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Advanced Small and Medium Sized Reactor (SMRs) Part 1

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International Atomic Energy Agency

Advanced Small and Medium Sized Reactors (SMRs) - Part 1

Prepared by Vladimir KUZNETSOV

(IAEA)

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Definition/ SMR Story

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

- **In the early decades, civil nuclear power essentially borrowed from the experience of reactors for nuclear submarines, which came first and were essentially small-capacity reactors**

- **Since 1970's, the major focus for nuclear power was on the design and construction of nuclear plants of increasing size, with average size levelling out at about 1000 MWe with a tendency for further increase.**

- **In the end of 2007, of the 439 operating NPPs, 134 were with small and medium sized reactors (SMRs)**

- **Of the 23 newly constructed NPPs, 9 were with SMRs**

- **In 2008, not less than 35 concepts and designs of innovative SMRs are analyzed or developed in** Argentina, Brazil, China, Croatia, India, Indonesia, Italy, Japan, the Republic of Korea, Lithuania, Morocco, Russian Federation, South Africa, Turkey, USA, and Vietnam

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 resolution of enabling infrastructure issues common to future SMRs of various types

Project “Common Technologies and Issues for

cipants:

ipants:

tina, Brazil, China, Croatia, European Commission, NEA-CD, France, India, Indonesia, Italy, Japan, the Republic of ic of Korea, Lithuania, Morocco, Russian Federation, South Africa, USA, Vietnam

Definition

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

The majority of SMRs provide for power station configurations with 2, 4, or more NPPs or reactor modules .

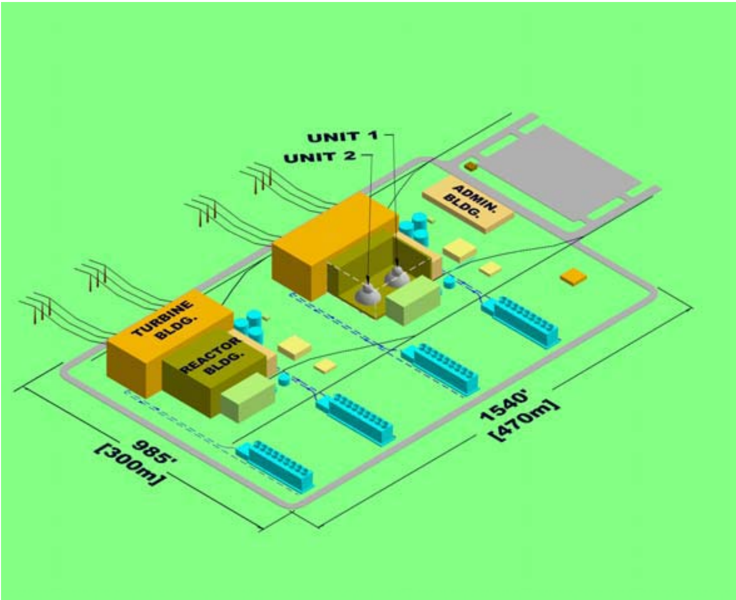
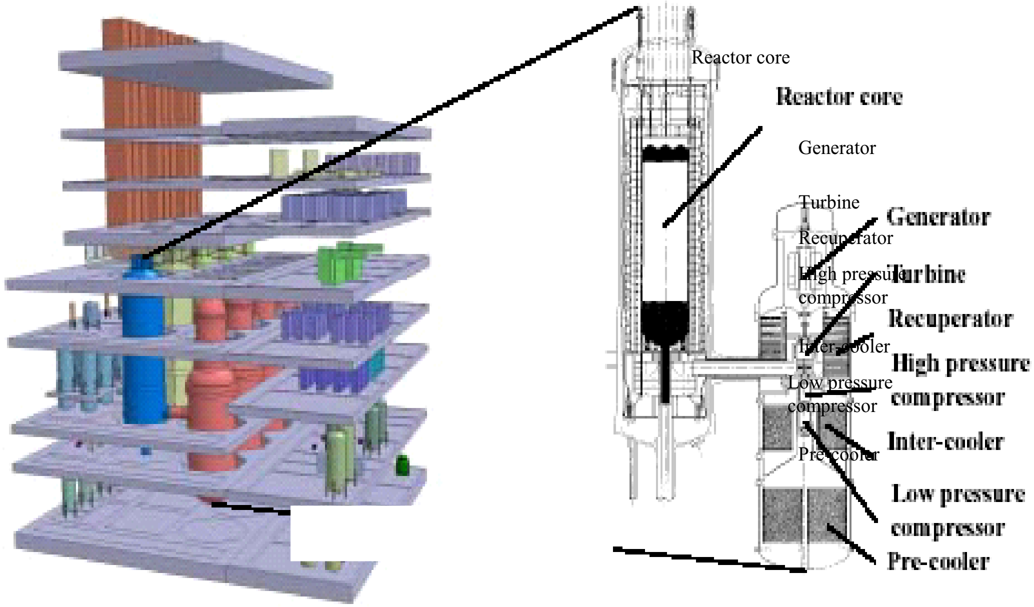


FIG. II-10. Perspective view of IRIS multiple twin-unit site layout.

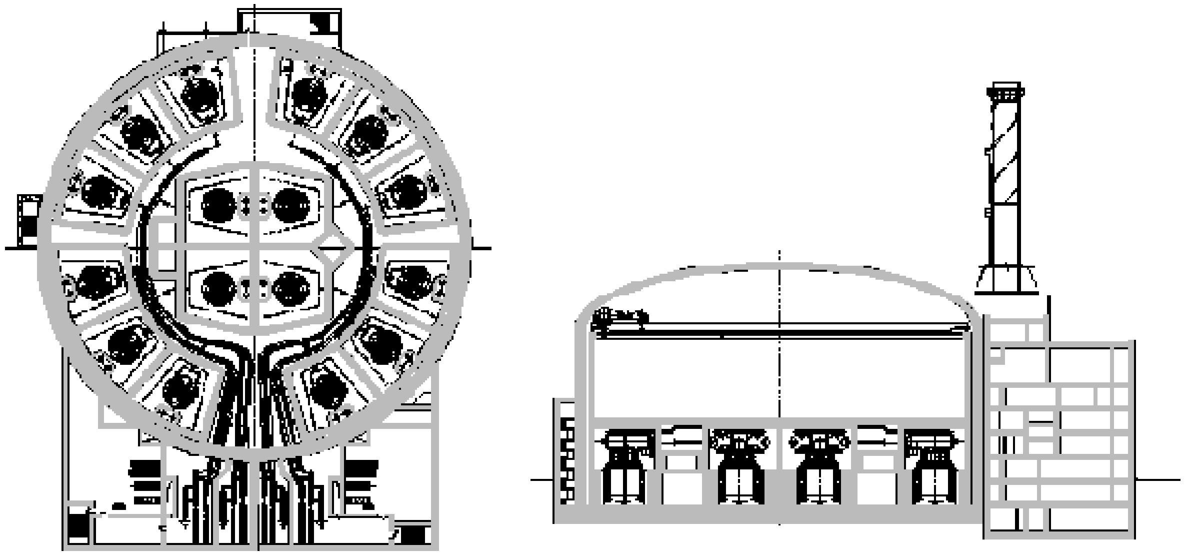


FAPIG-HTGR 4 Module Plant

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

Definition

Small reactor does not necessarily mean low-output NPP!



Clustered modular nuclear steam supply system SVBR-1600 with 16 SVBR-75/100 modules (IPPE-Gidropress, Russian Federation)

Incentives for SMRs

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

- ***Countries with small or medium electricity grids (< 7000 - 10000 MW(e) peak load)***
- ***Settlements and energy intensive industrial sites in remote off-grid locations (permanent frost, islands, remote draught area, etc.)***
- ***Countries with limited investment capability (incremental capacity increase)***
- ***In the future, utilities (worldwide) and, possibly, merchant plants for non-electric energy services (look at aircraft, car and other mature industries)***

Incentives for SMRs

Looking into the future:

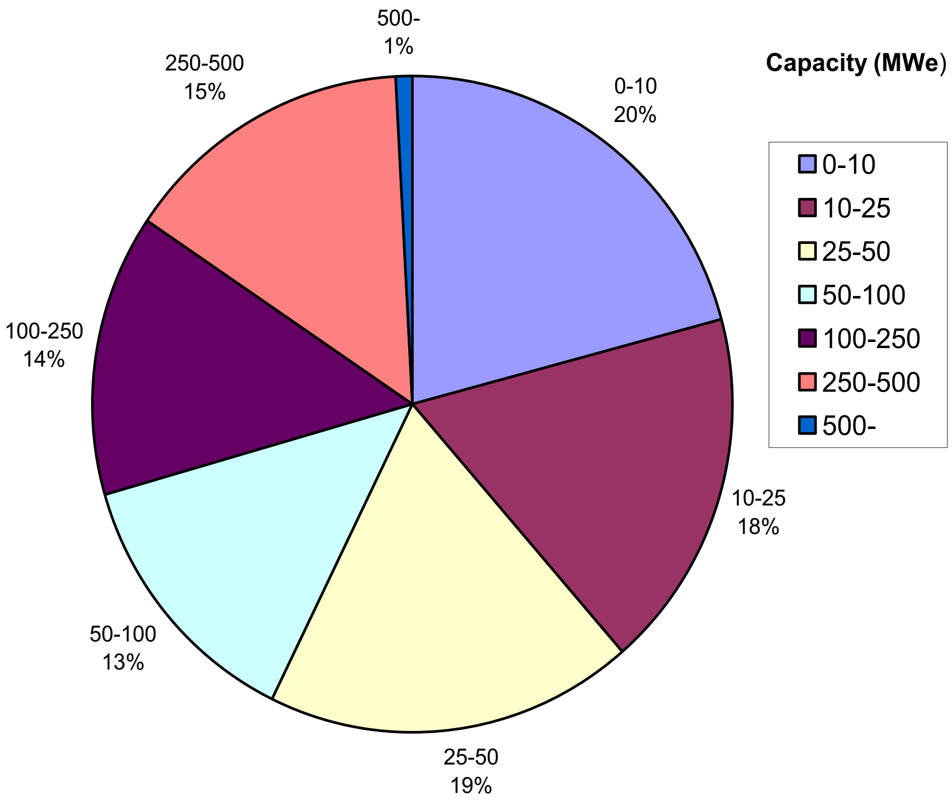
Primary energy (in developed countries) is utilized in three roughly equal fractions [*]:

- ✓***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

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 [22].

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

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)**

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

- 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

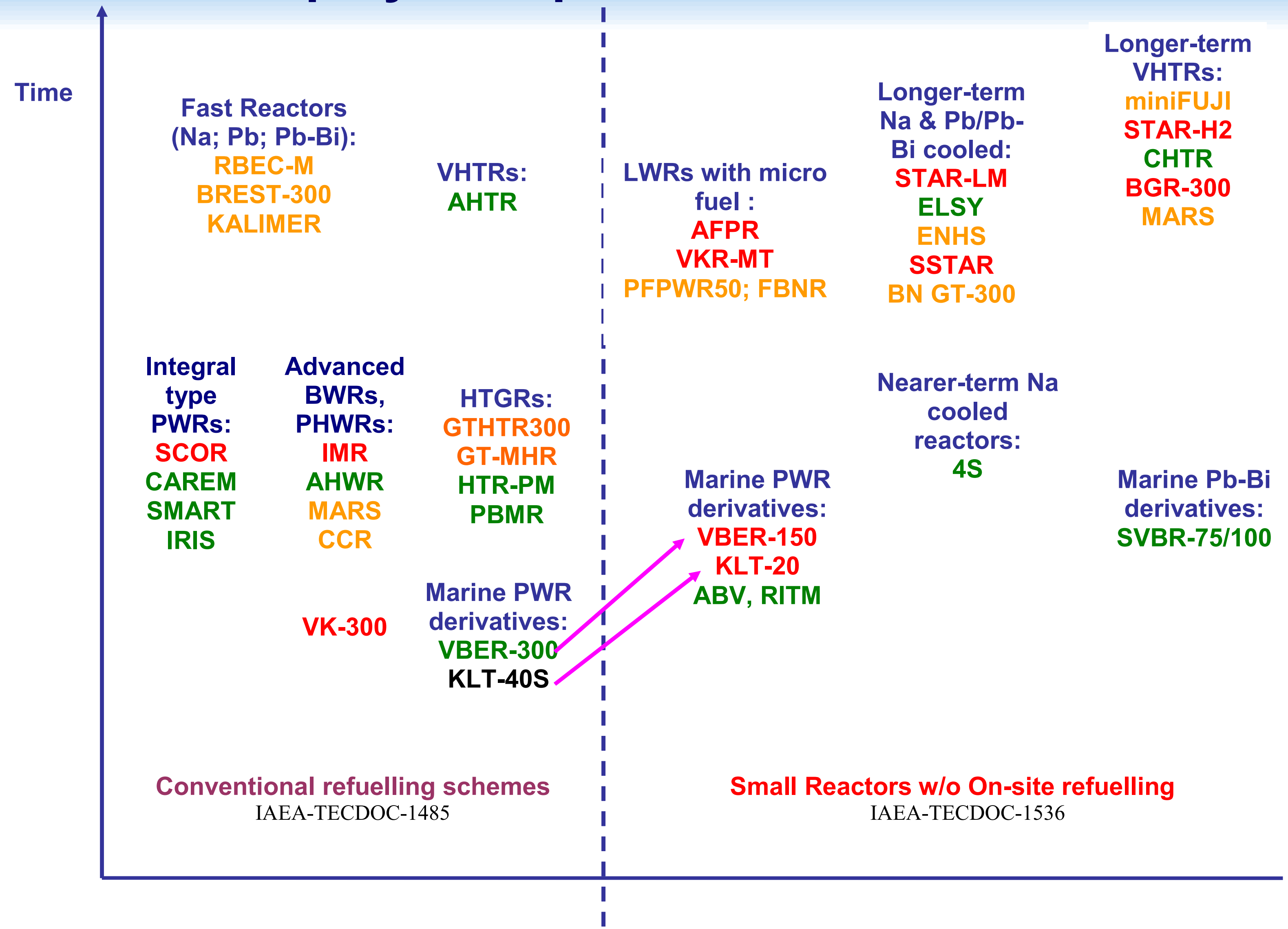
  (b) Reactors with once-at-a-time core reloading on the site performed by an external team that brings in and takes away the core load and the refuelling equipment

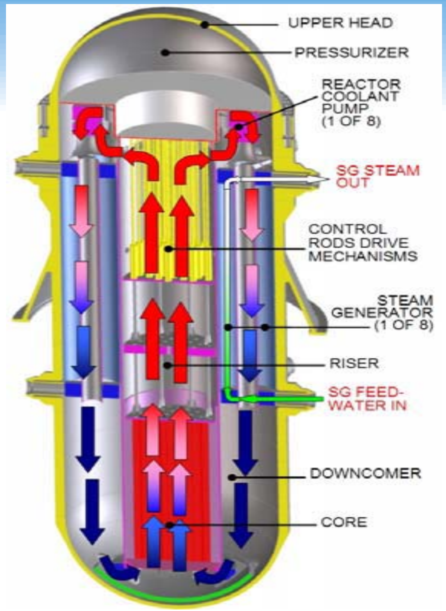
- SRWOR incorporate increased refuelling interval (from 5 to 30+ years) consistent with plant economy and considerations of energy security

SRWOR – Summary of Design Approaches

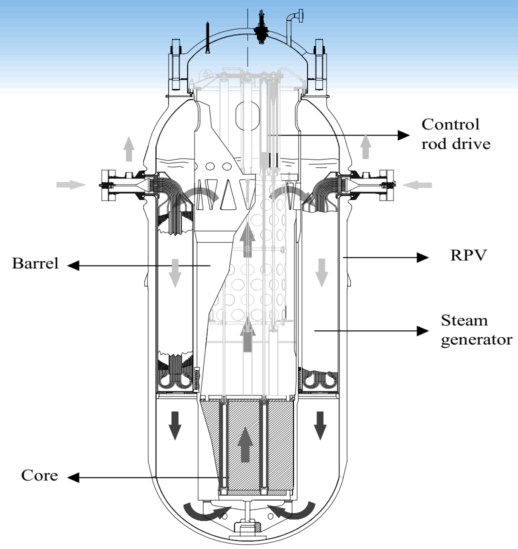
- Design approaches to ensure long-life core operation include:
  - ✓ *Reduced core power density;*
  - ✓ *Burnable absorbers (in thermal reactors);*
  - ✓ *High conversion ratio in the core (in fast reactors)*
  - ✓ *Refuelling performed without opening the reactor vessel cover*
- SRWORs end up at the same or less values of fuel burn-up and irradiation on the structures, although achieved over a longer period than in conventional reactors

Deployment potential of innovative SMRs

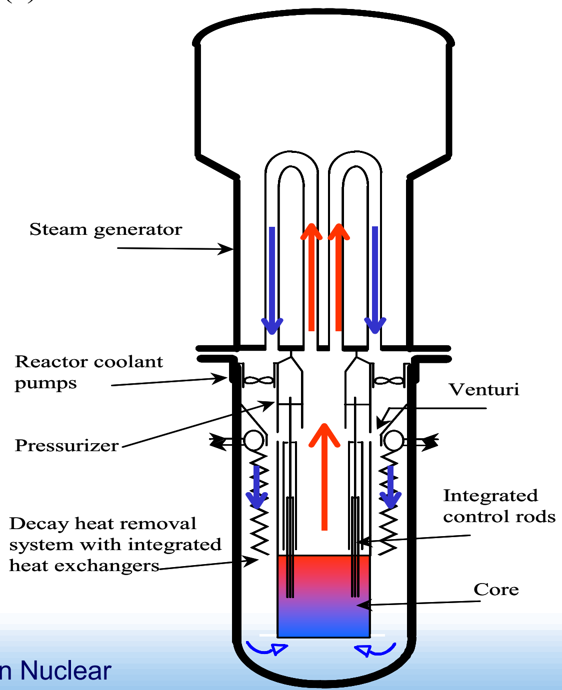




(a)



(b)



(c)

Reactor Types/ Distinct Groups (Examples)

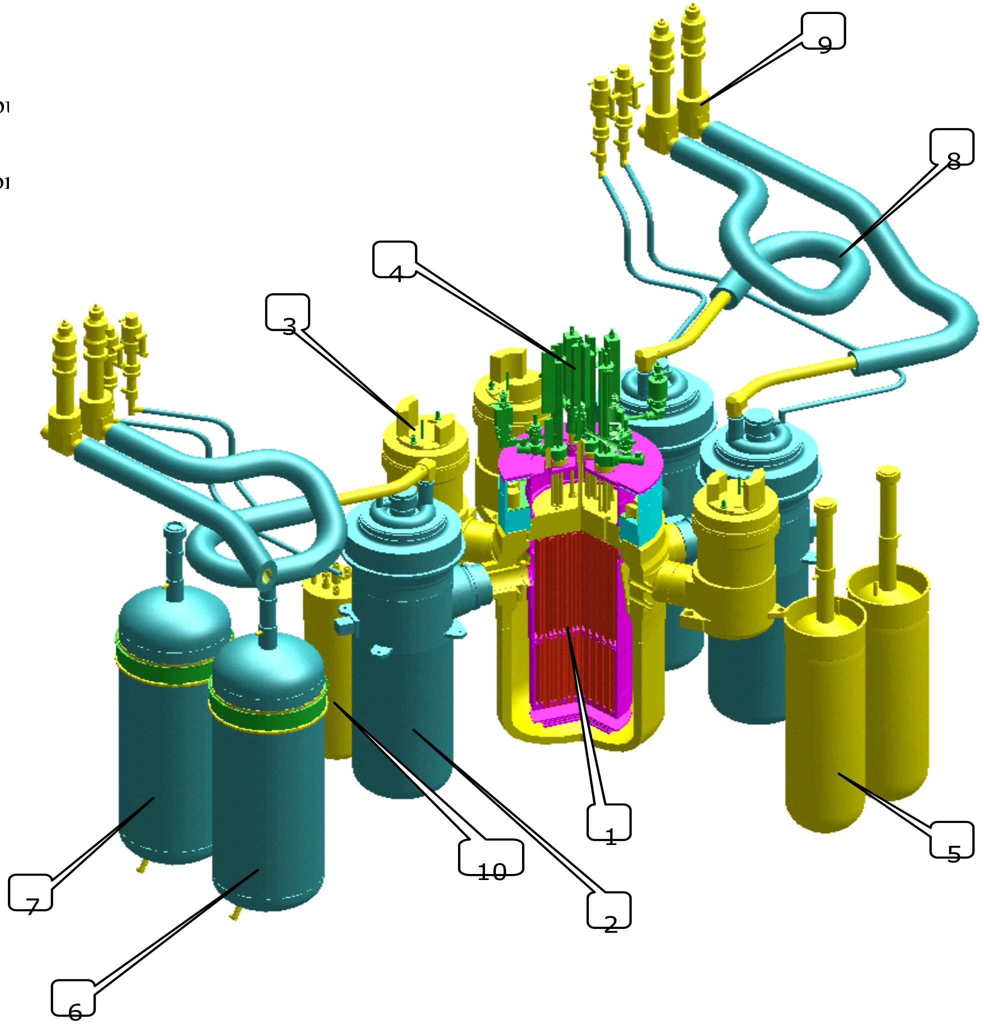
Pressurized Water Reactors/ Integral Design PWRs

- **(a) IRIS – Westinghouse, USA**
- **(b) CAREM – CNEA, Argentina**
- **(c) SCOR – CEA, France**

Reactor Types/ Distinct Groups (Examples)

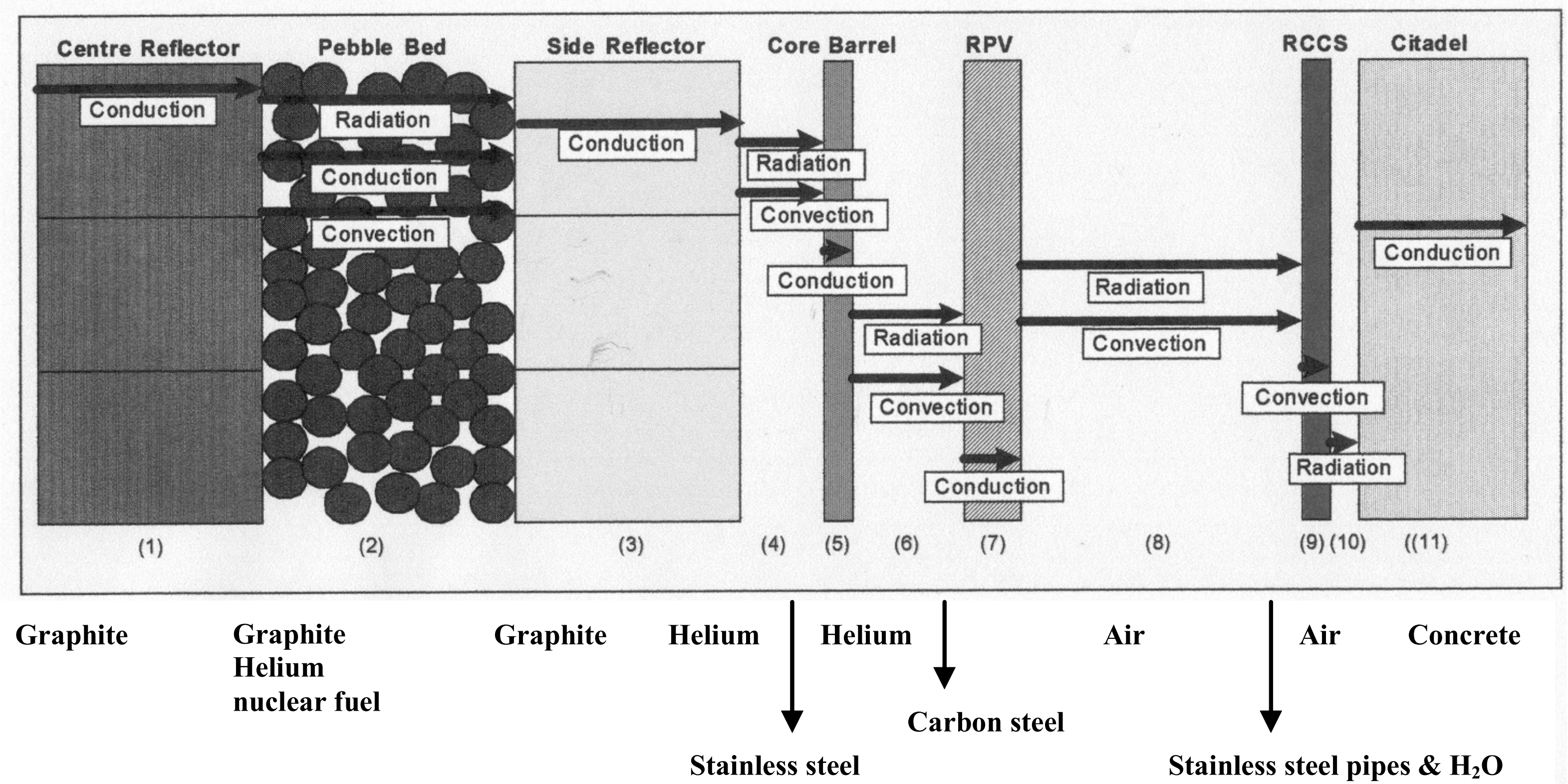
Pressurized Water Reactors/ Marine Reactor Derivatives

1 Reactor
2 Steam generator
3 Main circulating pu
4 CPS drives
5 ECCS accumulator



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

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/ Direct gas turbine Brayton cycle

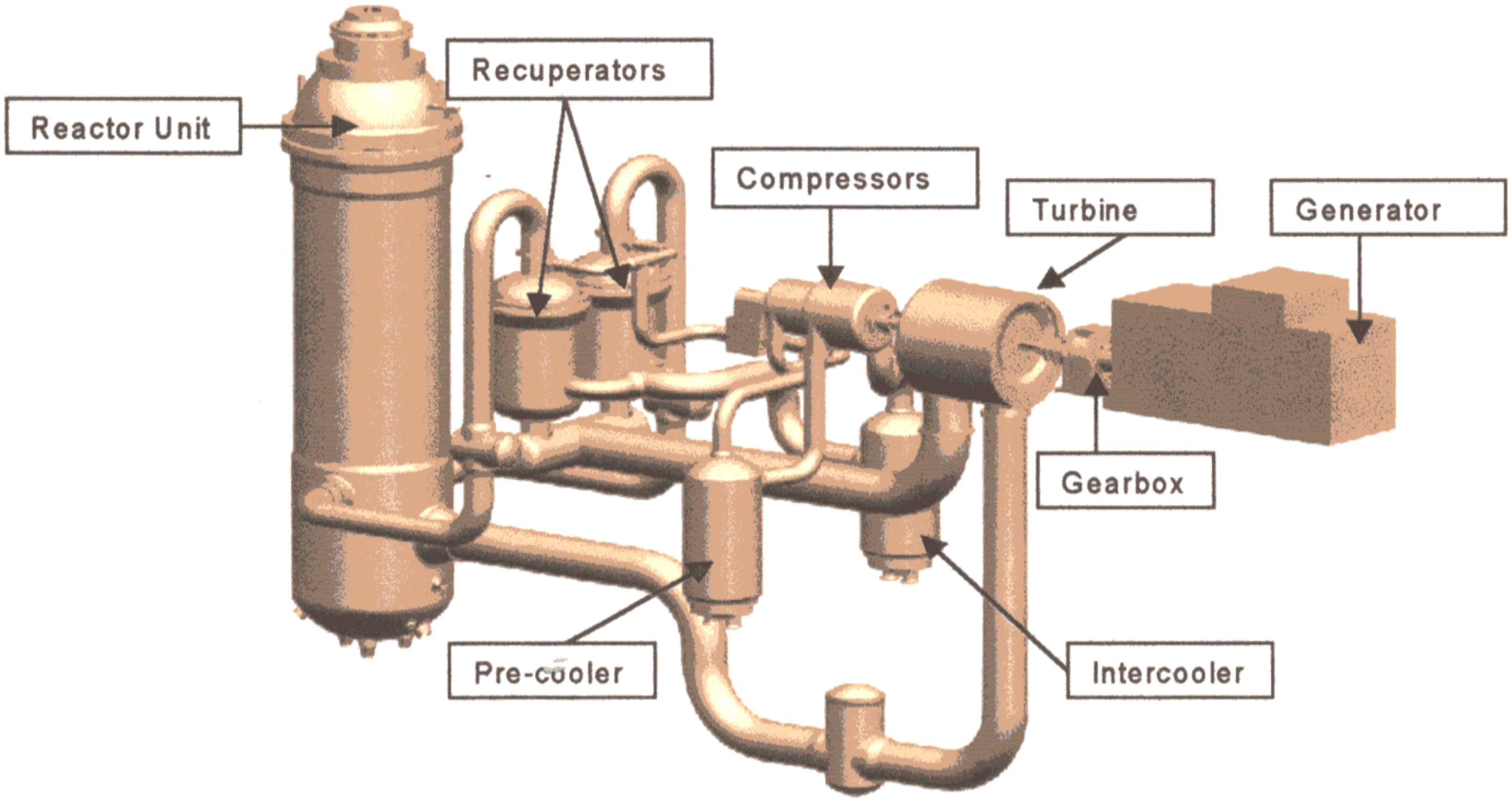


FIG. XIV-2. Conceptual layout of the PBMR primary system [XIV-3].

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

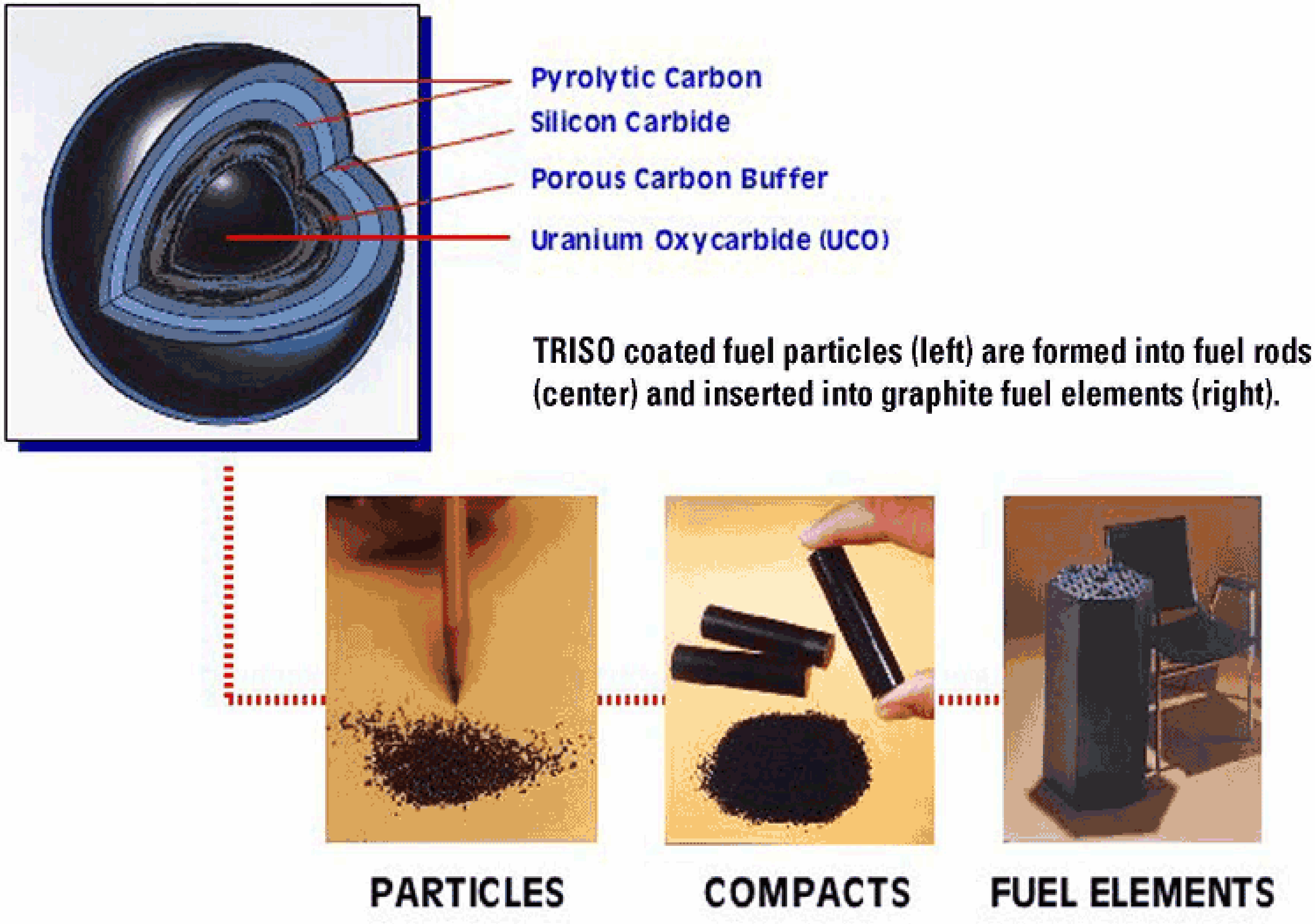
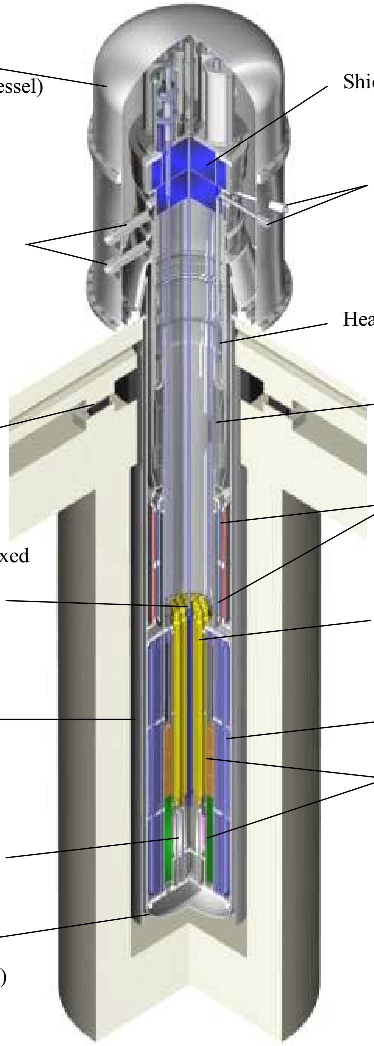


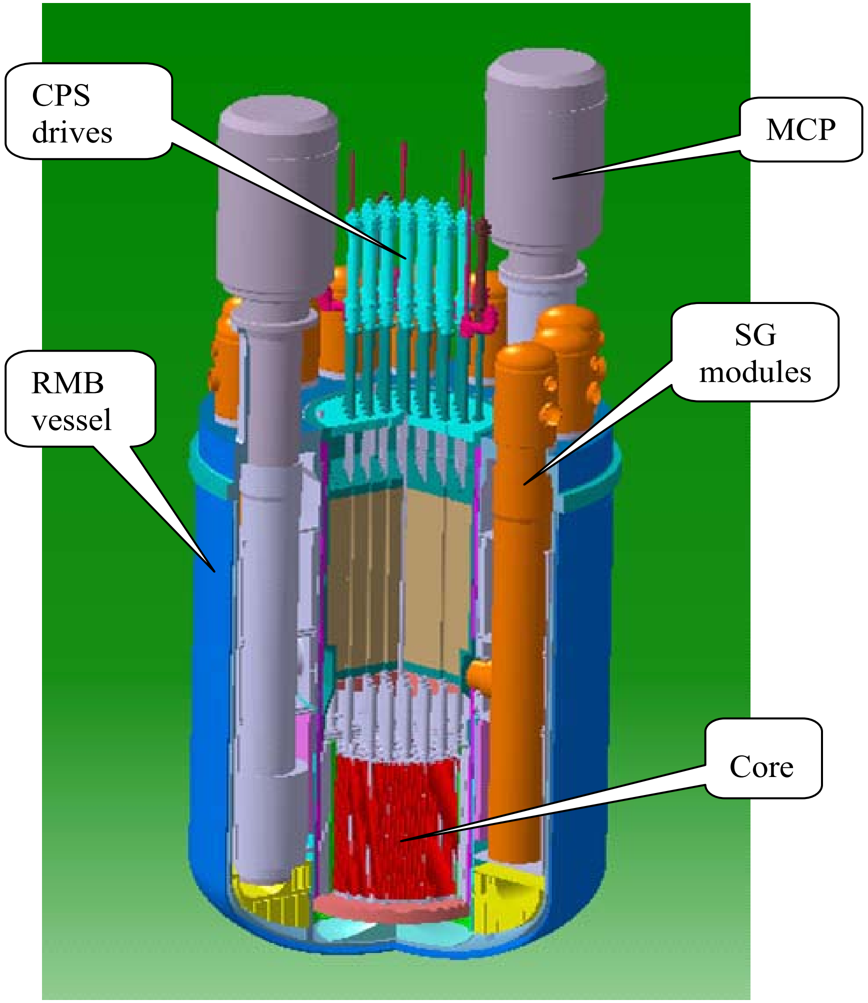
FIG. XV-11. GT–MHR fuel element.

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



4S sodium cooled reactor with a 10 – 30-year refuelling interval for a 50 MW(e) plant (Toshiba – CRIEPI, Japan)

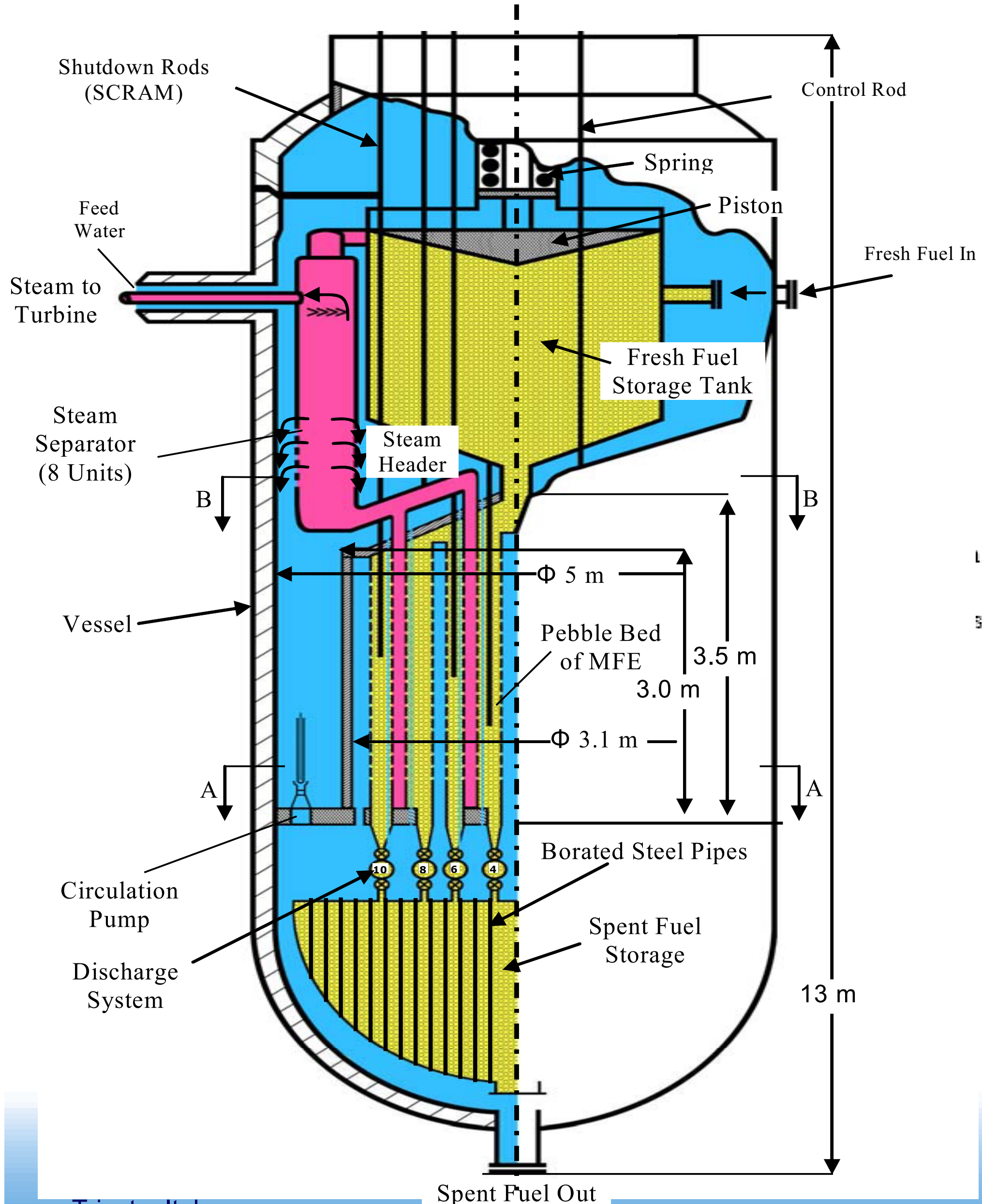
Reactor Types/ Distinct Groups (Examples)
Lead-Bismuth Cooled Reactors/ SRWOR

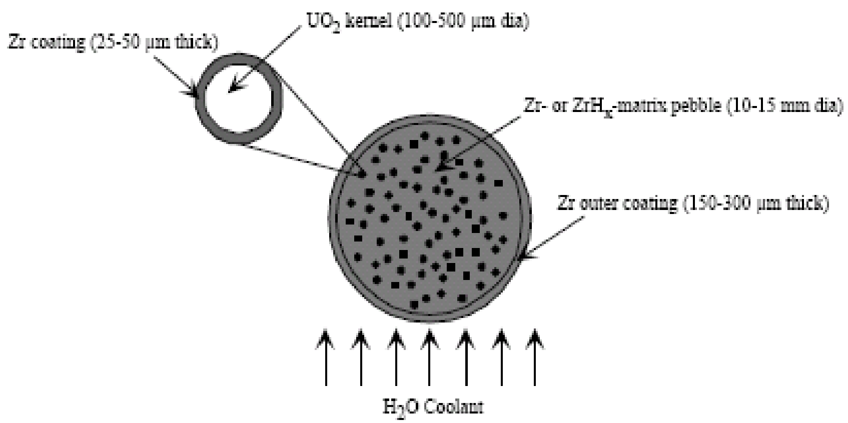


Pb-Bi cooled SVBR-75/100 reactor of 100 MW(e) with 6-9 EFPY refuelling interval (IPPE-“Gidropress”, Russia)

Reactor Types/ Distinct Groups (Examples)

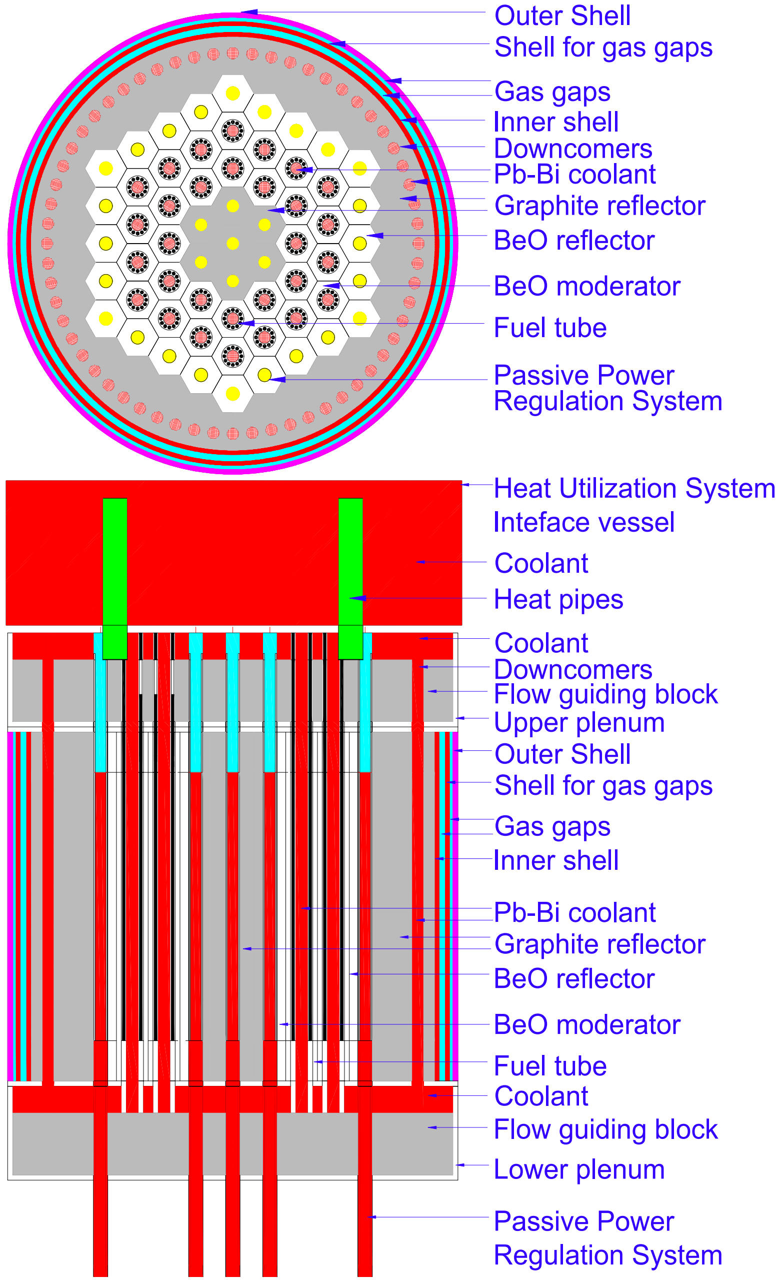
Non-conventional Water Cooled SRWOR/ AFPR (PNNL, USA)





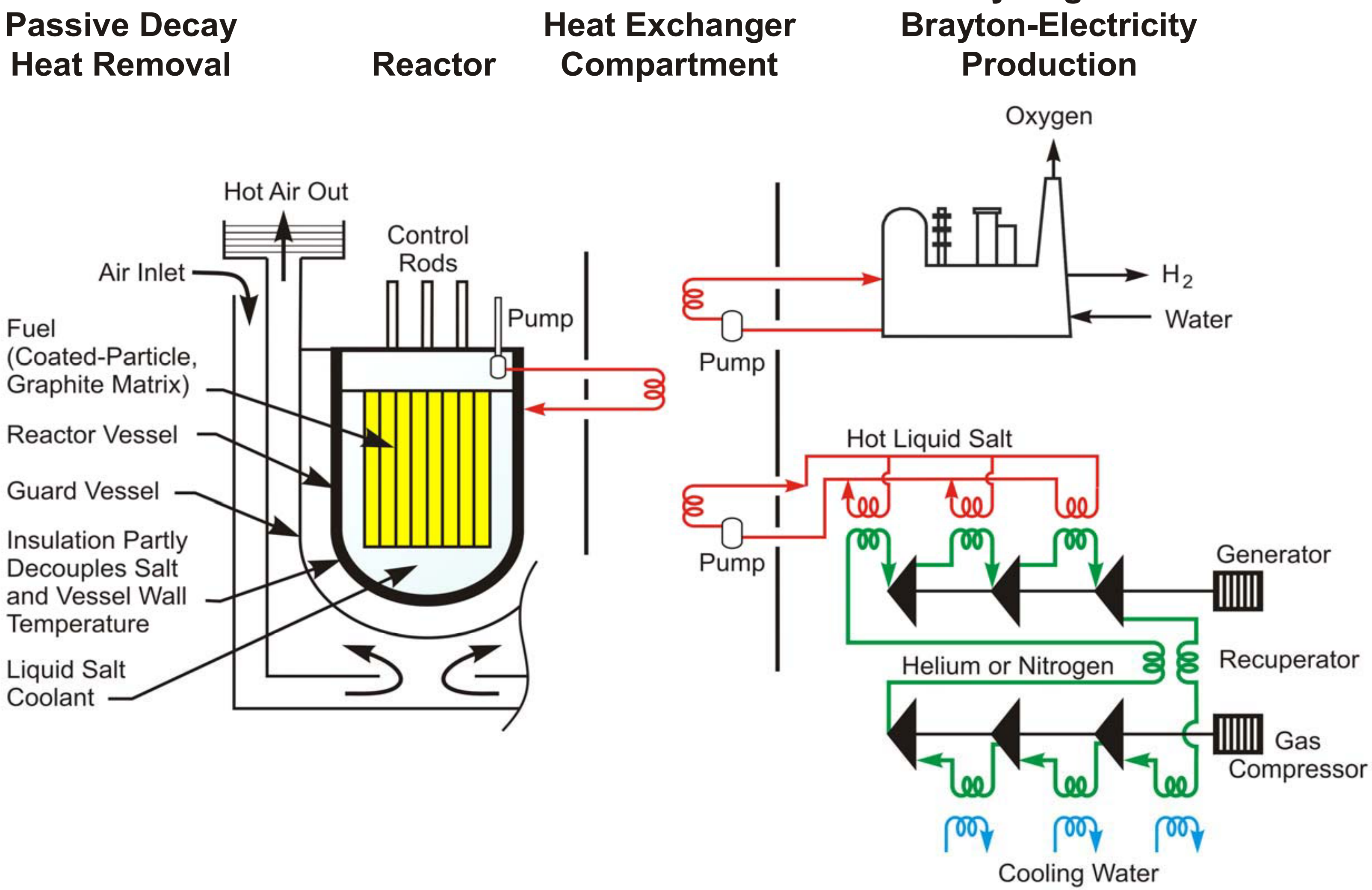
Reactor Types/ Distinct Groups (Examples)

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



Reactor Types/ Distinct Groups (Examples)

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



Nuclear Data for Calculations of Advanced SMRs

- Some designs may include unusual neutron spectra/ material combinations
  - ***Point-wise Monte-Carlo calculations with different evaluated nuclear data libraries may be recommended (i) as a reference, and (ii) to make initial assessment of possible magnitude of the errors related to uncertainties in nuclear data***

- SRWOR: Lump fission product models need to be checked, because:

λ versus (σ Φ) will be different in a SRWOR

$$\frac{dN_i}{dt} = \sum_{\substack{\text{all relevant}\\ \text{source}}} \lambda_j N_j + \sum_{\substack{\text{all relevant}\\ \text{source}}} \sigma_j \phi N_j - \lambda_i N_i - \sigma_i \phi N_i$$

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

Economics:

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

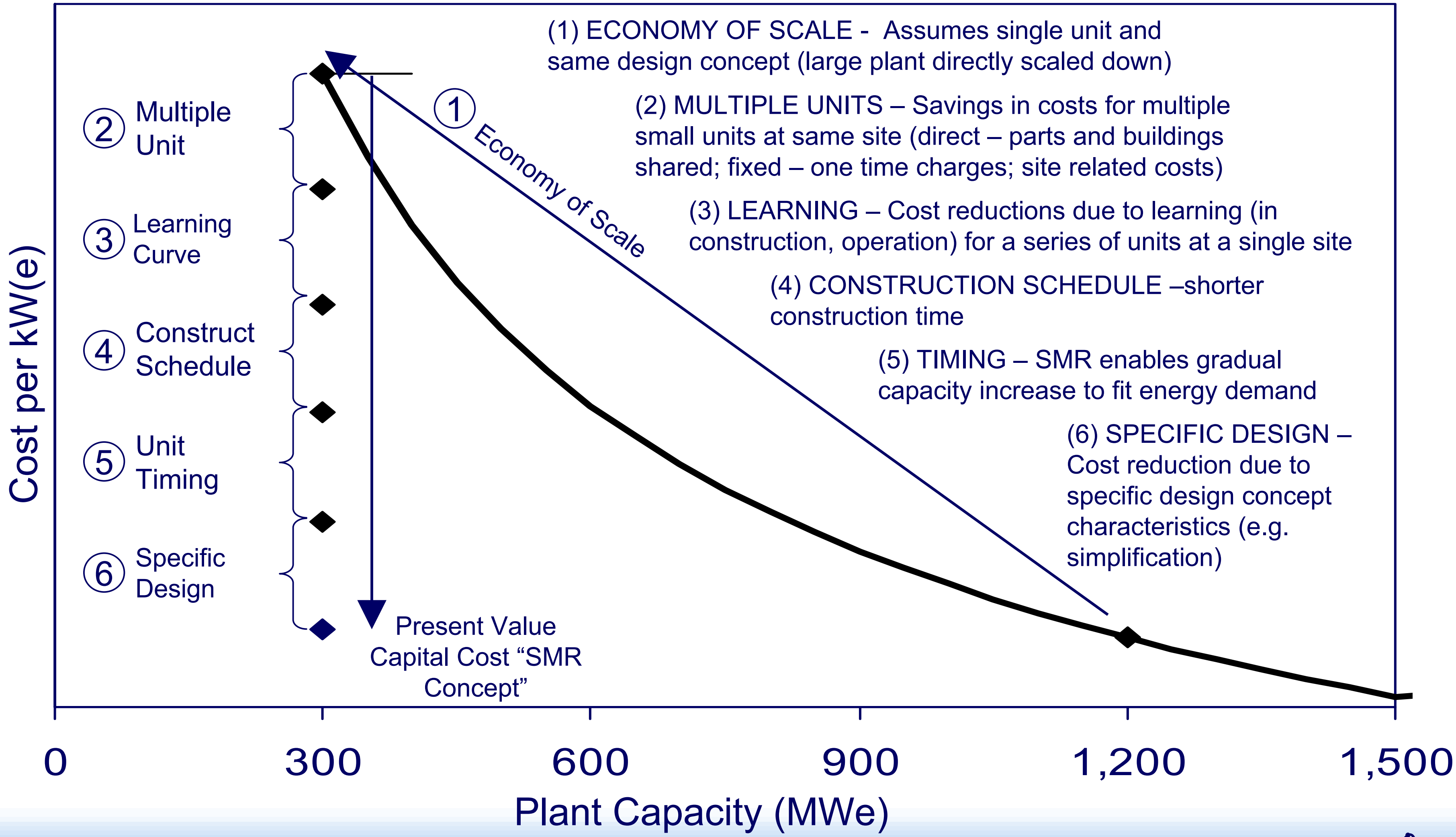
Investments:

- ✓ **Cash flow profile**
- ✓ **Capital-at Risk**

Factors: Expenditure and Production Profiles

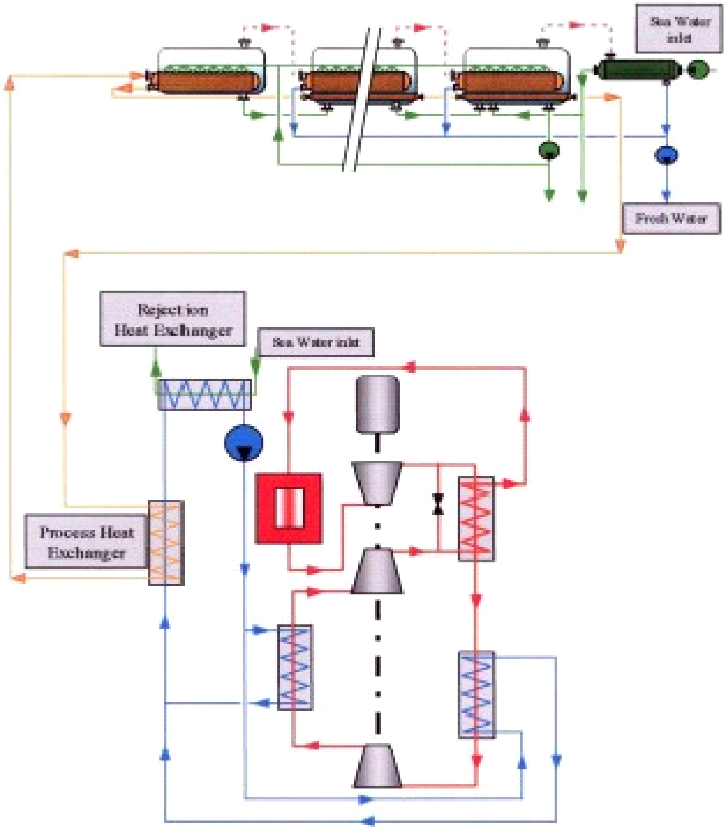
Cash flow profile for construction/ operation of four SMRs versus a single large plant (Westinghouse, USA)

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



Economics and Investments

➢*Increased energy conversion efficiency and use of reject reject heat for cogeneration reduce LCC for the plant*

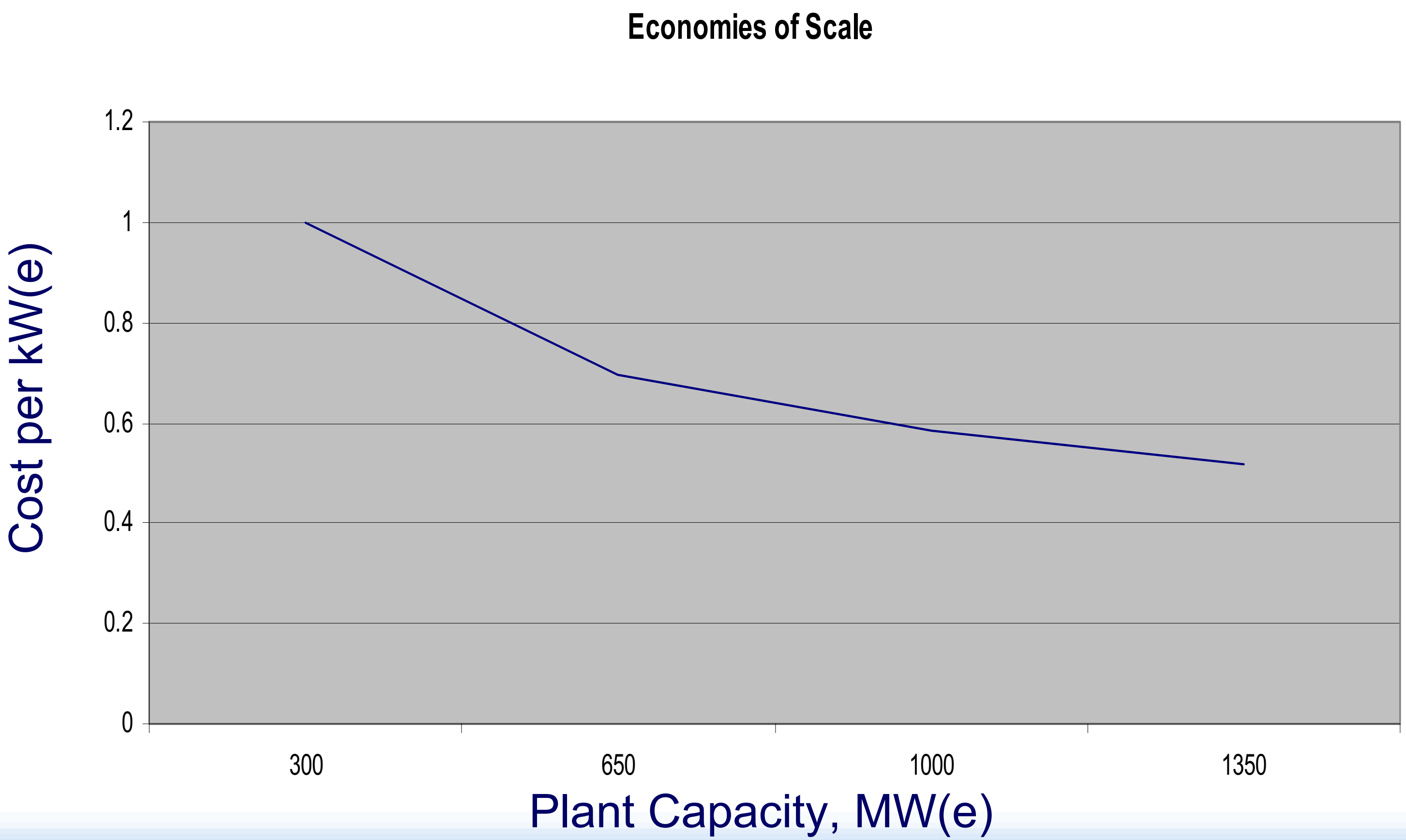


GT-MHR Desalination Process Diagram, GA(USA) – OKBM(Russia)

Targeted plant efficiency – 48%

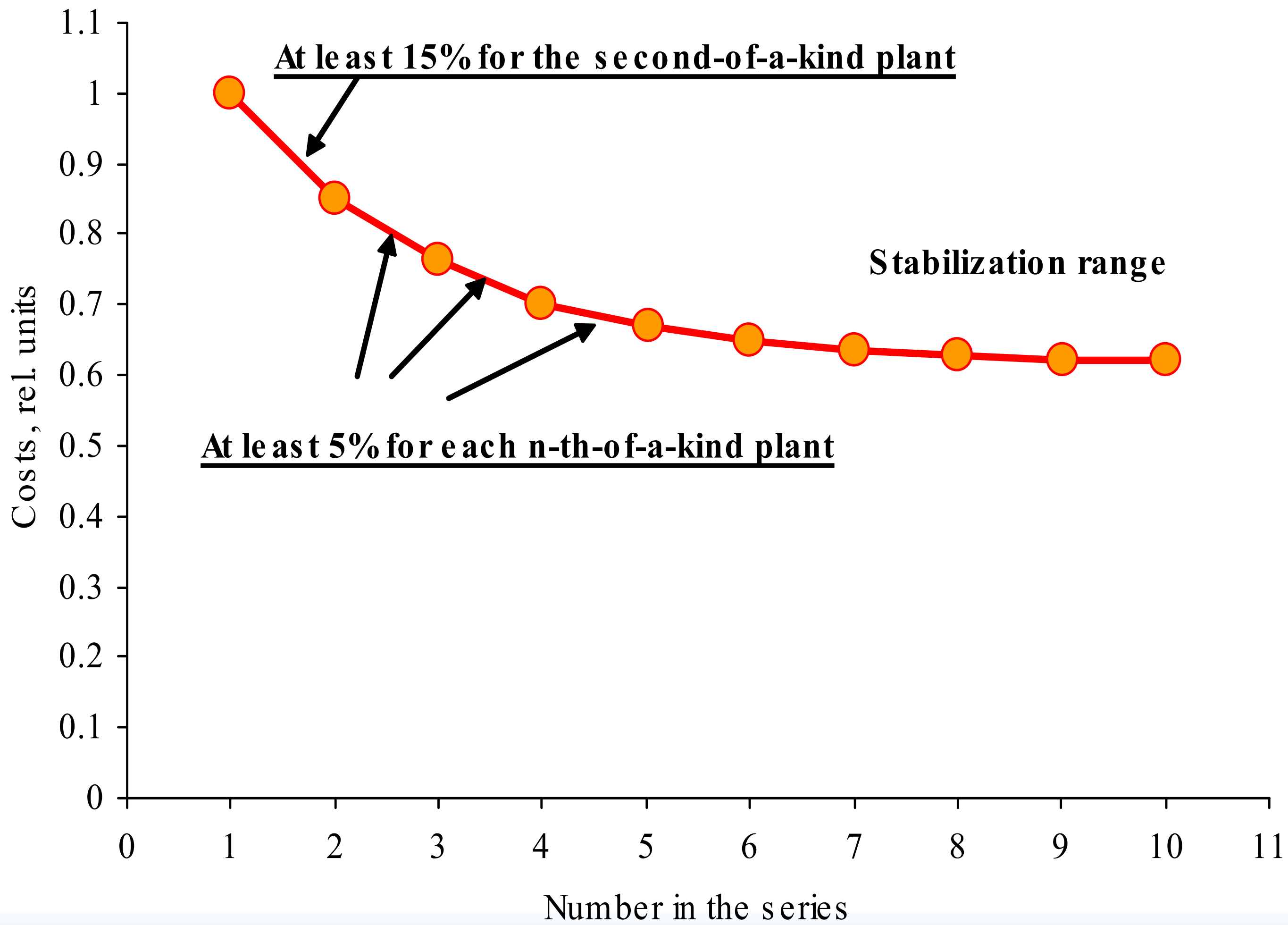
Economy of Scale

- **Based on the OECD/NEA study "Reduction of Capital Costs of Nuclear Power Plant", case of France for 300, 650,1000, and 1350 MW(e)**



Economics and Investments

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

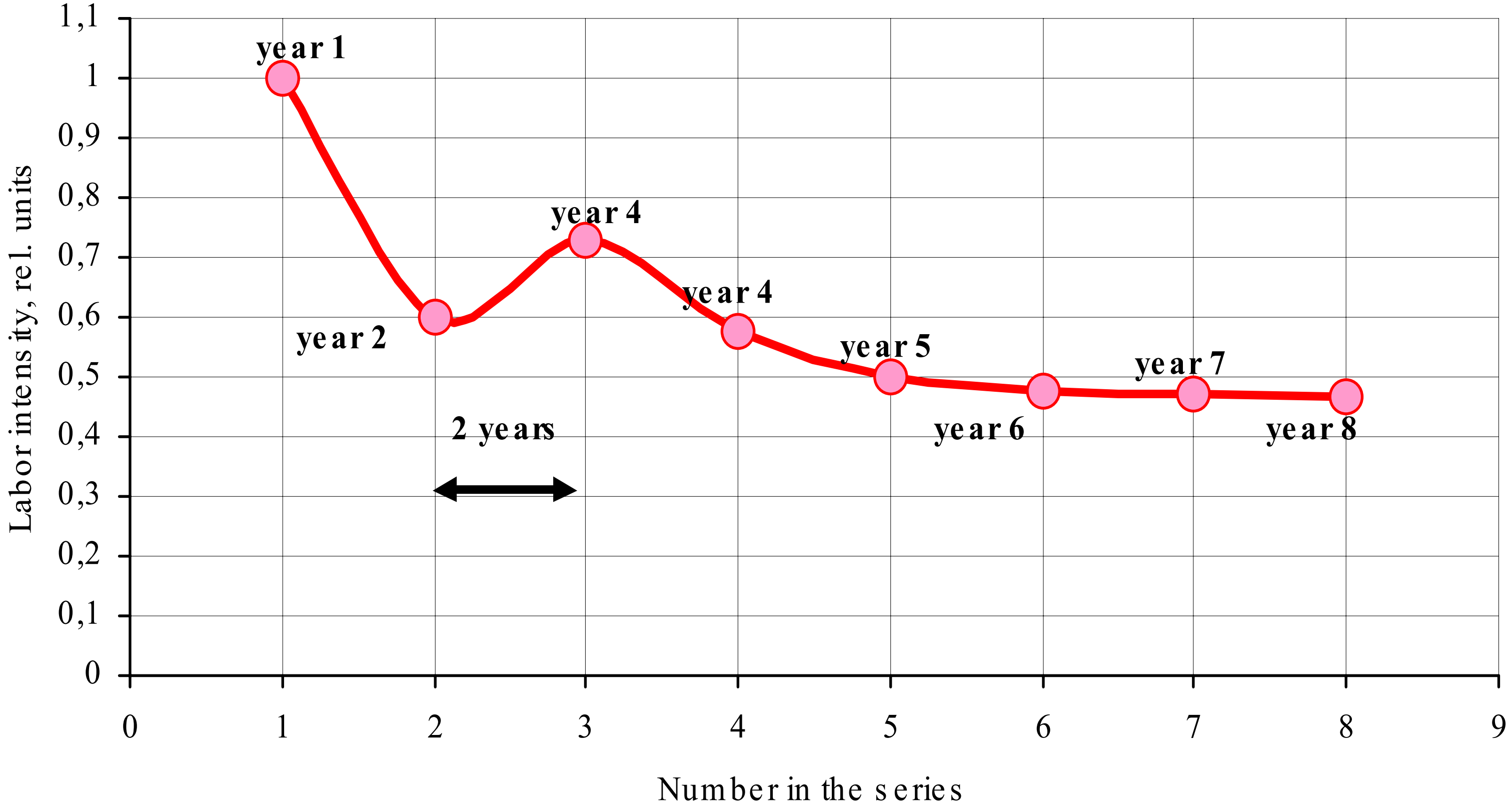


Economics and Investments

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**

Economics and Investments
Learning Curve – Continuity



Production continuity vs. specific labour intensity in the production of marine propulsion reactors (OKBM, Russian Federation)

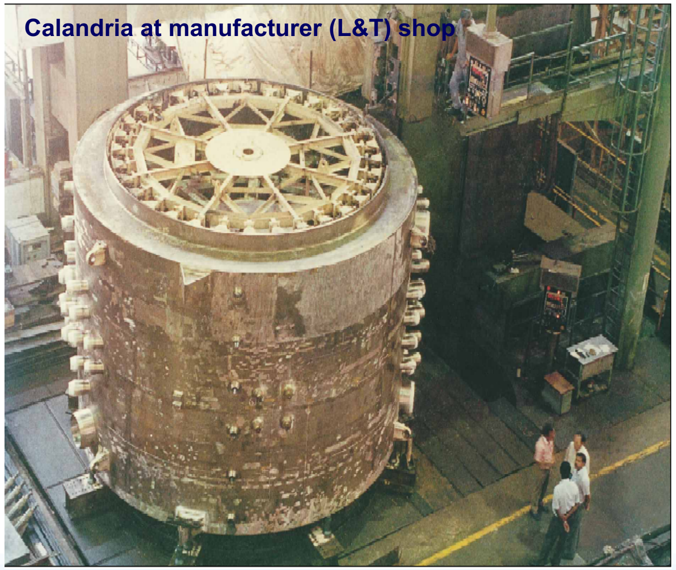
Economics and Investments

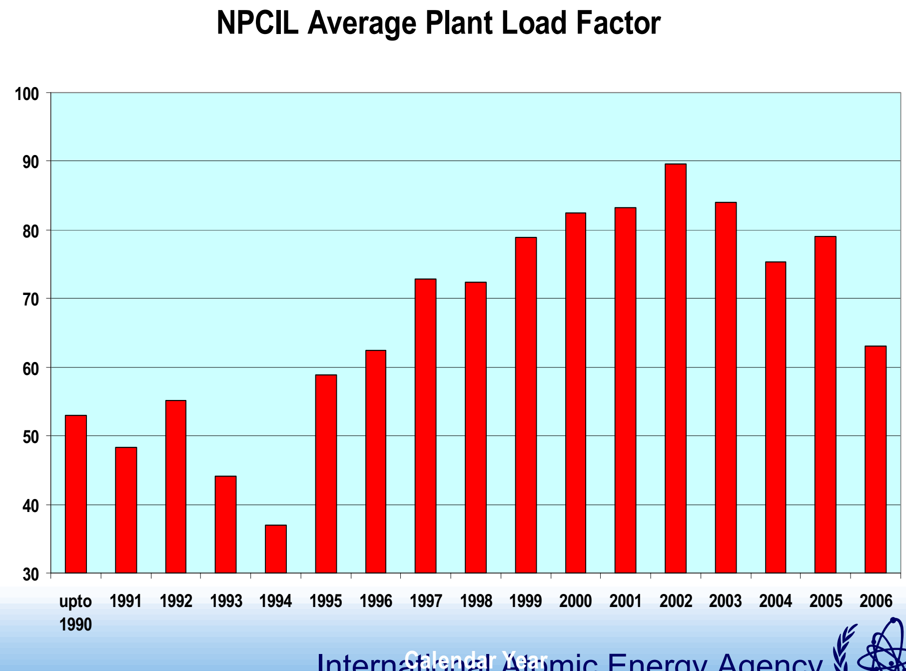
SMRs could be much cheaper if produced in a developing country with higher purchasing power of a hard currency

Is it a solution for less developed countries?

- Indian PHWRs - 220,540 & 700 MWe

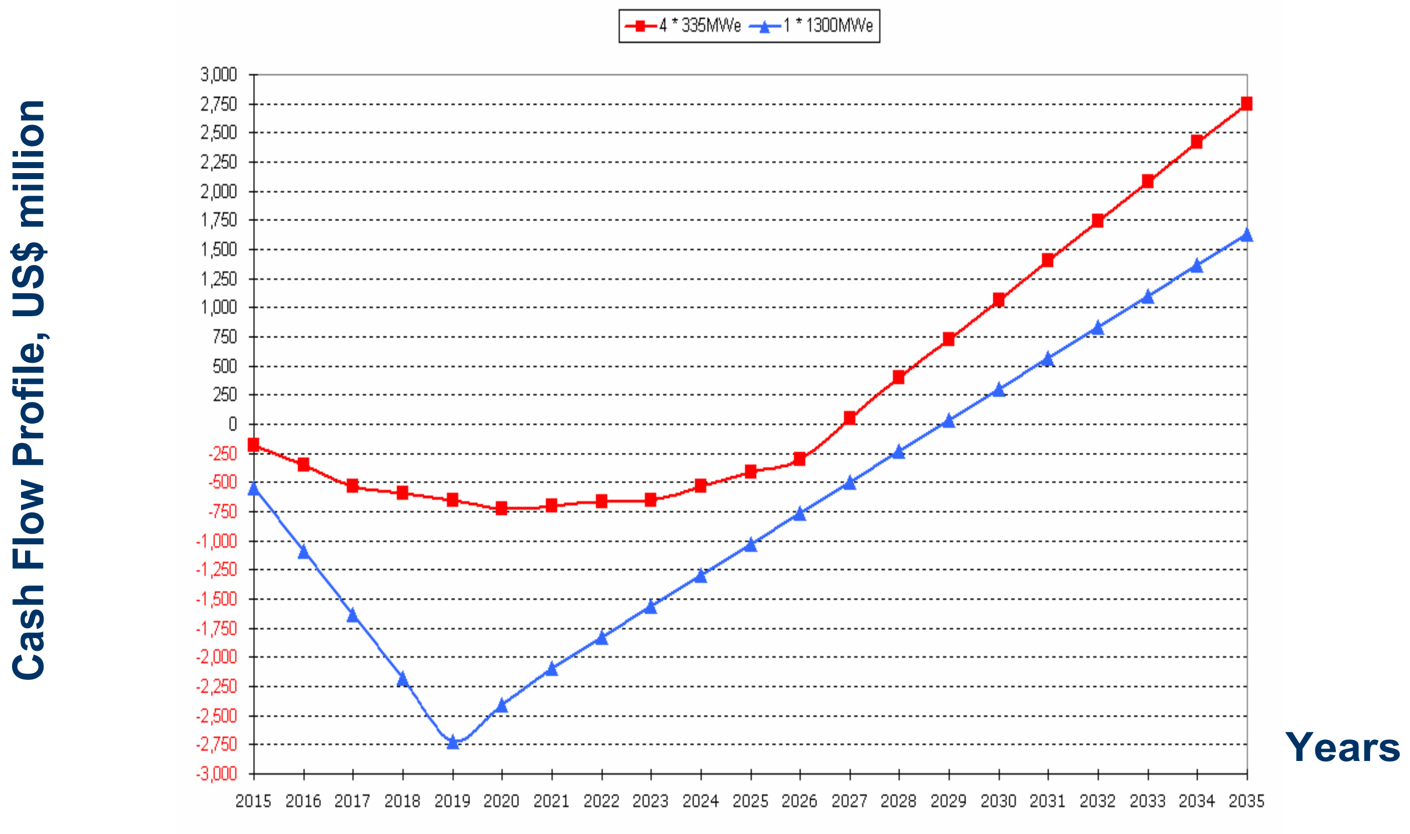
The Indian experience has shown that the reactors of 220 MWe and 540 MWe have been set up with completion cost (inclusive of escalation till completion and interest during construction) of US $1200 to 1400 per kWe. The 700 MWe reactors to be set up in future are expected to cost about US $1200 per kWe.





Economics and investments

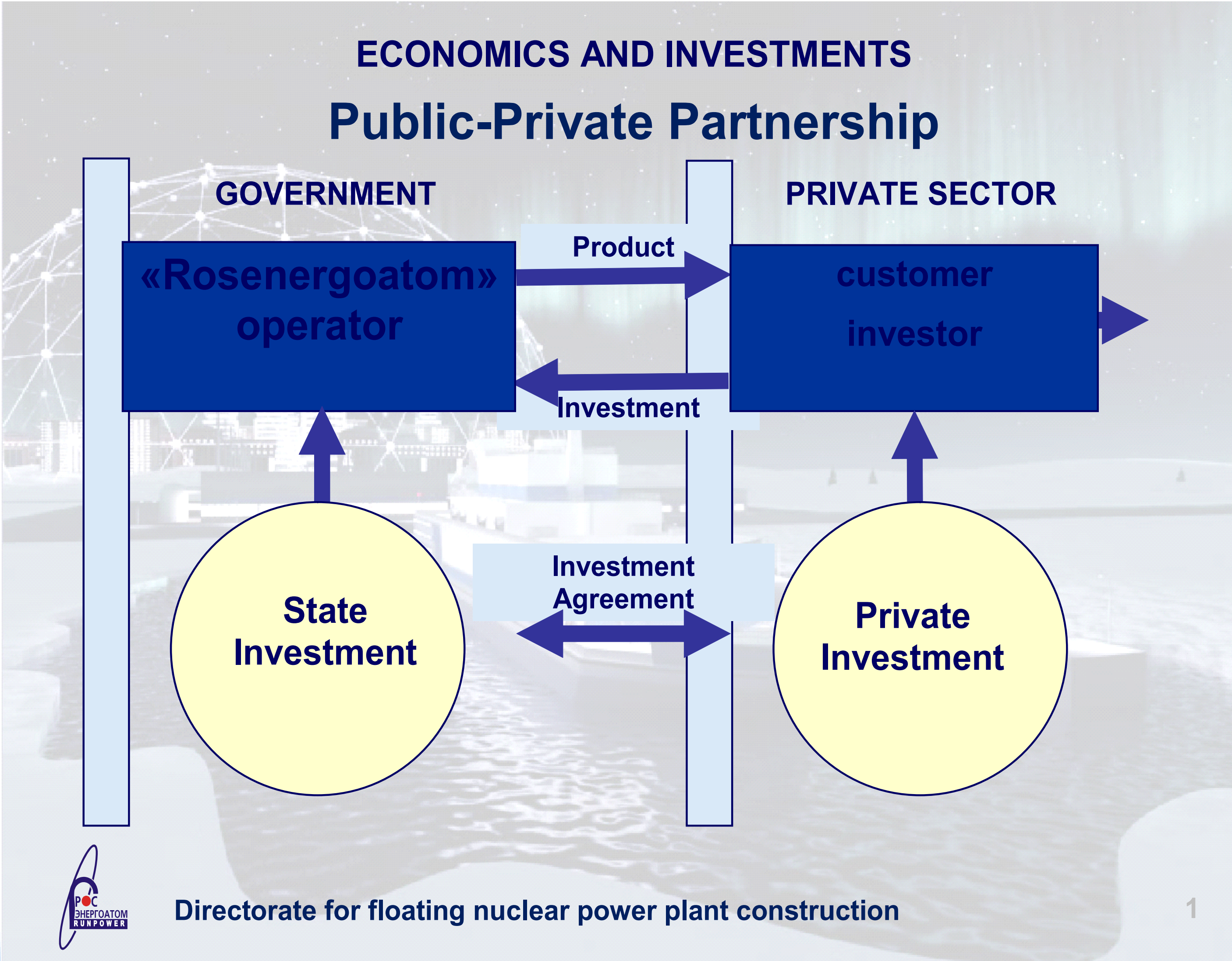
➢ ***Incremental capacity increase reduces the required front end investment and the Capital-at-Risk***



Cash flow profile for construction/ operation of four SMRs versus a single large plant (Westinghouse, USA)

Economics and investments

Attractive investment profile may make SMRs attractive for private investors – Example from Rosenergoatom (Russia)



Economics and Investments

Ongoing IAEA activity 1.1.5.4/2: Case Studies on SMR Competitiveness in Different Applications

➢ *Combined application of the PVCC model Westinghouse (USA) and G4-ECONS model (EMWG GIF) to selected deployment scenarios*

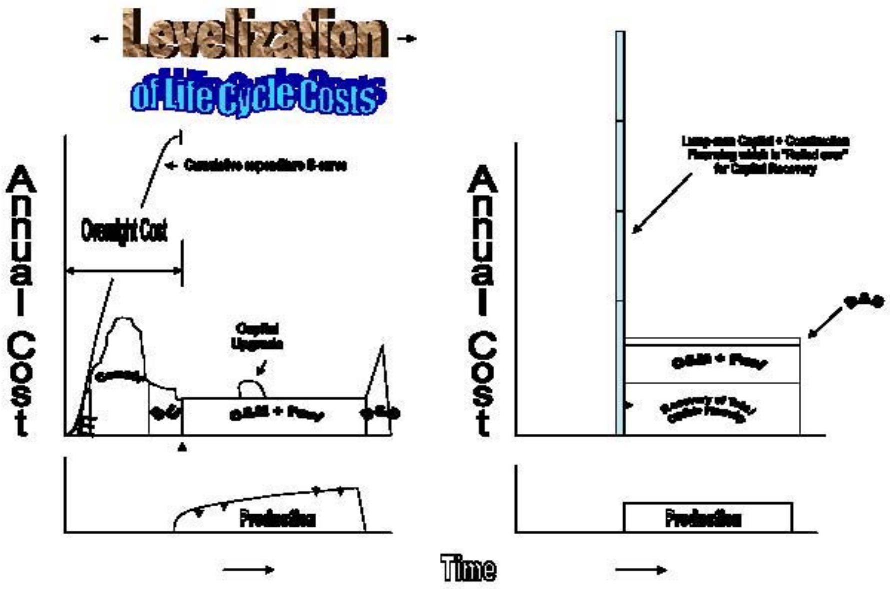
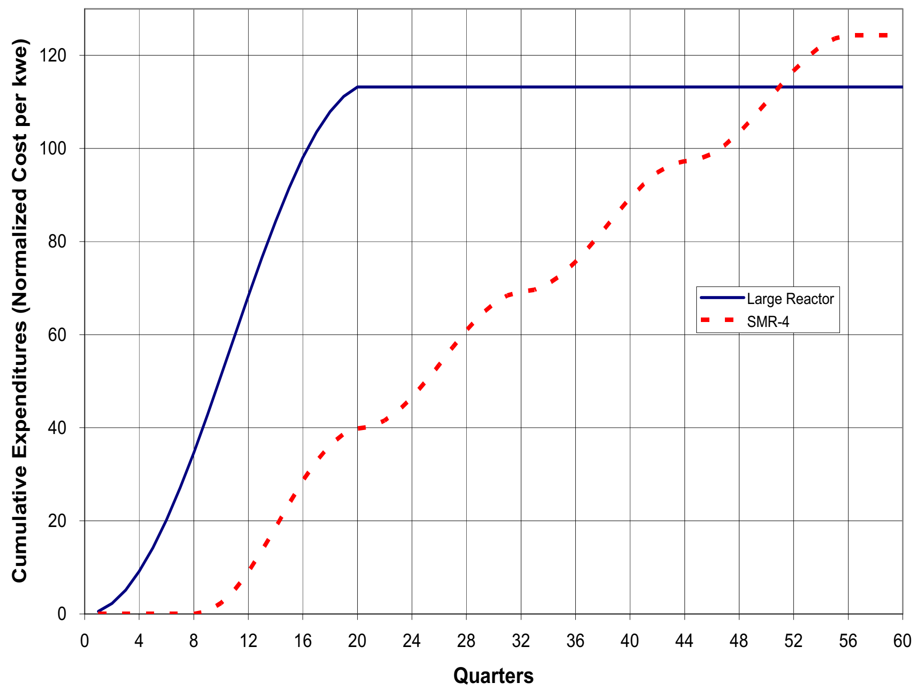
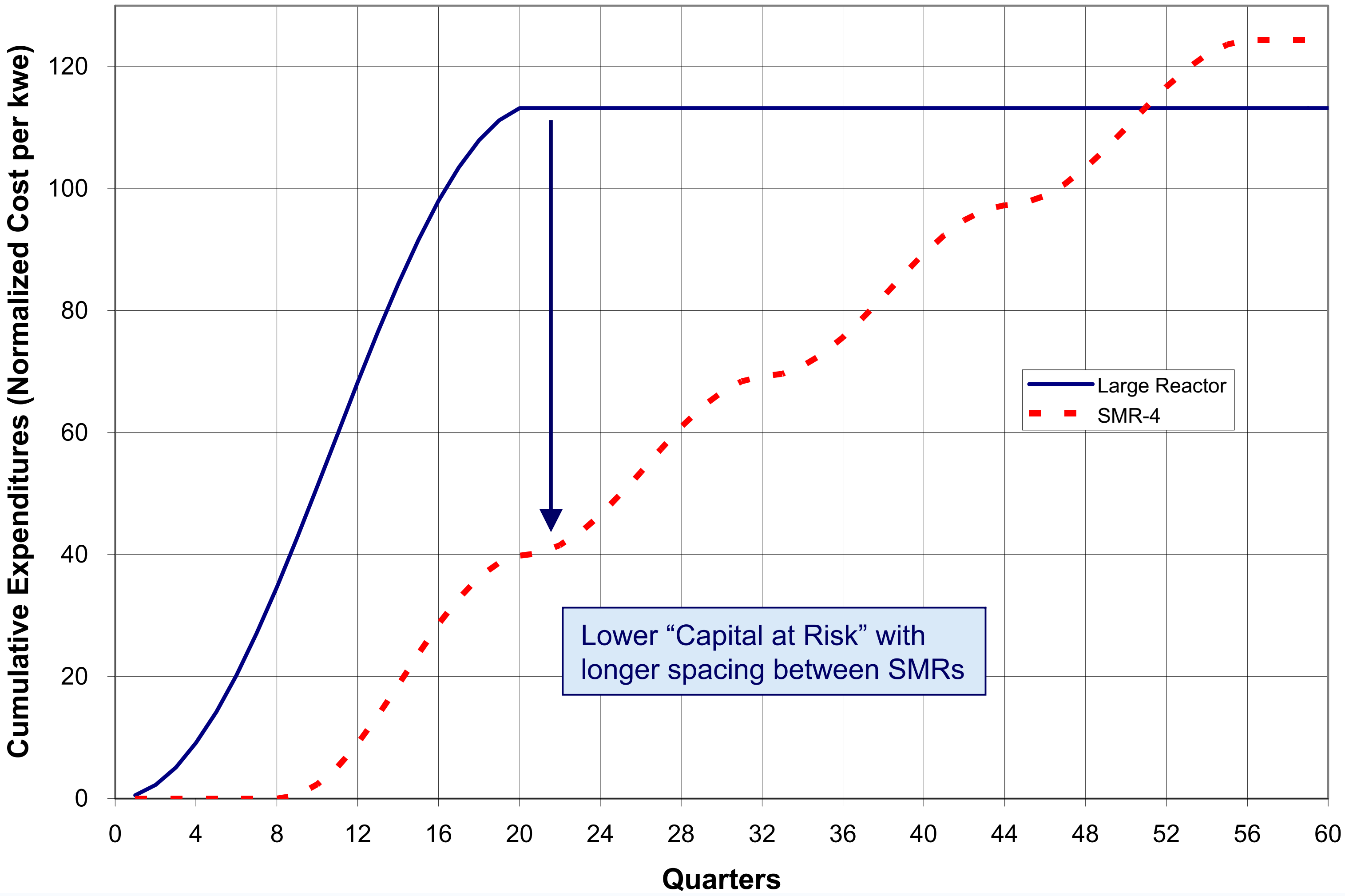


Figure 1. Concept of cost levelization.



Economics and Investments

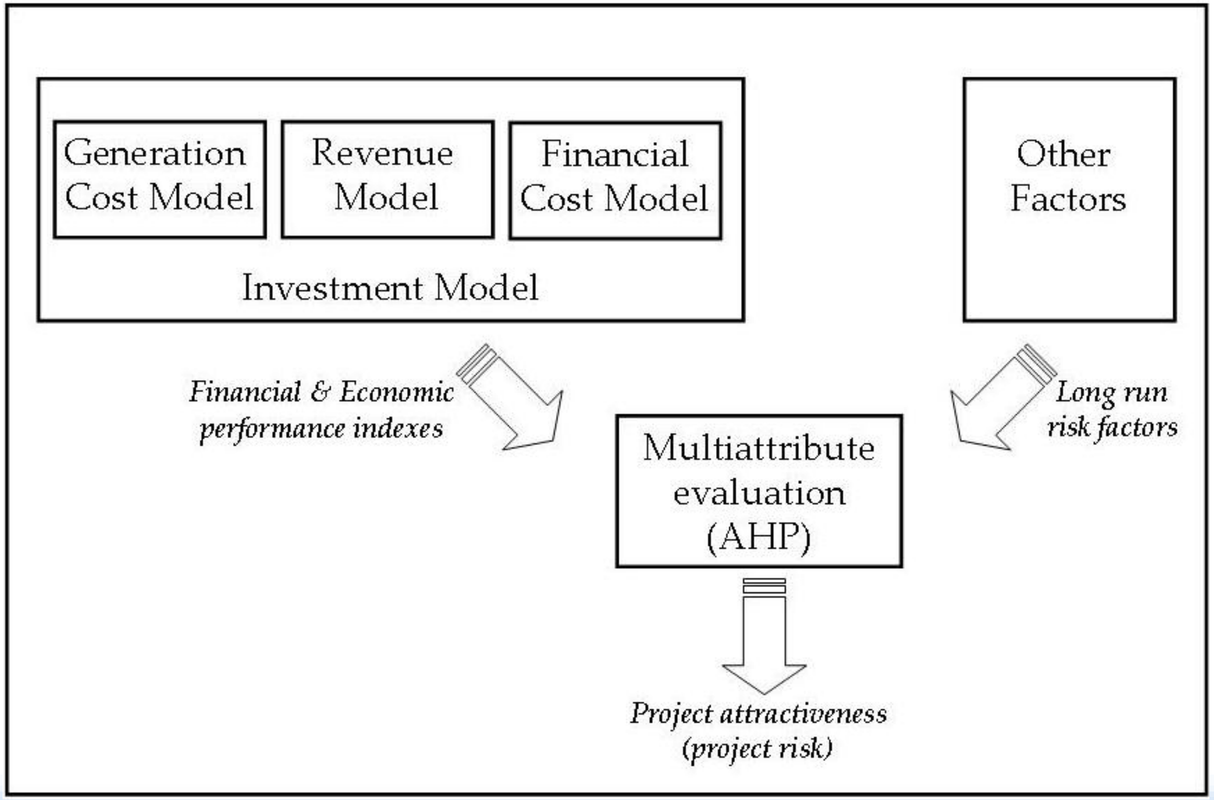
PVCC Example - Cumulative Expenditures (36 months between each of 4 SMRs)



Models to Support Decision Making of Public and Private Investors

AN OPEN MODEL FOR THE EVALUATION OF SMRs ECONOMIC OPPORTUNITIES (Politecnico di Milano and ENEA, Italy)

- **A framework for coherent use of available models**
- **Provisions to ass new models as they become available**



A QUESTION OFTEN ASKED: IS SMALLER REACTOR MORE SAFE THAN A LARGER ONE?

- **Typical Answers Appear Black and White:**

  - A decisive YES! , or

  - Not less decisive NO!

- **WHAT COULD BE A BALANCED AND OBJECTIVE ANSWER?**

SAFETY

Current Safety Approach:

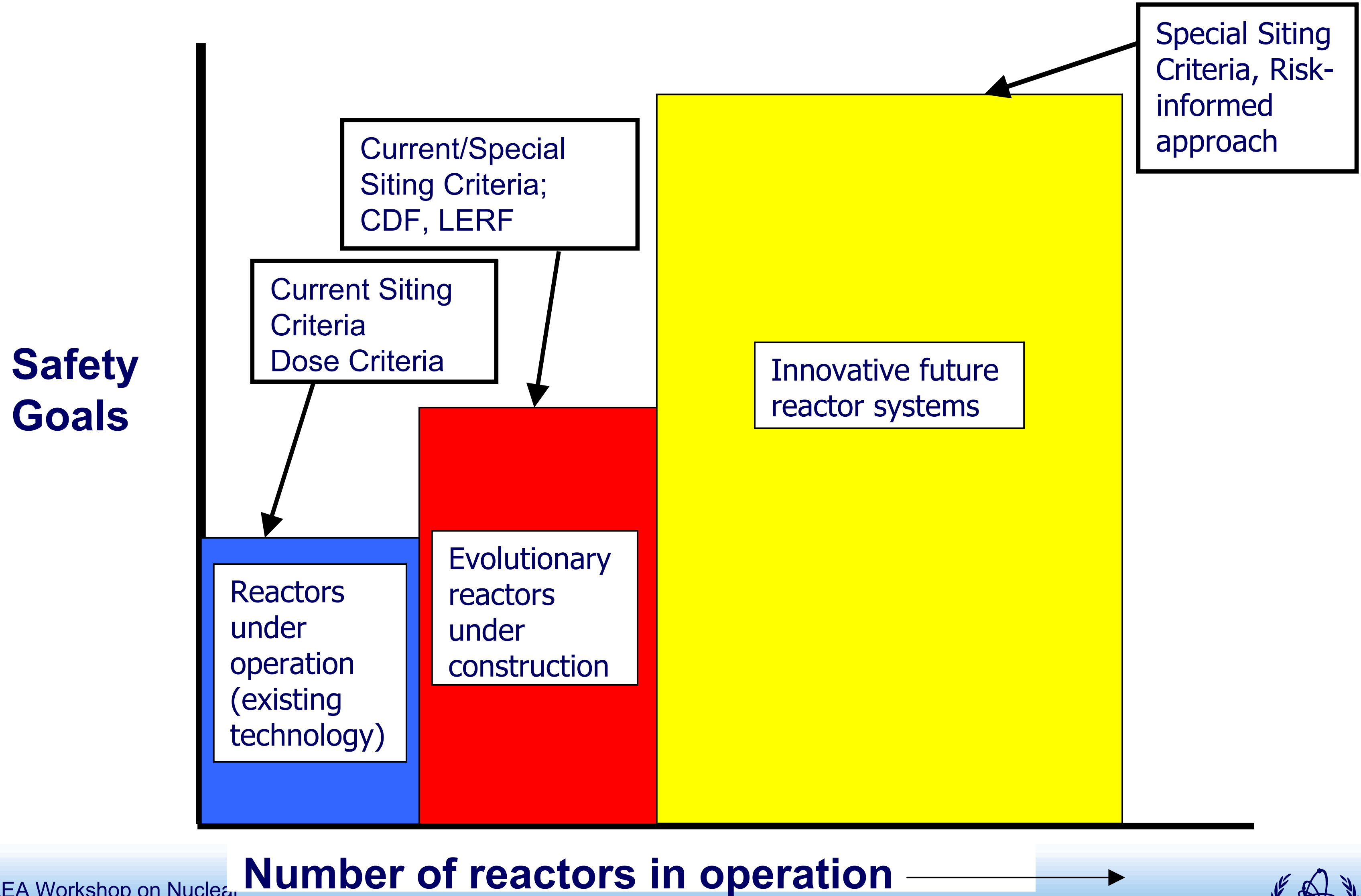
IAEA Safety Standard NS-R-1 "Safety of the Nuclear Power Plants: Design Requirements"

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)



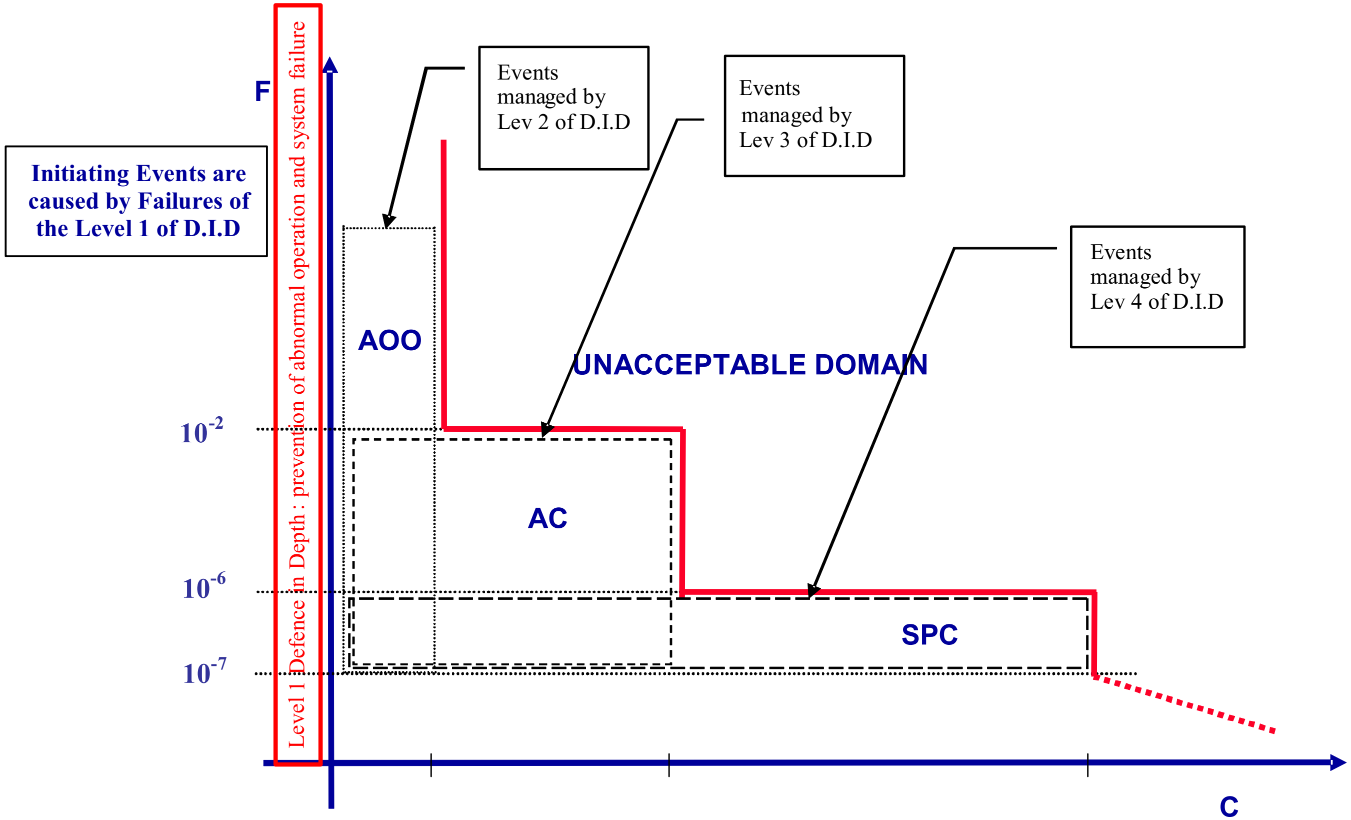
SAFETY

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*

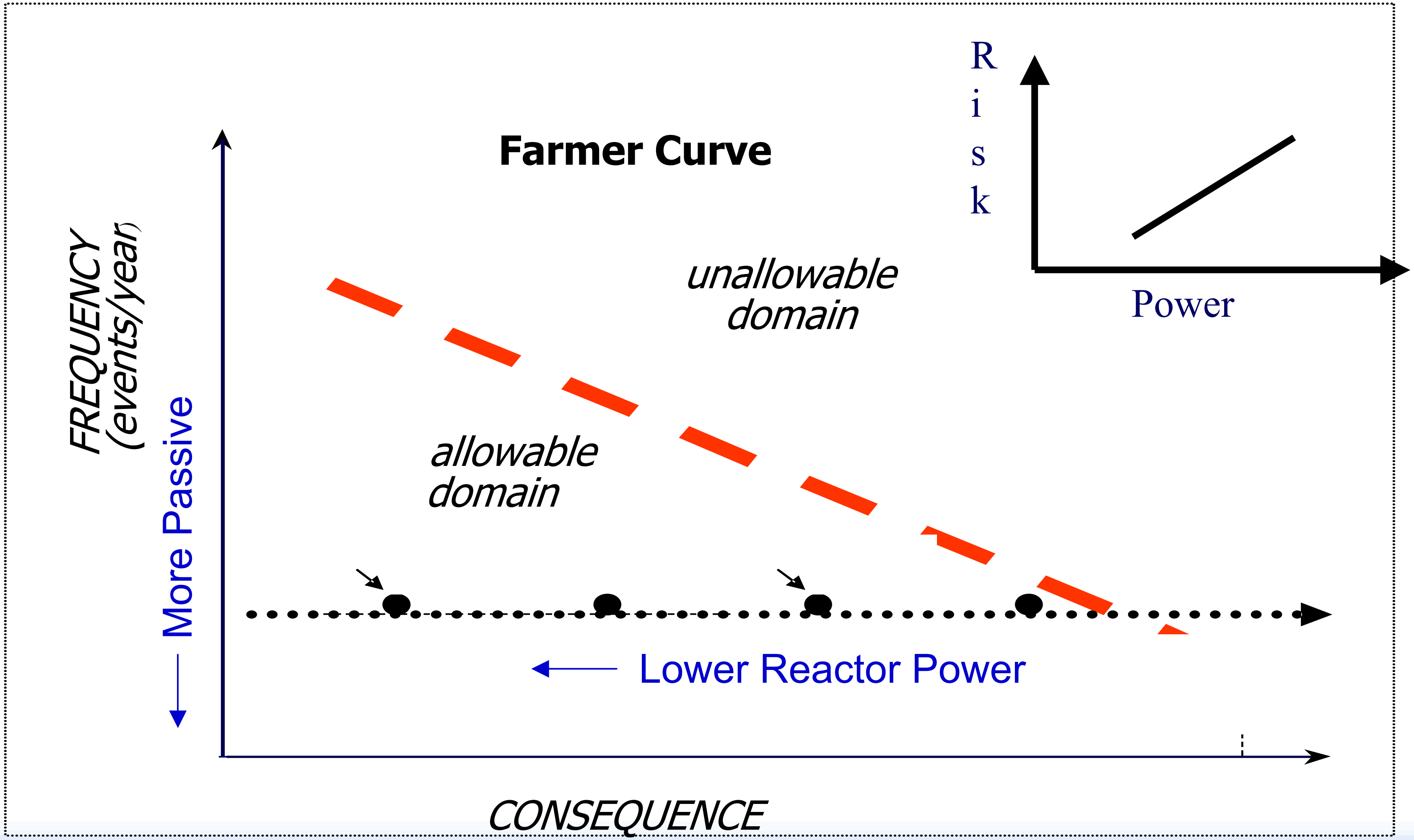
SAFETY IAEA-TECDOC-1570



AOO – abnormal operation occurrences
AC – accidental conditions
F – frequency
C – consequences
SPC – severe plant conditions

FIG. 2. Quantitative Safety Goal and Correlation of Levels of Defence (FIG. 5 from reference [13]).

SAFETY
The role of passive safety features and reactor power (BARC, India)



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*

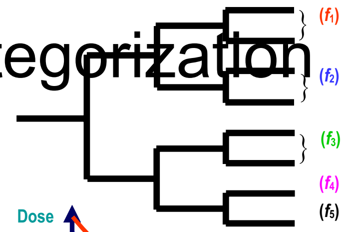
- **Benefits of the smaller source-term could be recognized in full when a technology-neutral and risk informed approach is established**
- **Smaller source terms of SMRs could help justify their licensing with a reduced or eliminated emergency planning zone (EPZ)**

IAEA activity 1.1.5.4/10: Coordinated Research Project "Small Reactors without On-site Refuelling" (2004 – 2008)

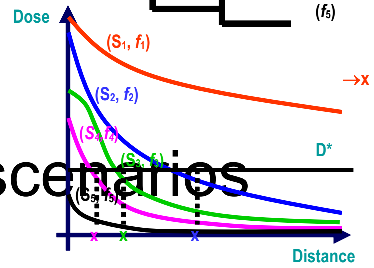
Group 1: "Revising the Need for Relocation and Evacuation Measures Unique to NPPs with Innovative SMRs"

EPZ Redefinition Methodology

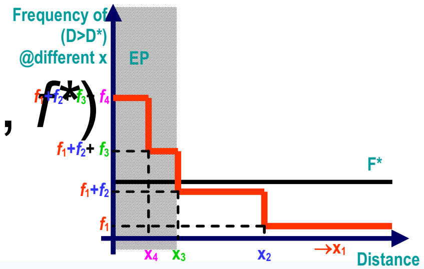
- Step1
  PRA accident sequences re-categorization and release scenario definition



- Step2
  Deterministic dose vs distance evaluation for relevant release scenarios



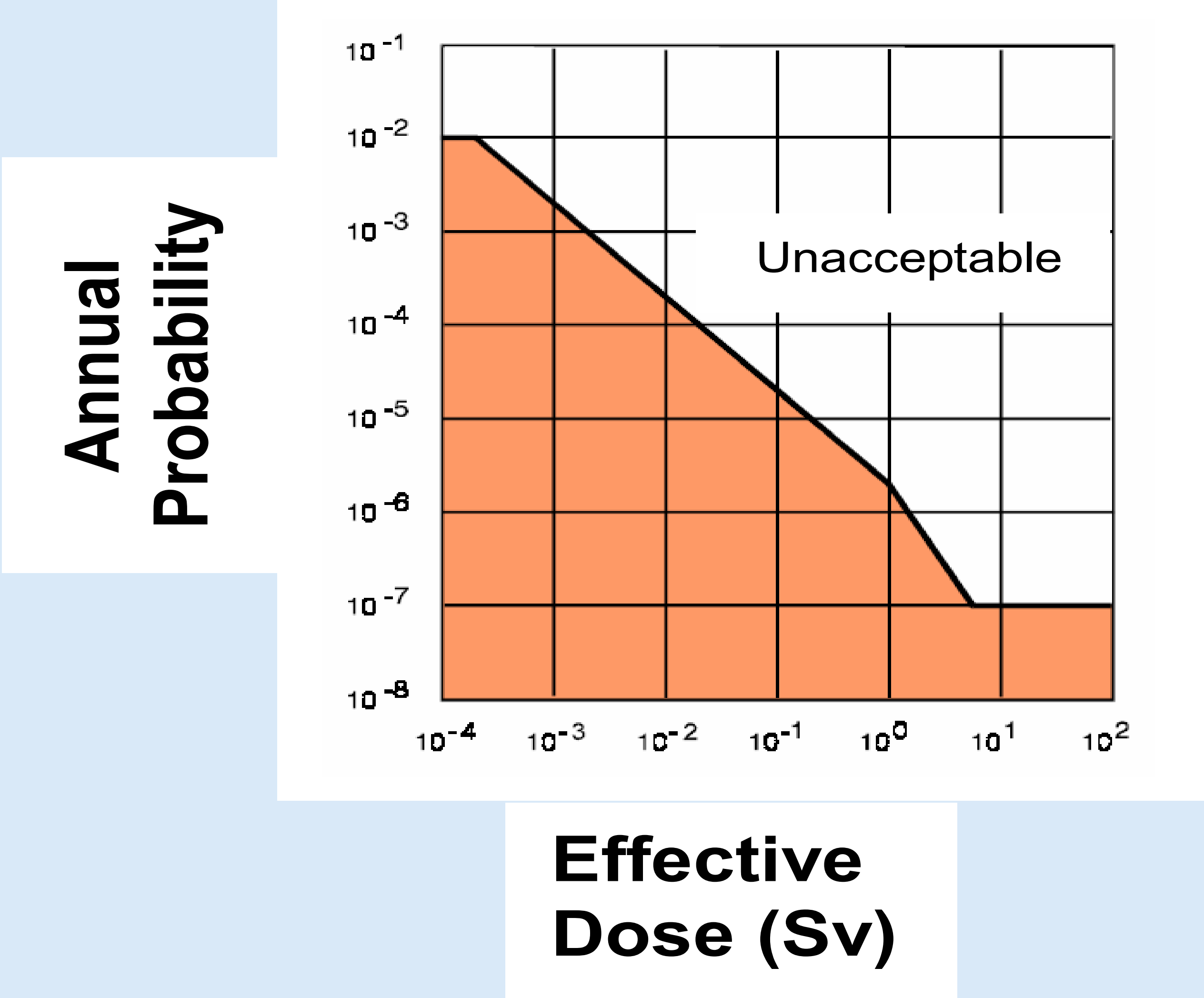
- Step3 (Limiting dose, D*)
- Step4 (Limiting frequency, f*)
- Step5 (EPZ definition)



SAFETY

IN SOME COUNTRIES RISK-INFORMED REGULATORY APPROACH IS ALREADY IN PLACE

Argentina's regulations (severe accidents)



A QUESTION OFTEN ASKED: IS SMALLER REACTOR MORE SAFE THAN A LARGER ONE?

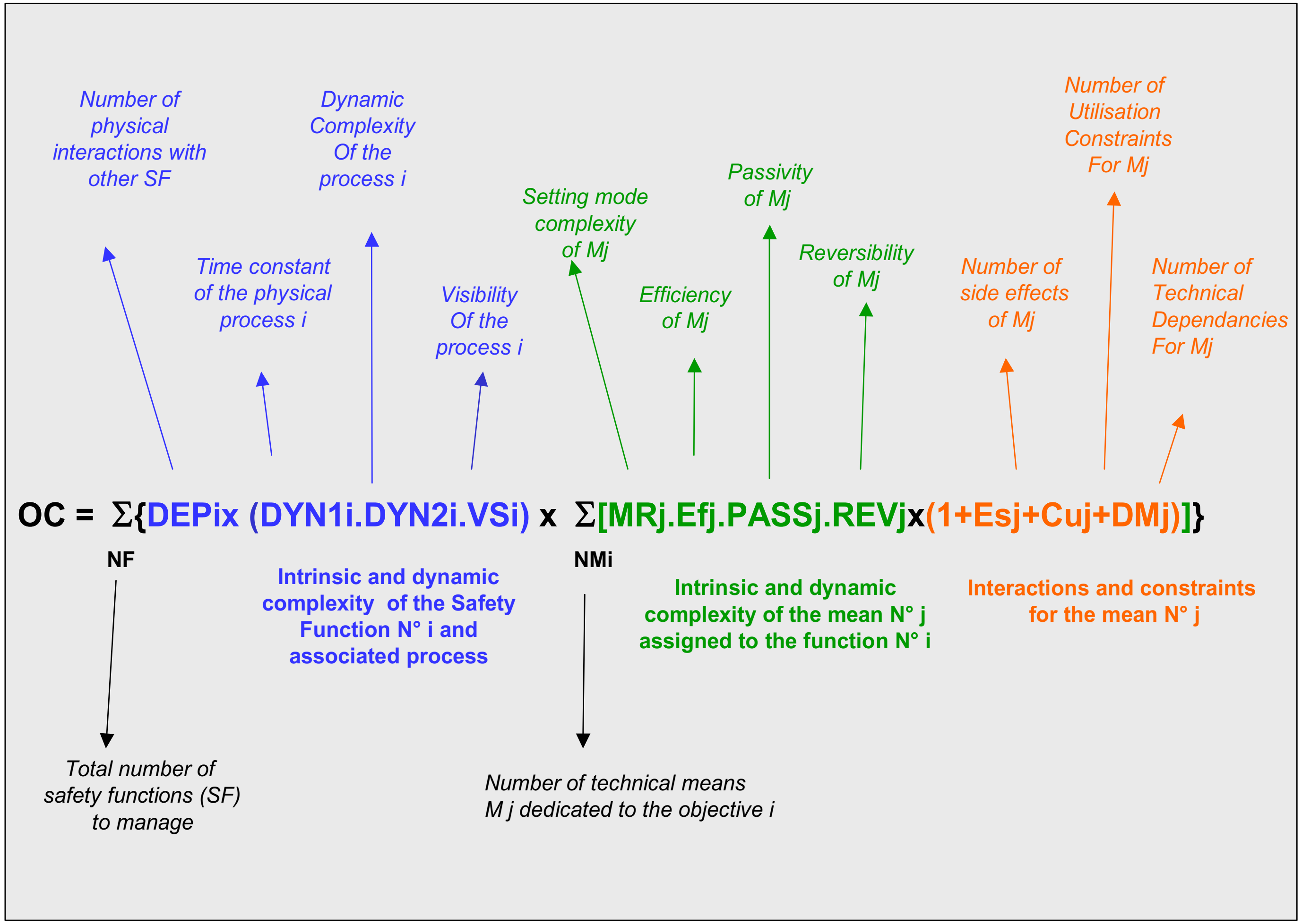
- **A BALANCED AND OBJECTIVE ANSWER COULD BE THAT BOTH LARGE AND SMALL REACTORS MAY HAVE A HIGH SAFETY LEVEL FOR THEIR SPECIFIC CONDITIONS OF USE**

- ***For smaller reactors these conditions may include EPZ reduced against that needed for a large reactor***

- ***Reduced or eliminated 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

Conditions of use may include Operational Complexity

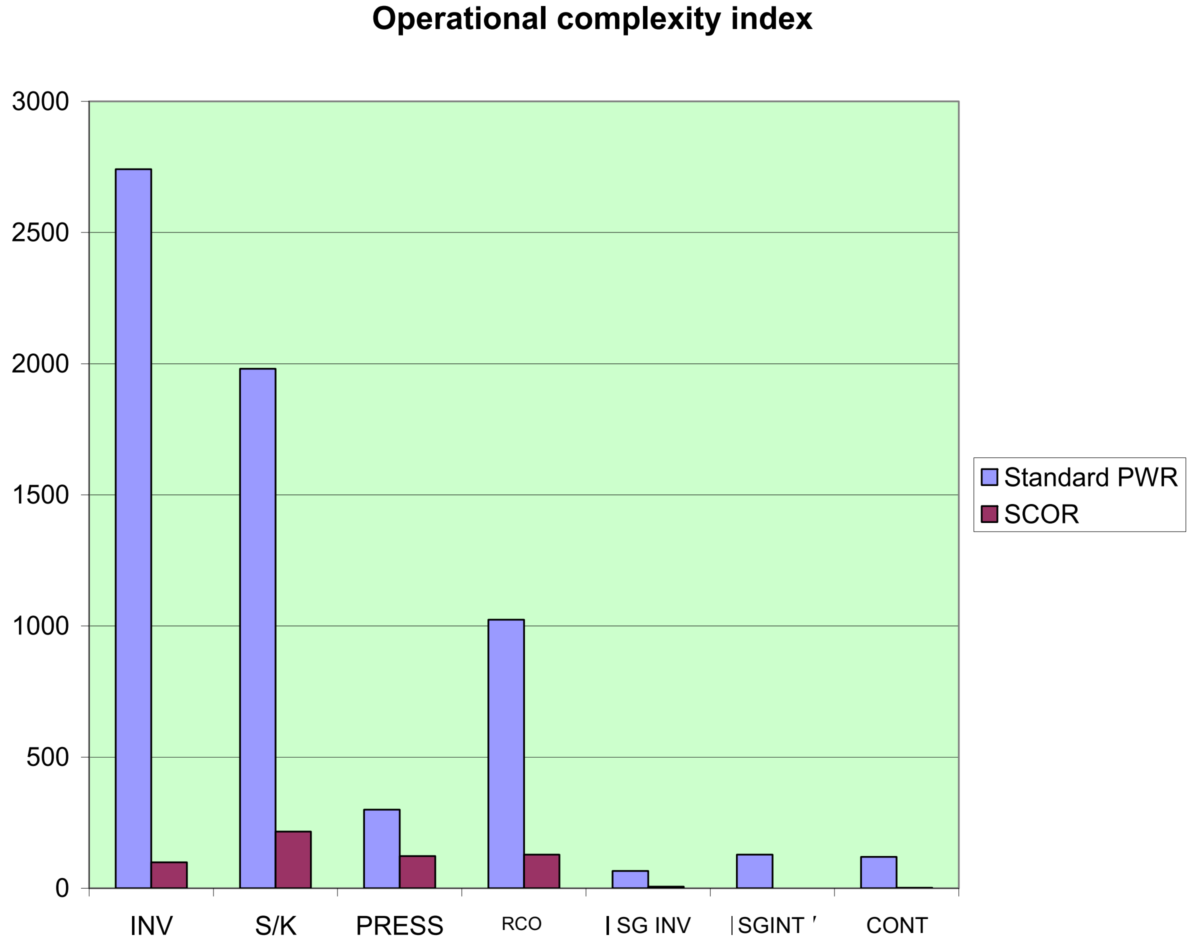


Quantification of complexity – Operational Complexity Index (OC)

Courtesy of CEA (France)

Safety

Example of comparative analysis using Operational Complexity Index



Operational complexity vs. safety functions for the integral design SCOR and a standard PWR; CEA (France) – IAEA-TECDOC-1485

Systems dedicated to: INV – coolant inventoty; SGIN – steam generator integrity; RCO – reactor cooling; S/K – Subcriticality, etc.

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**

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

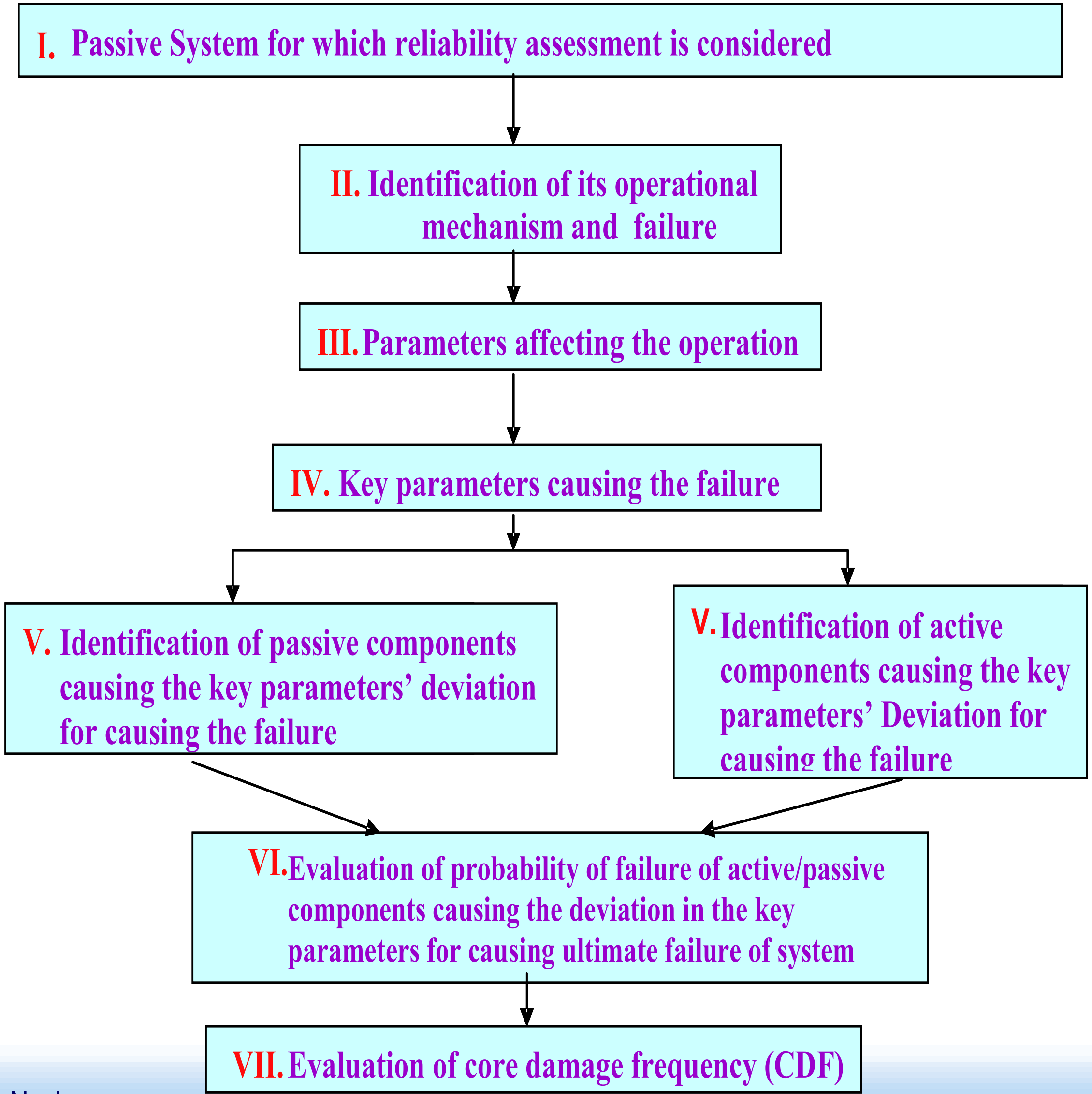
- **Lack of data on some phenomena, missing operating experience over the wide range of conditions, and the smaller driving forces make the reliability evaluation of passive system phenomena a challenging one.**

- **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.*).**

- **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.**

SAFETY

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



SAFETY

Methodologies for Reliability Assessment of Passive Safety Systems

French (CEA) L and Indian (BARC) R Approaches

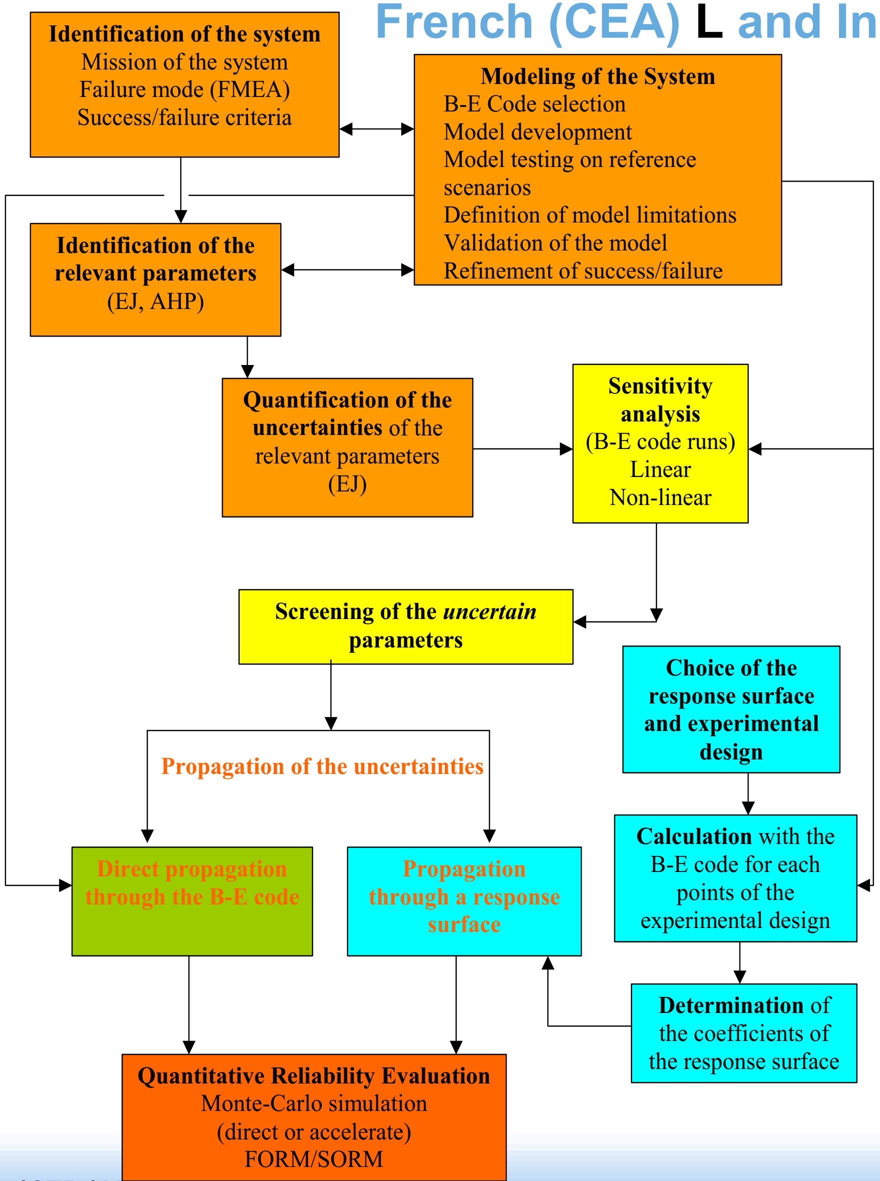


FIG. 13. Schematics of the RMPS methodology.

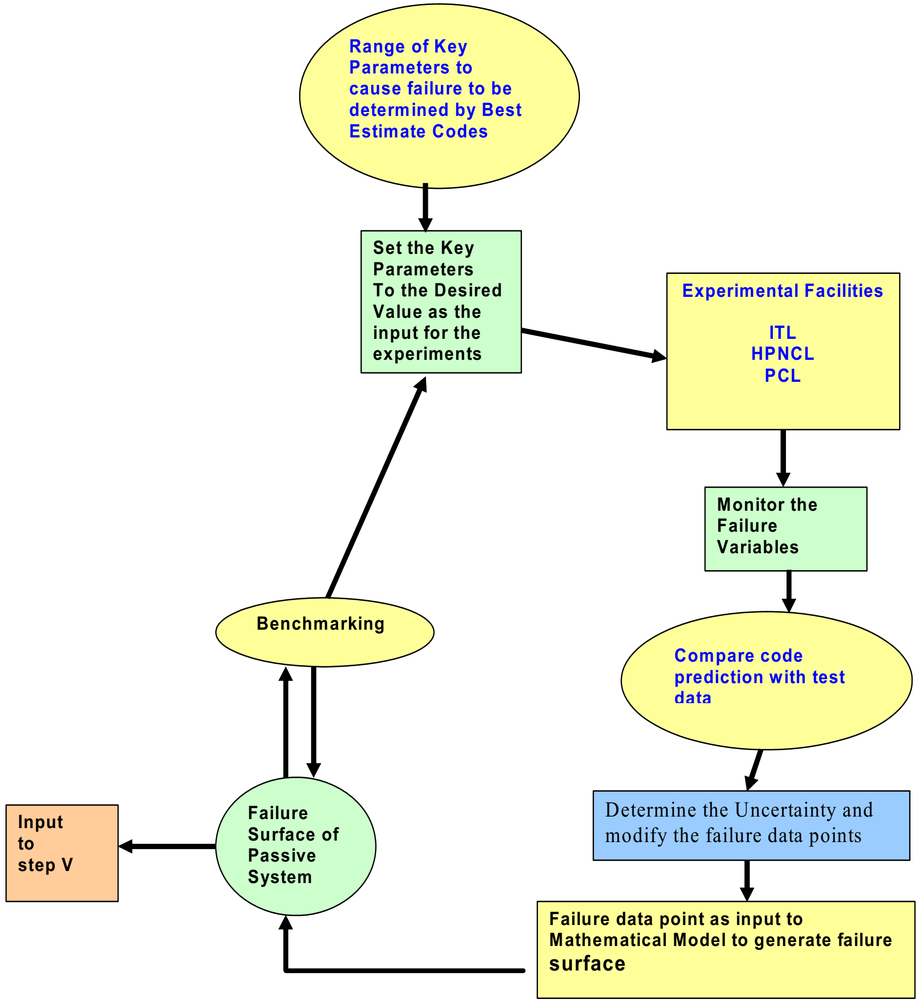


FIG. 15. APSRA methodology: flowchart of the programme for benchmarking of the failure surface based on experimental data.

SAFETY

Reliability Assessment of Passive Safety Systems

Alternative approaches

Example from ENEA (Italy)

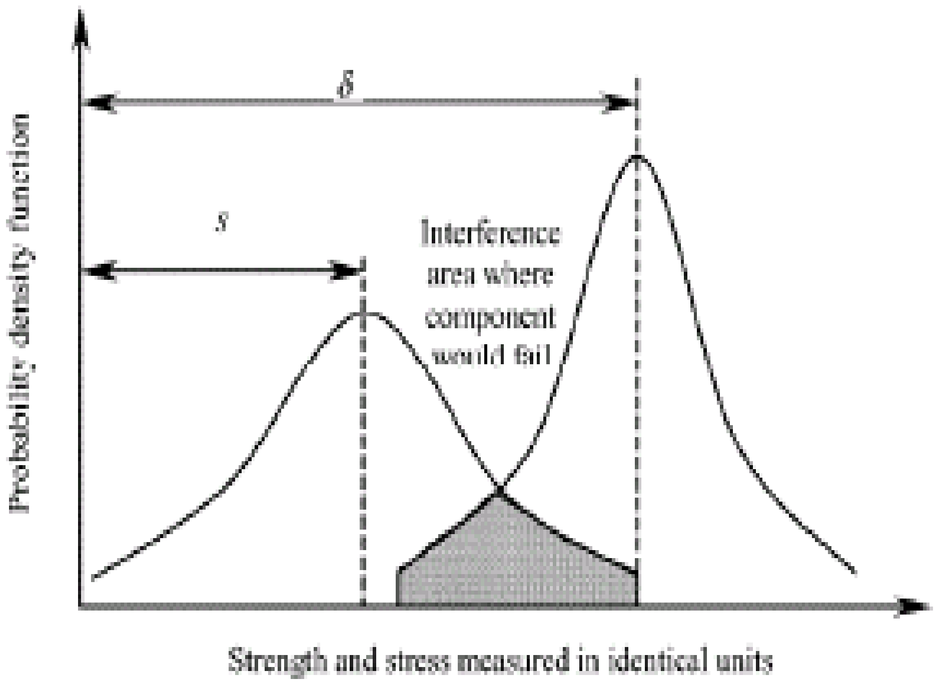


Fig. 1 Load (s) and strength (δ) interference diagram

IAEA Activities Ongoing

Nuclear Energy Series Report "Passive Safety Design Options for SMRs"
Due in 2008

10 representative SMR concepts reviewed against the requirements of the IAEA Safety Standards and Guides, with a focus on Defence in Depth Strategy

KLT-40S, IRIS, CAREM-25, SCOR, MARS, AHWR, GT-MHR, 4S-LMR, SSTAR & STAR-LM, CHTR

IAEA Activities Started in 2008-2009 (2)

1.1.5.4/11: Coordinated Research Project "Development of Methodologies for the Assessment of Passive Safety System Performance in Advanced Reactors"; P&B Codes 2008 1.1.5.4/11-leads, 1.1.5.1/16, 1.1.5.2/15, and J.3.2.3.3/04

First Research Coordination Meeting is due in 2009.

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.

THANK YOU!

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