performance in Advanced Reactors" French (CEA) and Indian (BARC) Approaches

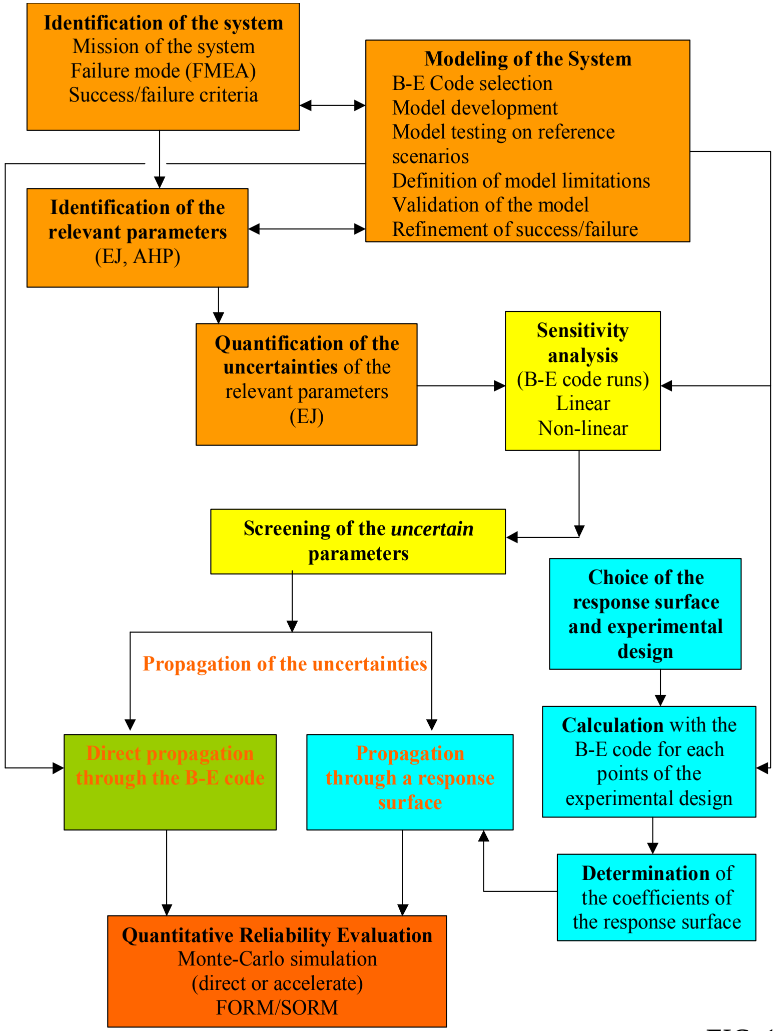


FIG. 13. Schematics of the RMPS methodology.

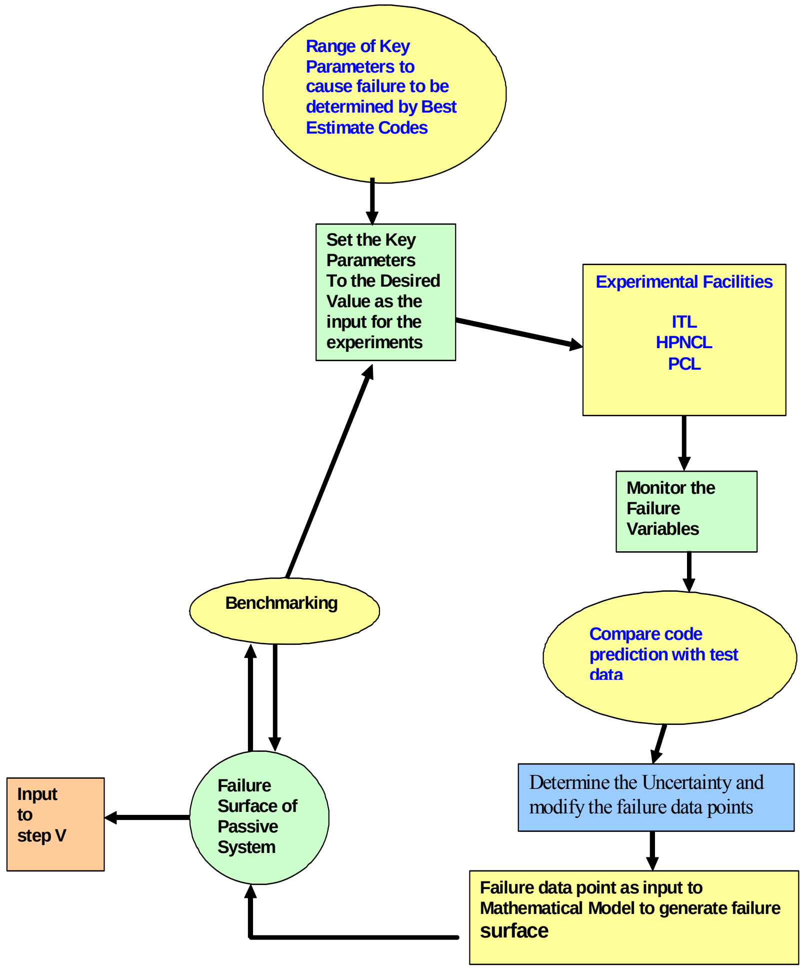


FIG. 15. APSRA methodology: flowchart of the programme for benchmarking of the failure surface based on experimental data.

CRP "Development of Methodologies for the Assessment of Passive Safety System Performance in Advanced Reactors"

Tasks:

- Elaboration of requirements to the method of reliability assessment of passive safety systems

- Elaboration of a set of definitions for reliability assessment of passive safety systems and their treatment by PSA

- Verification and validation of methodologies:

- **Benchmark problems**
- **Direct verification on tests**

- Algorithms to minimize necessary number of calculations

- Integration of the assessed reliability of a passive safety system in the overall PSA

- Developing a framework for creating a databank to generate probability density functions for process parameters.

CRP “Development of Methodologies for the Assessment of Passive Safety System Performance in Advanced Reactors”

Approaches to Communicate Methodology (suggestion by ENEA, Italy)

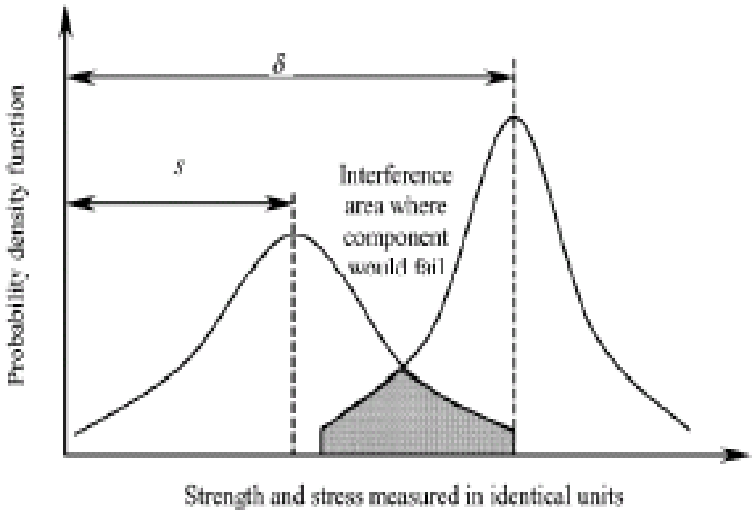


Fig. 1 Load (s) and strength (δ) interference diagram

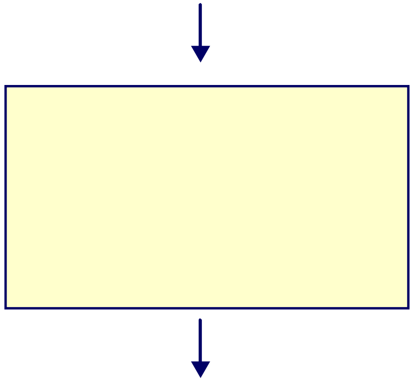
?

ENERGY SUPPLY SECURITY

Countries with small electricity grids/ Non-electric applications of a NPP requiring proximity to the user – Example from LEI (Lithuania)

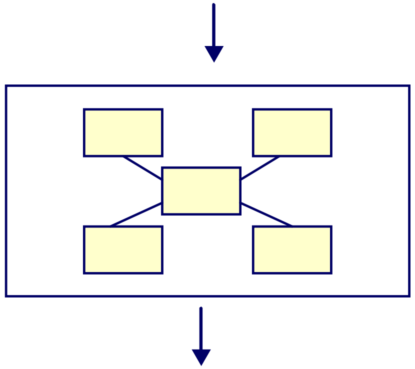
Consequences of a shutdown of one reactor:

LR ~ 1650 MW



Difficult to compensate for lost energy supply supply

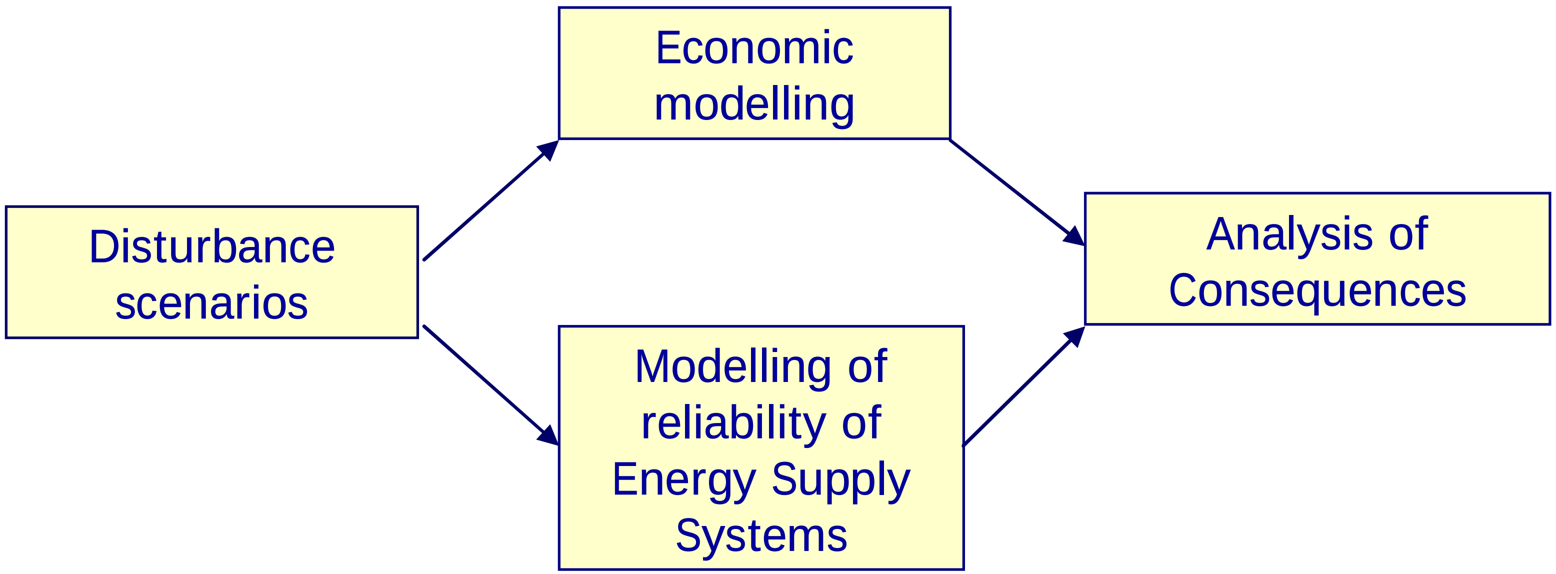
5 SMRs of 330 MW



More ‘mild’ variant with reserve energy available (4/5)

ENERGY SUPPLY SECURITY

Integrated energy security of supply (ESS) methodology – An example from LEI (Lithuania)



INNOVATIVE OPTIONS FOR LOAD FOLLOW OPERATION *– Example (C. Forsberg, ORNL – MIT, USA)*

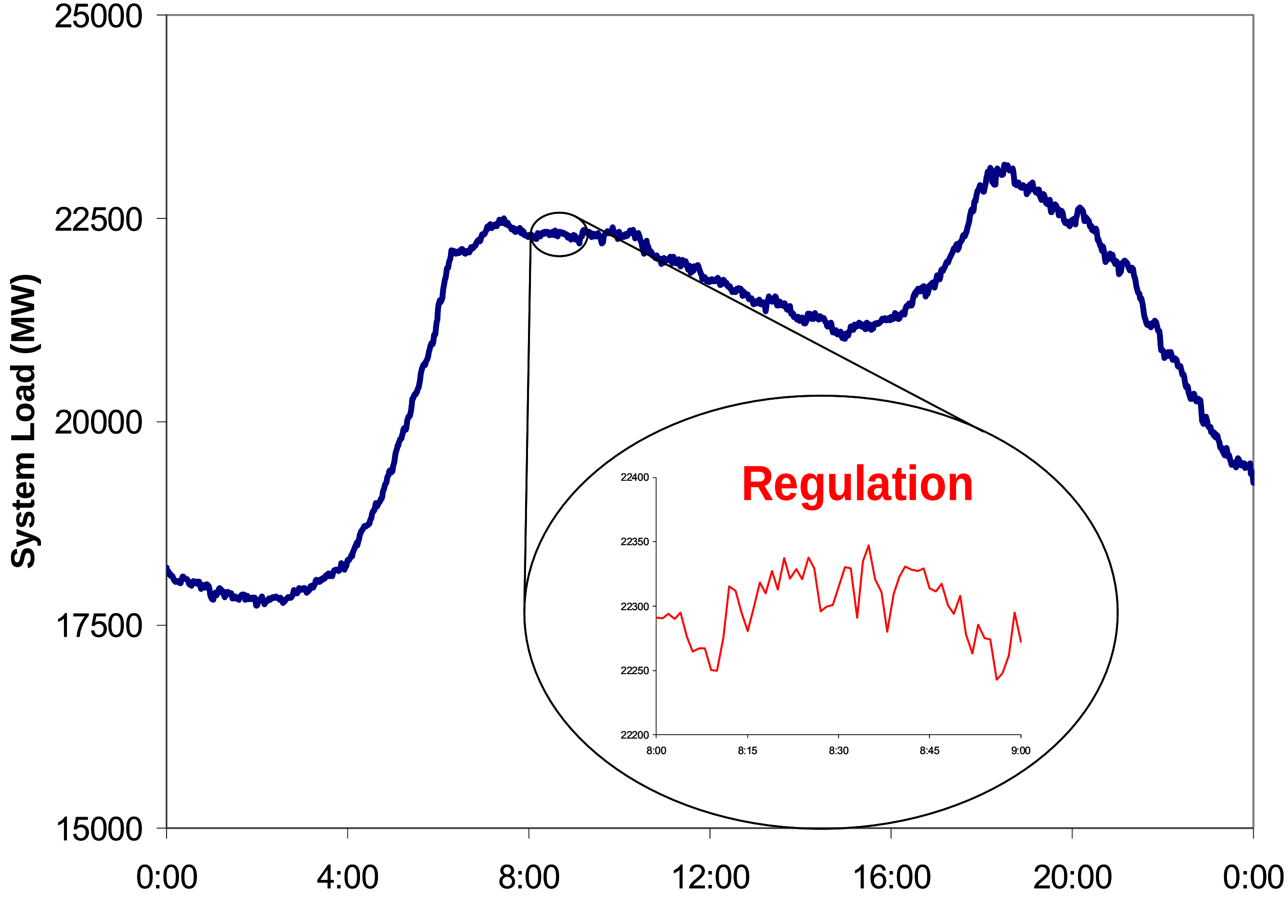


Fig. 5. A typical electric-power demand load on the ERCOT (Electric Reliability Council of Texas) electric grid over a 24-h period on a winter day.[16]

INNOVATIVE OPTIONS FOR LOAD FOLLOW OPERATION
– *Example (C. Forsberg, ORNL – MIT, USA)*

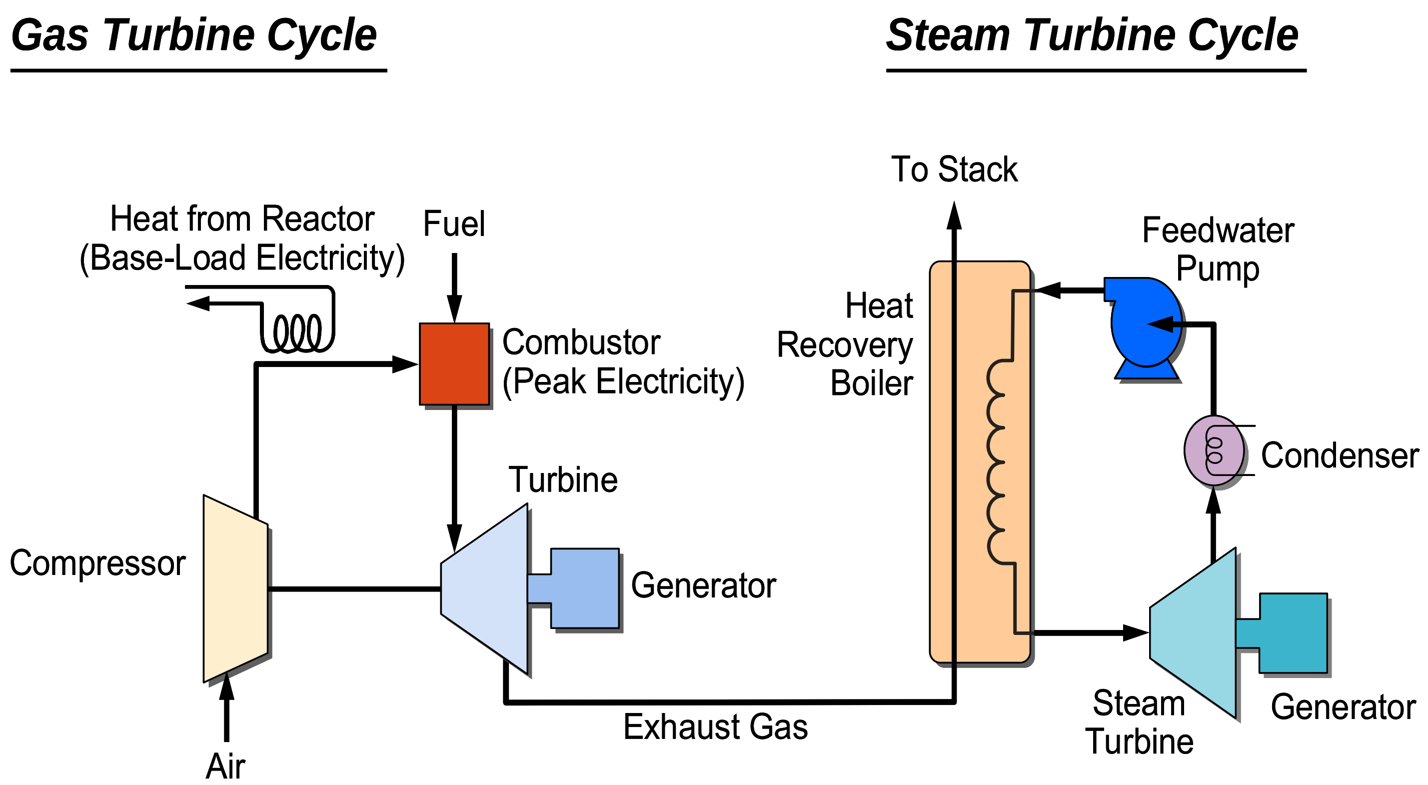
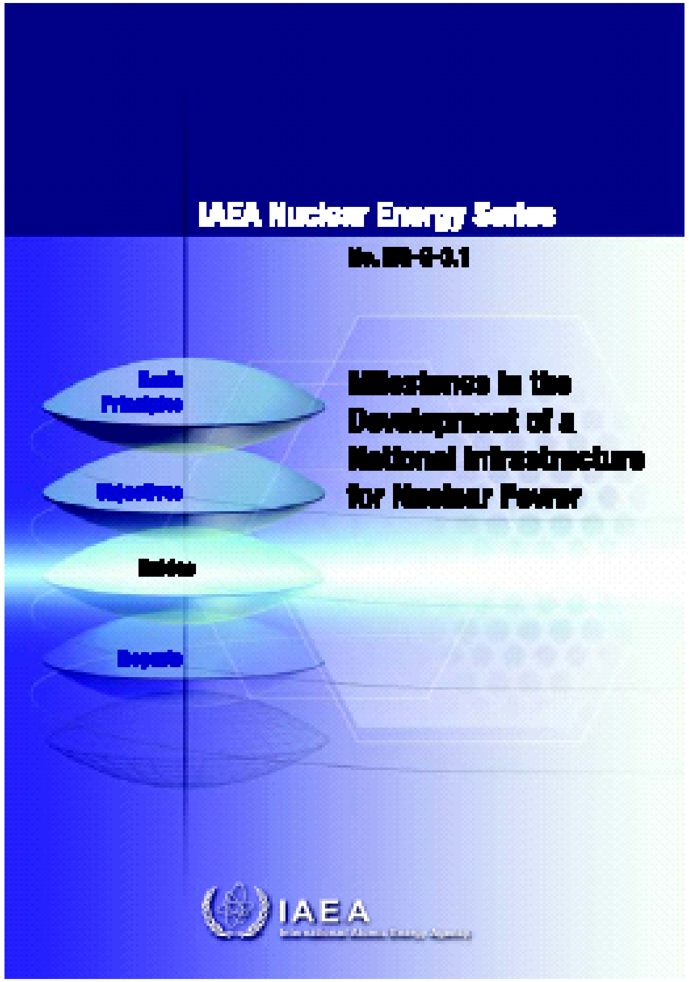
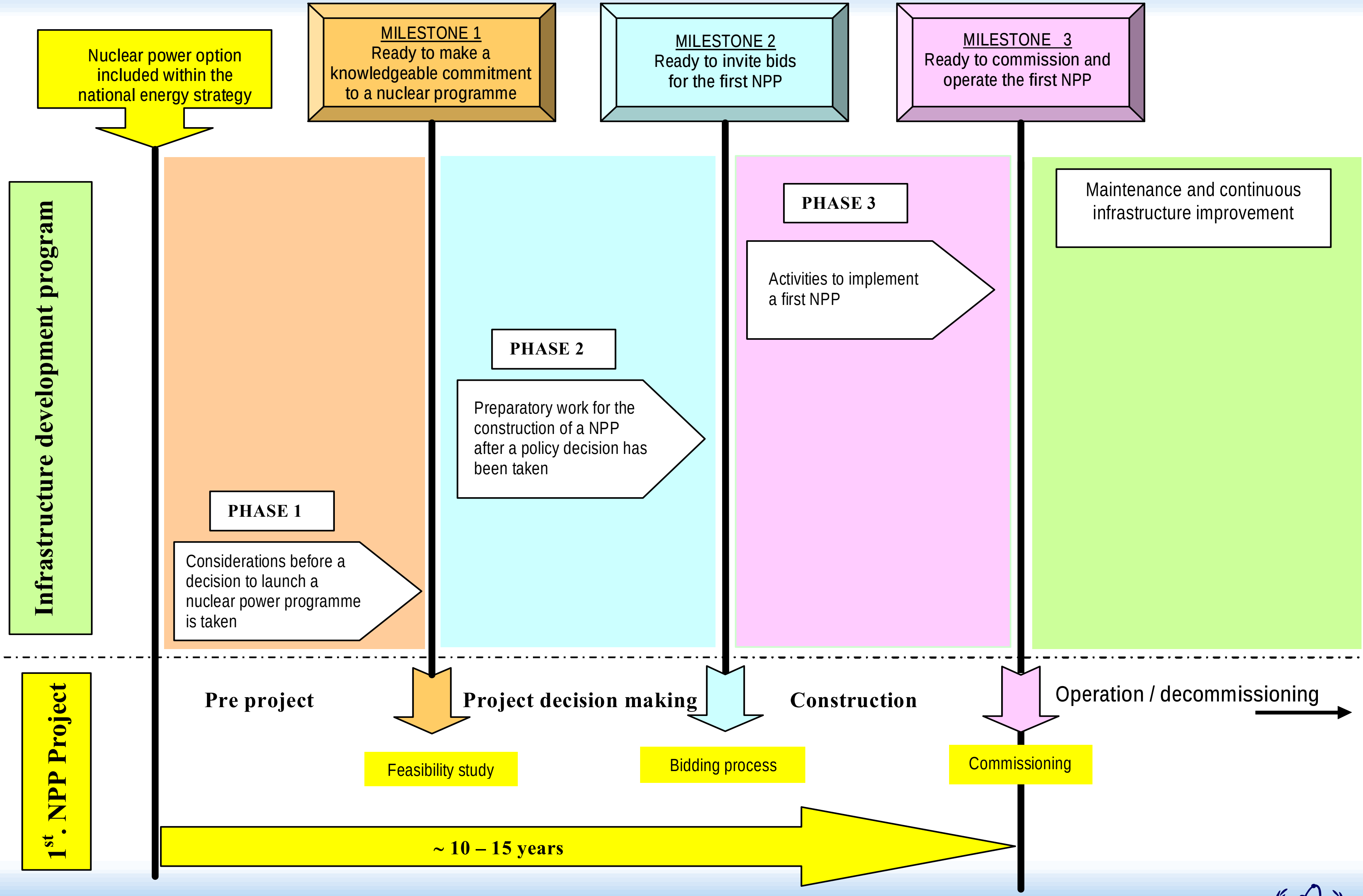


Fig. 1. Nuclear-combustion combined-cycle electric plant.

BASIC INFRASTRUTURE DEVELOPMENT – IAEA Nuclear Energy Series Guide NE-G-3.1 “Milestones in the Development of a National Infrastructure for Nuclear Power” (2007)



BASIC INFRASTRUTURE DEVELOPMENT – NE-G-3.1



BASIC INFRASTRUTURE DEVELOPMENT – NE-G-3.1

Table 2. Infrastructure issues and milestones (NG-G-3.1)

ISSUES	MILESTONE 1	MILESTONE 2	MILESTONE 3
National position			
Nuclear safety			
Management			
Funding and financing	CONDITIONS	CONDITIONS	CONDITIONS
Legislative framework			
Safeguards			
Regulatory framework			
Radiation protection			
Electrical grid			
Human resources development			
Stakeholder involvement			
Site and supporting facilities			
Environmental protection			
Emergency planning			
Security and physical protection			
Nuclear fuel cycle			
Radioactive waste			
Industrial involvement			
Procurement			

- **RECOMMENDATIONS ON BASIC INFRASTRUCTURE DEVELOPMENT WOULD APPLY TO LAND BASED SMRs WITH CONVENTIONAL REFUELLING SCHEMES AND LAND BASED SRWORs WITH ONCE-AT-A-TIME REFUELLING ON THE SITE**

- ***HOWEVER, THERE MIGHT BE CERTAIN LEGAL AND INSTITUTIONAL CHALLENGES FOR THE FACTORY FABRICATED, FUELLED AND TESTED TRANSPORTABLE REACTORS***

- ***AND FOR FLOATING NPPs***

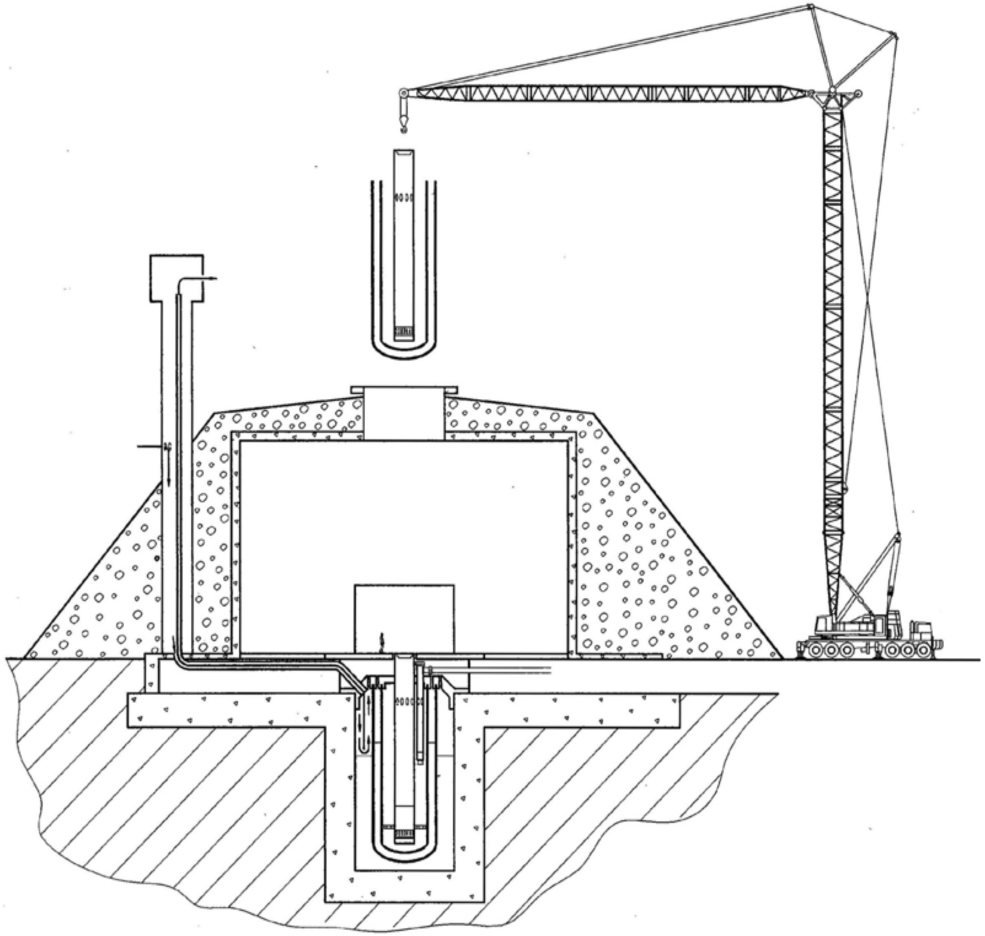
The objectives of this activity:

- Study challenges for deployment of transportable SMRs with a focus on legal and institutional aspects but considering their economics and technical aspects and various deployment options related to ownership and contract

- Propose solutions and associated action plans to address the identified challenges

- Study implications to the infrastructure of the recipient countries

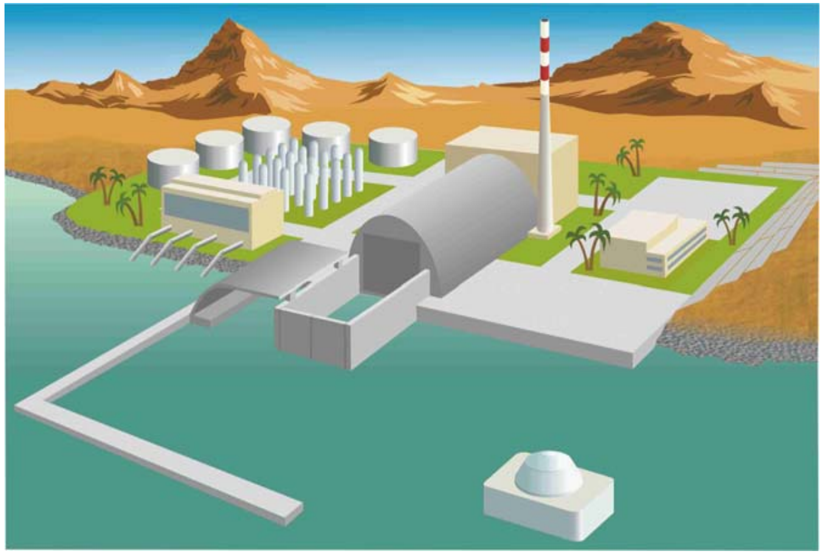
Innovative Infrastructure Options – *Small Reactors without On-site Refuelling*

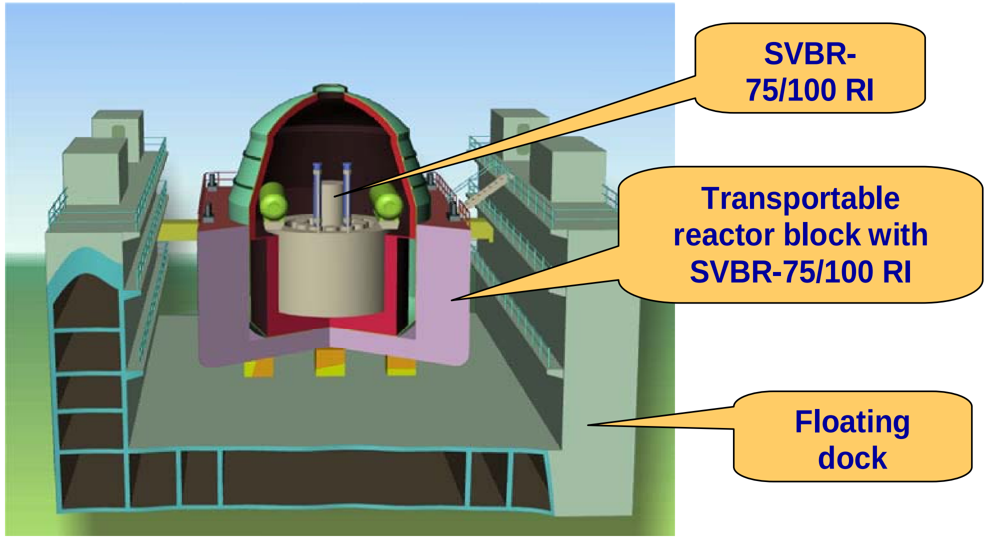


Rapid site assembly of STAR-H2 reactor (ANL, USA)

Innovative Infrastructure Options – *Barge-Mounted NPPs*

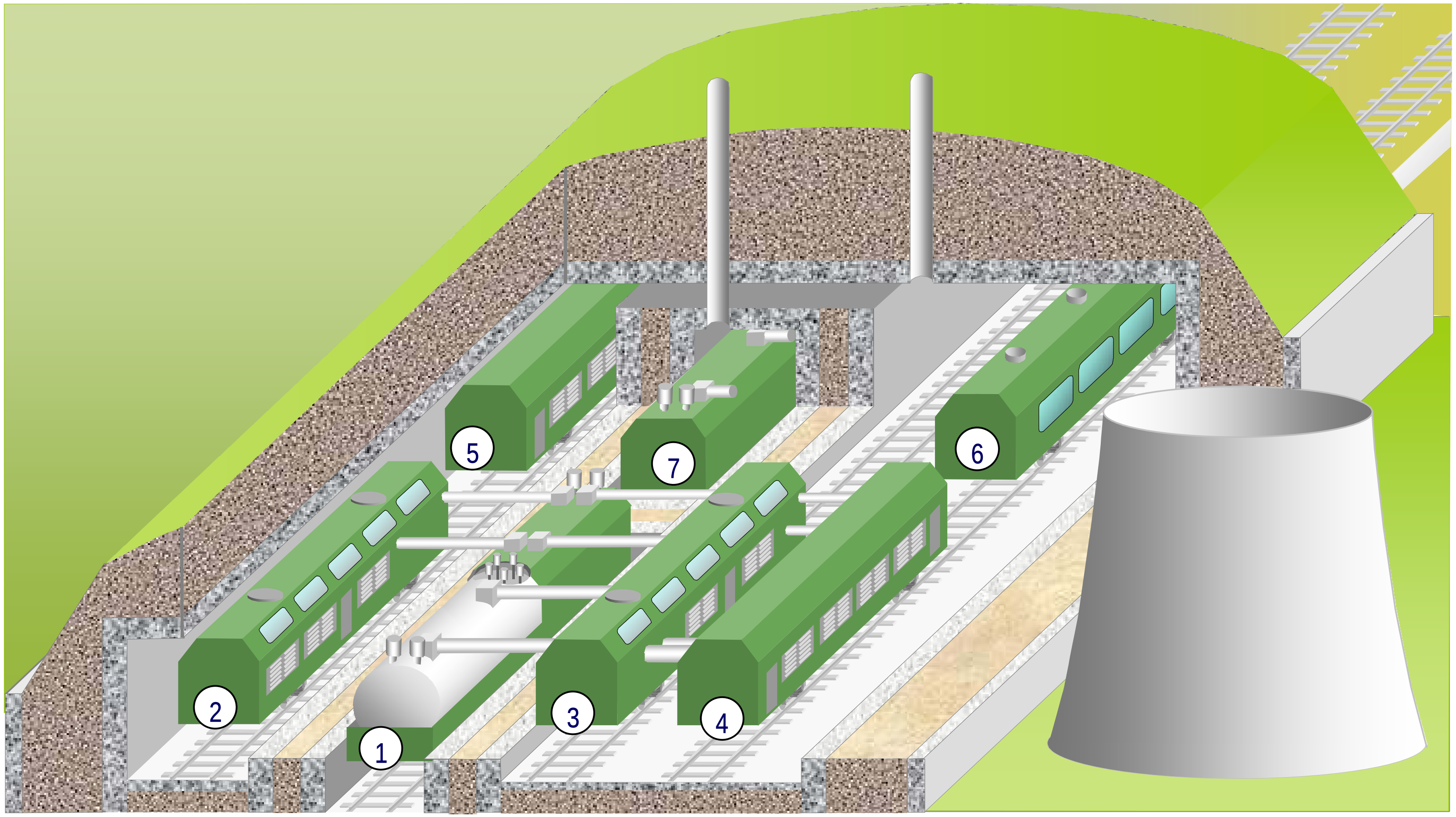
Innovative Infrastructure Options – *Leasing of transportable reactor modules*





Floating NPP for Pb-Bi cooled reactor SVBR-75/100
IPPE – Gidropress (Russia)

Innovative Infrastructure Options - *Transportable SMRs*



1 –Rail transportable reactor module; 2 – Generator module; 3 –Compressor module; 4 – Heat exchanger module;
5 –Auxiliary equipment module; 6 –Control room and reserve equipment module; 7- – Reserve reactor module**.**

FIG. XVIII-1. BN GT 300 single-unit nuclear power plant (NPP); section of the shelter building.

Examples of findings:

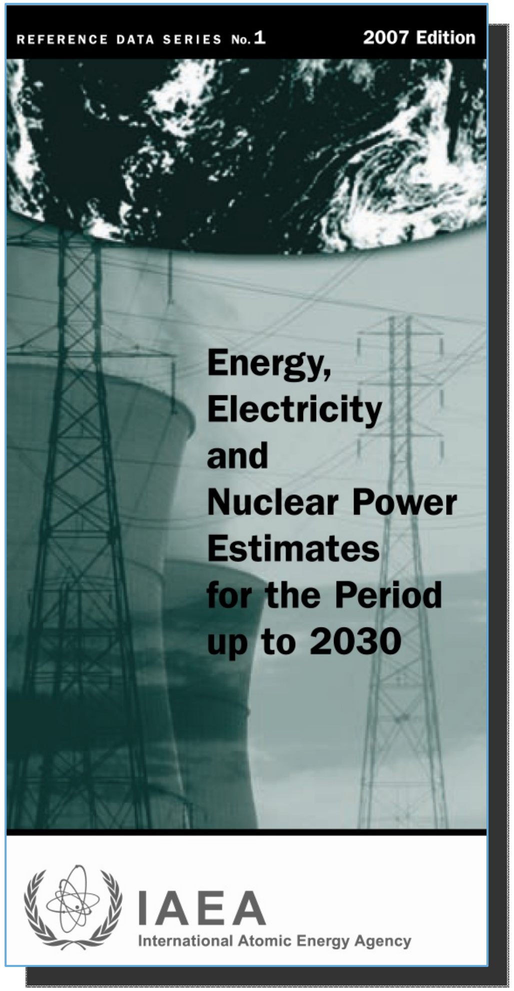
- **International legally binding Instruments: Conventions related to nuclear safety, Conventions related to Liability for nuclear damage, etc.]**

On themselves, these are rather generic and would not hamper export transactions of transportable reactors. However, bilateral and multilateral agreements to address specific features of transportable reactor construction and operation would be needed

- **Safeguards issues:**

There is nothing distinctive about the characteristics of the construction and operation of a transportable reactor that would differentiate it from a non-transportable nuclear installation. However, if the facility is to be constructed in a NWS and exported to NNWS, it would be useful for the NWS to enter into an arrangement with the IAEA whereby the IAEA is able to verify the design information of the facility while it is under construction

RDS-1: Energy, Electricity and Nuclear Power Estimates for the Period up to 2030



Reference Data Series No. 1 is an annual publication - currently in its twenty-seventh edition - containing estimates of energy, electricity and nuclear power trends up to the year 2030.

The future growth of energy, electricity and nuclear power up to the year 2030 is presented as low and high estimates in order to encompass the uncertainties associated with the future.

Available online at:
http://www.iaea.org/OurWork/ST/NE/Pess

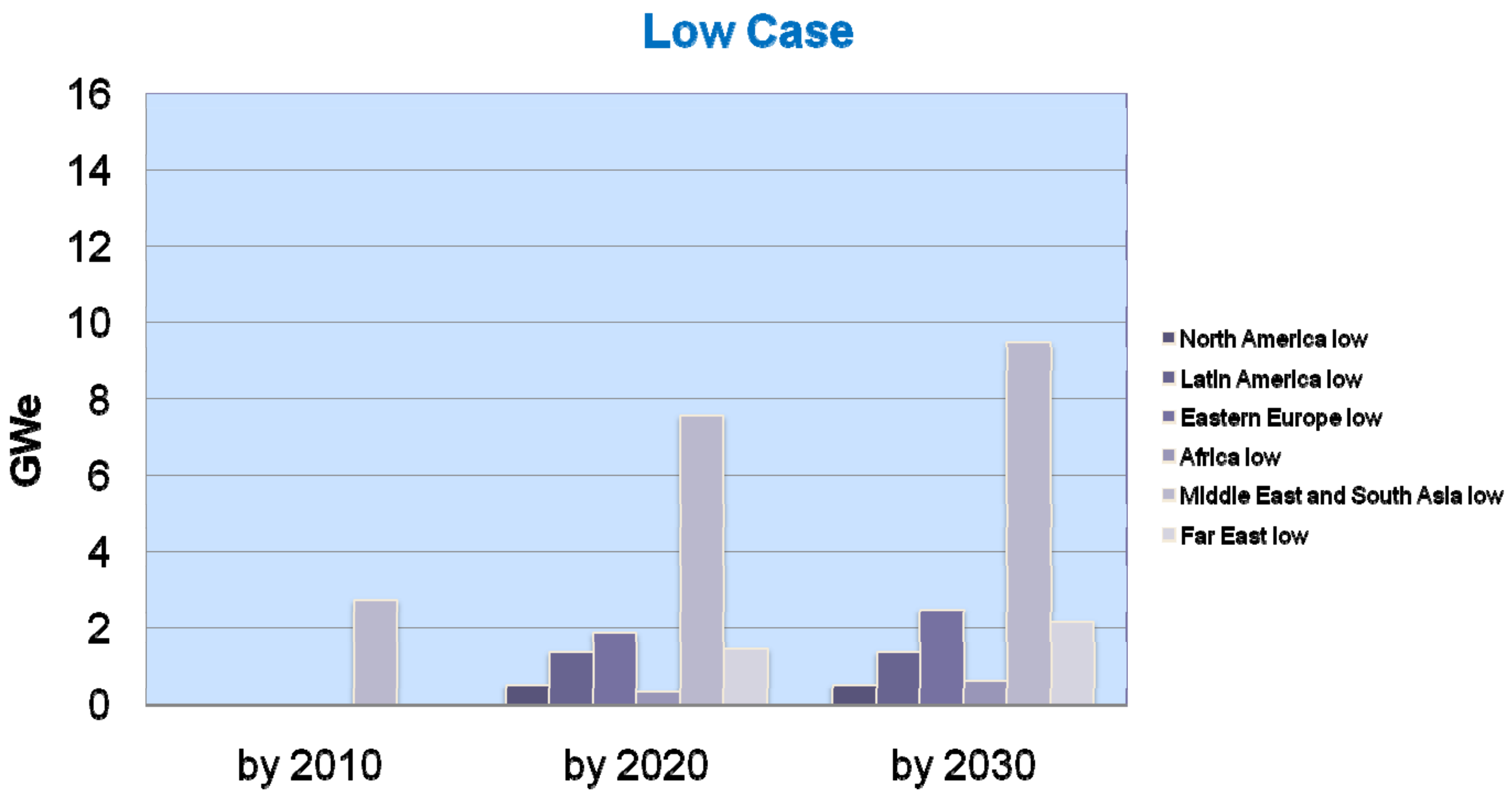
SMR estimates extracted from RDS-1 2008

Summary:

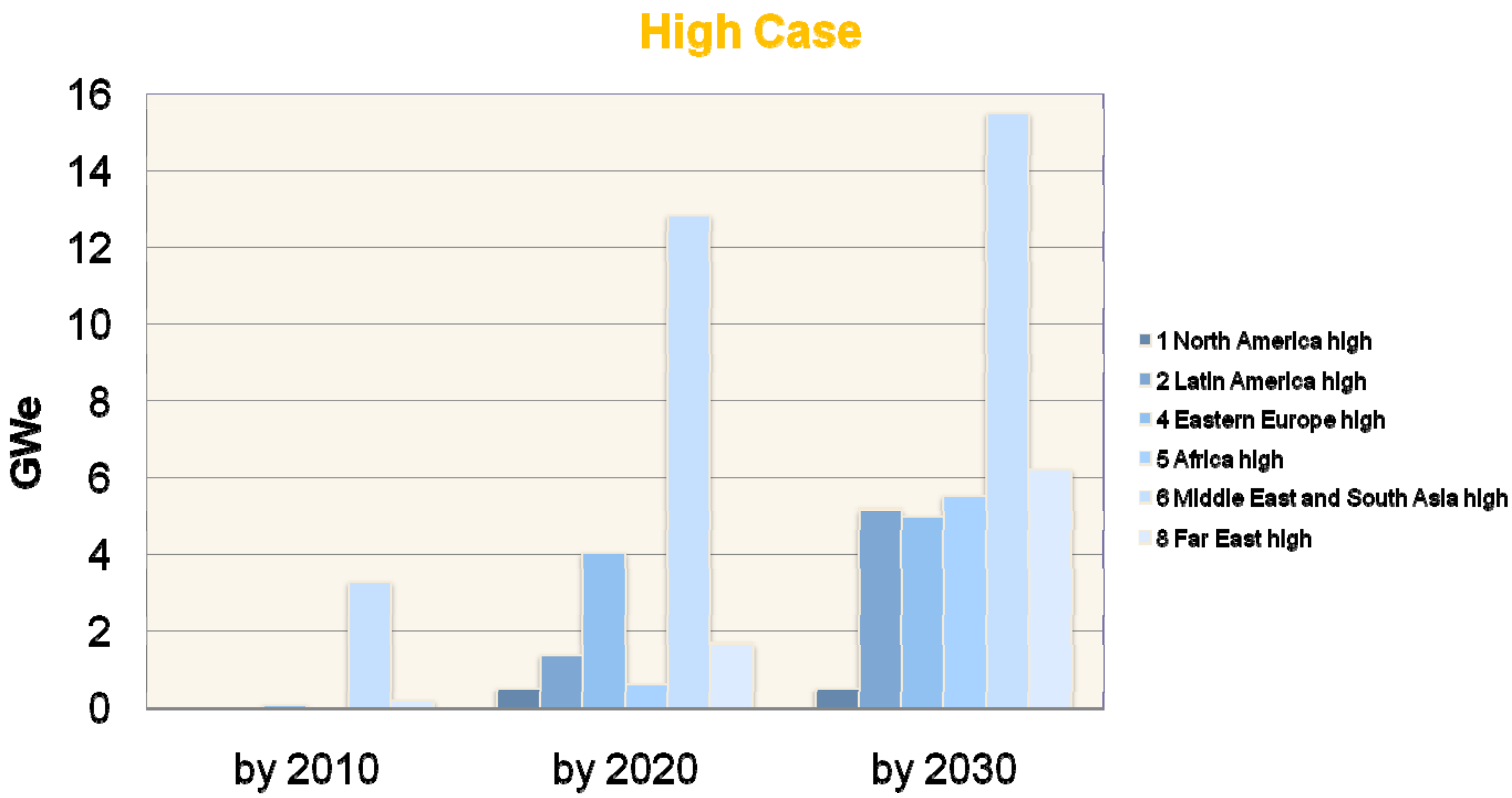
- 22 countries in High Case and 10 countries in Low Case
- Installed Net Capacities (GWe) and number of the units

Case	by 2010	By 2020	by 2030	Units
High	3.6	21.2	38.0	96
Low	2.8	13.2	16.8	43

SMR estimates extracted from RDS-1 2008



SMR estimates extracted from RDS-1 2008



Conclusions (1)

- **Several Member States have SMRs ready for deployment and others are building some of these designs. *The SMR designs available for immediate deployment, include the pressurized heavy water reactors CANDU 6 (650 MWe) by the AECL (Canada) and PHWR-220 or PHWR-540 by NPCIL (India), and small and medium sized pressurized water reactors (PWRs) of the Chinese design (PWR of 325 MW(e) (China) and CNP-600 of 600 MW(e).***

- **Recent construction and deployment of the pressurized heavy water reactors was accomplished in line with the original schedule and budget. The Indian PHWRs of 220 and 540 MW(e) were deployed with very competitive specific overnight capital costs. A CANDU 6 in Romania was started up in 2008 and discussions for completion of two more are at an advanced stage.**

Conclusions (2)

- **Innovative SMRs are under development for all principal reactor lines and some non-conventional combinations thereof. More than 45 innovative SMR concepts and designs are being developed within national or international research and development (R&D) programmes, involving both developed and developing countries. These designs are at very different stages of development. The target dates, claimed by the designers, of readiness for deployment range from 2012 to 2030.**

- ***Most of SMRs provide for or do not exclude non-electrical applications such as potable water, distric heating or hydrogen production.***

Conclusions (3)

- **Construction of a pilot floating cogeneration plant of 300 MW(th)/70 MW(e) with two water cooled KLT-40S reactors started in the Russian Federation in June 2006, is being continued.**

- **Plans were announced to build several such plants and also some plants with the ABV reactors of smaller (11 MWe) capacity for customers in the Russian Federation. *The deployment date of a pilot plant with the KLT-40S was shifted to 2012.***

Note: ABV is a small reactor without on-site refuelling

Conclusions (4)

- **Several integral PWR designs are in more advanced development stages and some could be available for deployment around the middle of the next decade. The 335 MW(e) IRIS design developed by an international consortium led by Westinghouse Electric Company of USA is the furthest along in testing and development. The 150 to 300 MWe CAREM developed in Argentina, has started licensing a 27 MWe scaled prototype. The 330 MW(th) SMART design developed in the Republic of Korea for a co-generation plant is still at an earlier stage.**

- **The Advanced Heavy Water Reactor of 300 MW(e), developed in India for co-generation plants, is planned to be built early in the next decade. The reactor is being designed for operation with 233U-Pu-Th fuel and uses boiling light water coolant and heavy water moderator. Licensing of this design is in progress, and the construction related actions are expected to start soon.**

Conclusions (5)

- **The 200 MW(e) per module HTR-PM, a high temperature gas cooled reactor with pebble bed fuel and indirect supercritical steam energy conversion cycle developed in China, is planned for a full size demonstration in 2013. Two-module plant configuration is foreseen for the commercial version of this reactor. At the moment, licensing of this design is in progress and construction related actions have been started.**

- **The 165 MW(e) PBMR, a high temperature gas cooled reactor with pebble bed fuel originally employing a direct gas turbine Brayton cycle, developed in South Africa, has undergone design strategy change and would be implemented first with an indirect steam power conversion cycle. Its demonstration at full size is still scheduled by 2014. Future configurations of this reactor will include 4 and 8-module plants.**

Conclusions (6)

- **In Japan, the Toshiba Corporation, in cooperation with the Central Research Institute of Electric Power Industry (CRIEPI) and Westinghouse Electric Company, is developing a detailed design of the 4S sodium cooled reactor. It has a design power of 10 MW(e), and a refuelling interval of 30 years. A pre-application review by the US NRC has been initiated in the end of 2007, and licensing process is scheduled to start in October 2010. Construction of a demonstration reactor and safety tests are planned for the first half of the next decade**

- **In the United States, two private companies acquired intellectual property rights and go on with design development and commercialization of two small reactors without on-site refuelling, a water-cooled NuScale and a heat-pipe based Hyperion Power Module employing uranium-hydride decomposable fuel.**

What could be done to support innovative SMR deployment?

➢*Adjust regulatory rules toward technology neutral and risk-informed approach*

➢*Quantify reliability(?) of passive safety systems*

➢*Justify reduced or eliminated EPZ (proximity to the users)*

➢*Justify reliable operation with long refuelling interval (Licence-by-test + periodic safety checks)*

✓*Demonstrate SMR competitiveness for different applications (many users require technology proven by operation)*

What would happen if this is not done?

- *All innovative SMRs are licensable against current safety requirements and regulations*
- *There are established methods for validation of passive safety systems*
- *Reduced EPZ can be partly justified using current regulations in some countries*
- *Long refuelling interval has experience with submarines*

✓ *Would SMRs be competitive if new regulatory approaches are not applied?*

Conclusions (9)

- **The IAEA Project "Common Technologies and Issues for SMRs" is On-going with Increased Emphasis on Issues of Competitiveness and Passive Safety System Performance Assessment**

- **Planning for the Biennium of 2010-2011 is completed, the activities will include:**

✓ ***Consolidation of Software Tools for The Assessment of SMR Competitiveness in Different Applications***

✓ ***Development of a Status Report on SMRs with Near-Term Deployment Opportunity***

✓ ***Maintenance and Updating of Electronic Data Base of Advanced Reactor Designs, in Parts Related to SMRs***

✓ ***Reports on Options to Enhance Energy Supply Security and Proliferation Resistance of Energy Systems with SMRs***

✓ ***Chapter on developments Status and Prospects of Advanced Computation Methodologies Using Computation Fluid Dynamics, etc.***

IAEA General Conference Resolution GC(51)/RES/14

Requests the Director General to continue taking appropriate measures to assist Member States, particularly developing countries in the development of safe, secure, economically viable and proliferation-resistant SMRs, including with respect to nuclear desalination and hydrogen production

THANK YOU!

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