Nuclear Power : Perceptions, Performance, Promises

V S Arunachalam

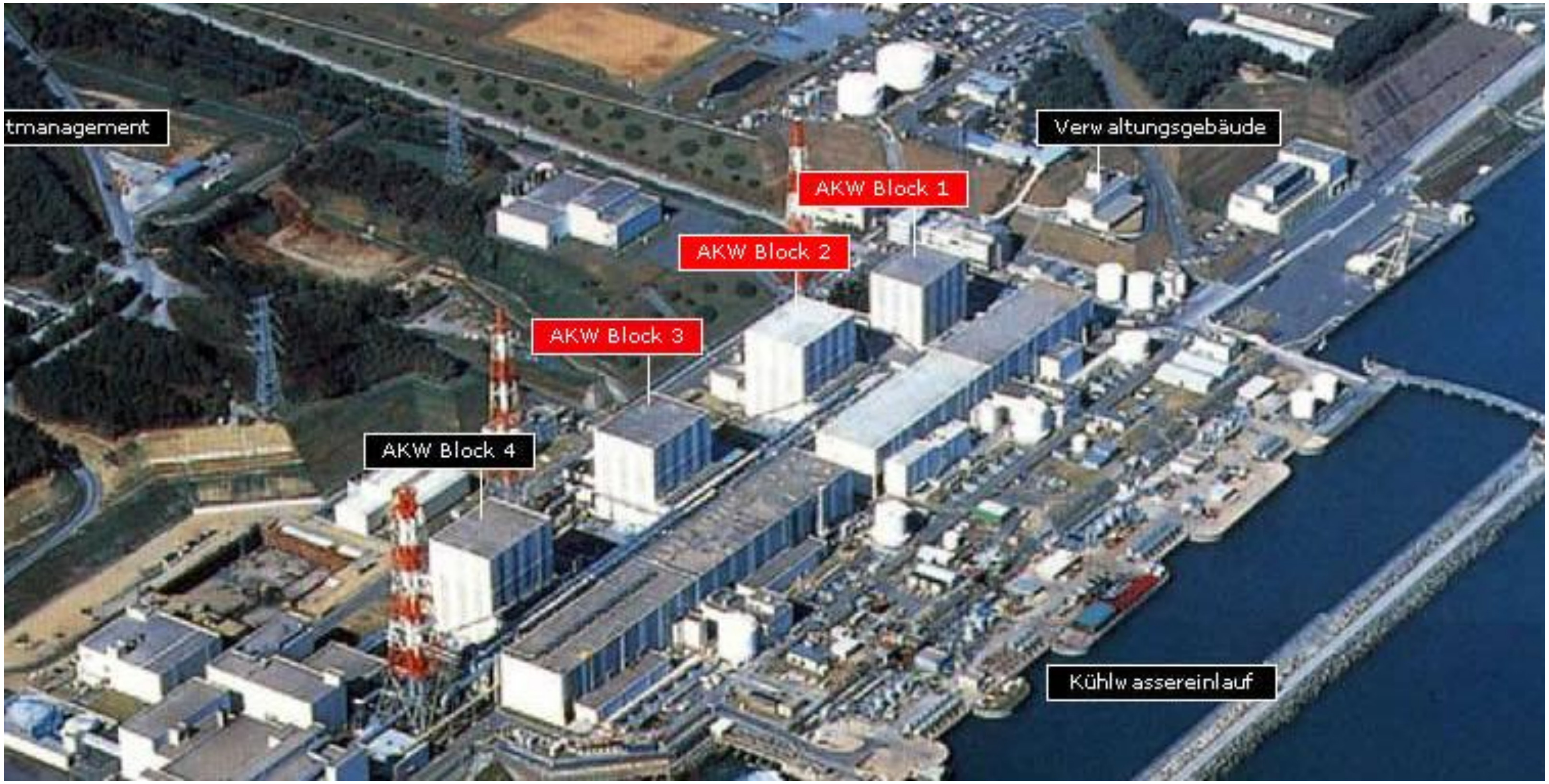
World Materials Summit, Washington DC, October 2011

PERCEPTIONS

Show Stoppers

- Radiation fears
- Safety and Security
- Proliferation Concerns
- Other energy resources not running out
- Options for containing CO_2 Emerging
- Economics

- **Fukushima Daiichi (Plant I)**
  - Unit I - GE Mark I BWR (439 MW), Operating since 1971
  - Unit II-IV - GE Mark I BWR (760 MW), Operating since 1974



Hydrogen Explosion : Fukushima

http://www.eutimes.net/2011/03/japan-tsumani-and-earthquake-america-on-nuclear-accident-radiation-alert/

Radiation exposures to people around Fukushima Reactors.

From measured levels of radioactive caesium deposited on the ground, exposures to about 360,000 persons now living in those areas have been estimated. (People within 20 km distance have all been evacuated)
About 335,000 of them would receive less than 40 mSv if they continue to live there for the next ten years. It could double if they are left undisturbed beyond that time period.
About 26,000 would require to be relocated to limit their exposures to the same level as the rest. About 6,000 of these would need to be relocated over the next six months to avoid higher exposures compared to the rest.

Deposits, External Doses Projected at 10 and 70 Years and affected Populations

<table>
<tr><th>Deposits of caesium
(137 + 134)
(Source MEXT)</th><th>> 300,000
Bq/m^2</th><th>> 600,000
Bq/m^2</th><th>> 1 million
Bq/m^2</th><th>> 3 millions
Bq/m^2</th><th>6 - 30 millions
Bq/m^2</th></tr>
<tr><td>External dose at 10 years
(70 mSv by MBq/m^2)</td><td>> 19 mSv</td><td>> 38 mSv</td><td>> 63 mSv</td><td>> 190 mSv</td><td>380 - 1,900 mSv</td></tr>
<tr><td>External lifetime dose
(70 years)
(160 mSv par MBq/m^2)</td><td>> 41 mSv</td><td>> 82 mSv</td><td>> 136 mSv</td><td>> 408 mSv</td><td>816 - 4,080 mSv</td></tr>
<tr><td rowspan="3">Affected population
(excluded the no-entry zone)</td><td rowspan="3">292,000</td><td colspan="4">69,400</td></tr>
<tr><td rowspan="2">43,000</td><td colspan="3">26,400</td></tr>
<tr><td>21,100</td><td>3,100</td><td>2,200</td></tr>
</table>

From,
ASSESSMENT ON THE 66TH DAY OF PROJECTED EXTERNAL DOSES FOR POPULATIONS LIVING IN THE NORTH-WEST FALLOUT ZONE OF THE FUKUSHIMA NUCLEAR ACCIDENT- OUTCOME OF POPULATION EVACUATION MEASURES -Report DRPH/2011-10
DIRECTORATE OF RADIOLOGICAL PROTECTION AND HUMAN HEALTH
Institut de Radioprotection et de Surete Nucleaire, France
NB - MEXT is Ministry of Education, Culture, Sports, Science and Technology of Japan.
MBq refers to radioactivity deposited on the ground (MegaBecquerels; 37 MBq is 1 milliCurie)

Perceptions : Safety and Security

Chernobyl Disaster

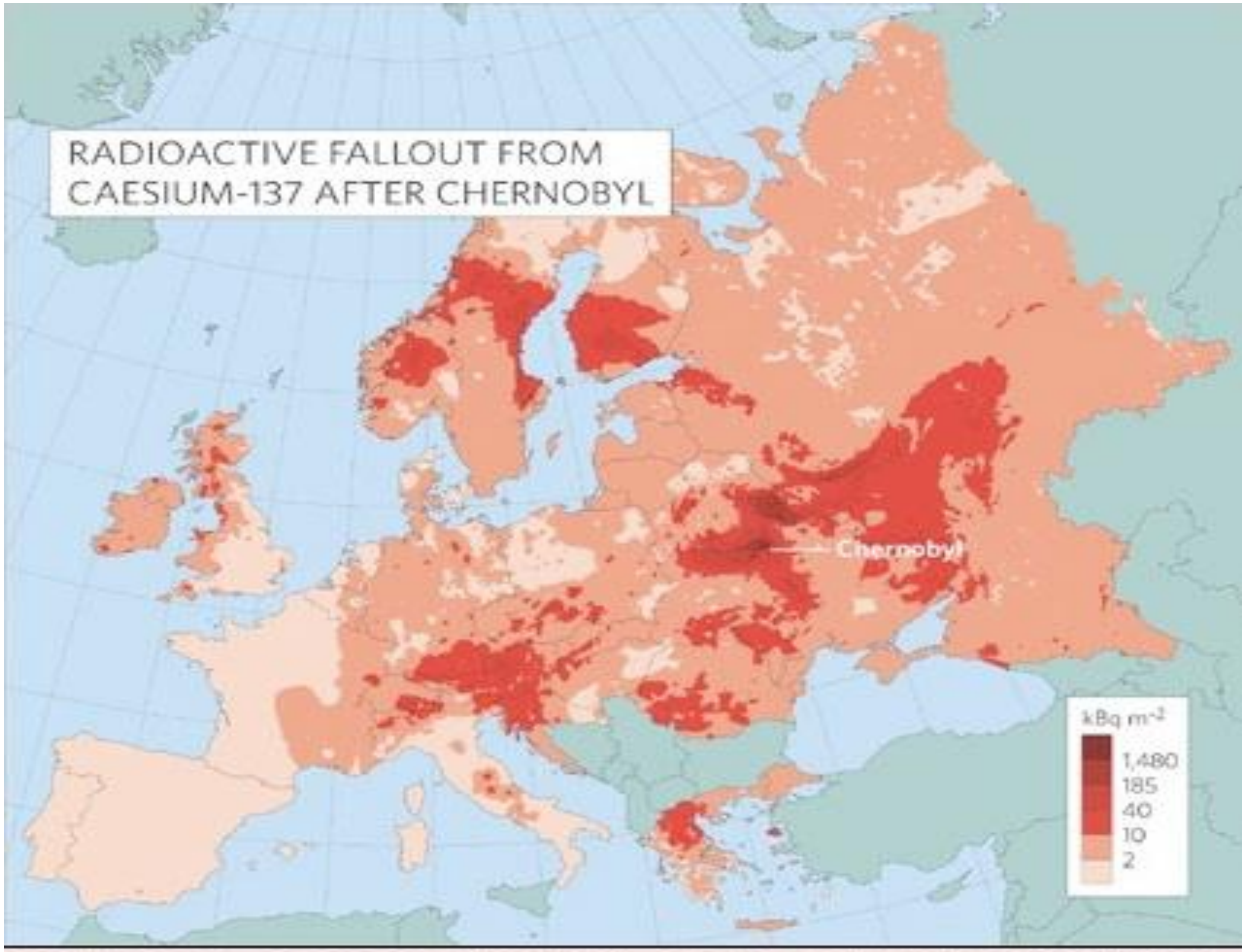
Two Aspects :

Technical : Reactivity control & cooling at all times (Including beyond Design basis)

Physical : Safety of fissile material (Guarding against terrorist threats)

http://schoolworkhelper.net/2011/05/chernobyl-disaster-history-events/

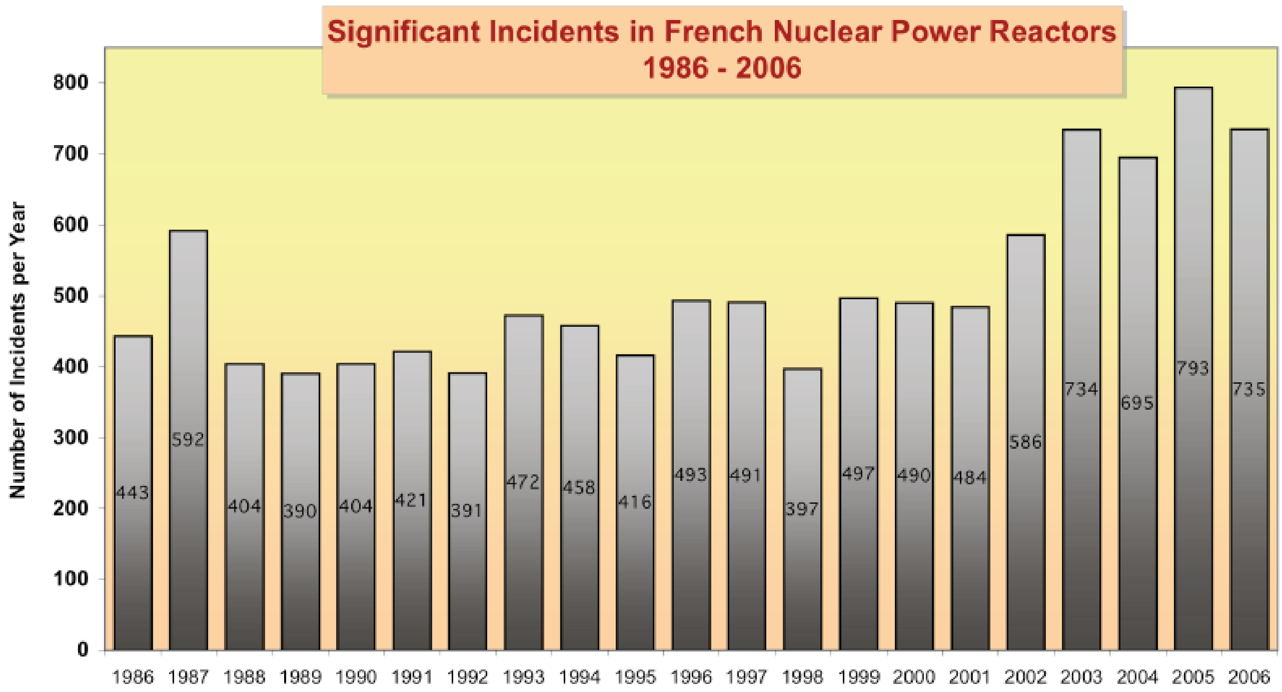
Perceptions : Radiation fear



J. SMITH & N. A. BERESFORD CHERNOBYL: CATASTROPHE AND CONSEQUENCES (PRAXIS, CHICHESTER, 2005)

http://homebrewedtheology.com/tag/japan-disaster

Total Number of Significant Incidents in French Nuclear Power Plants 1986-2006

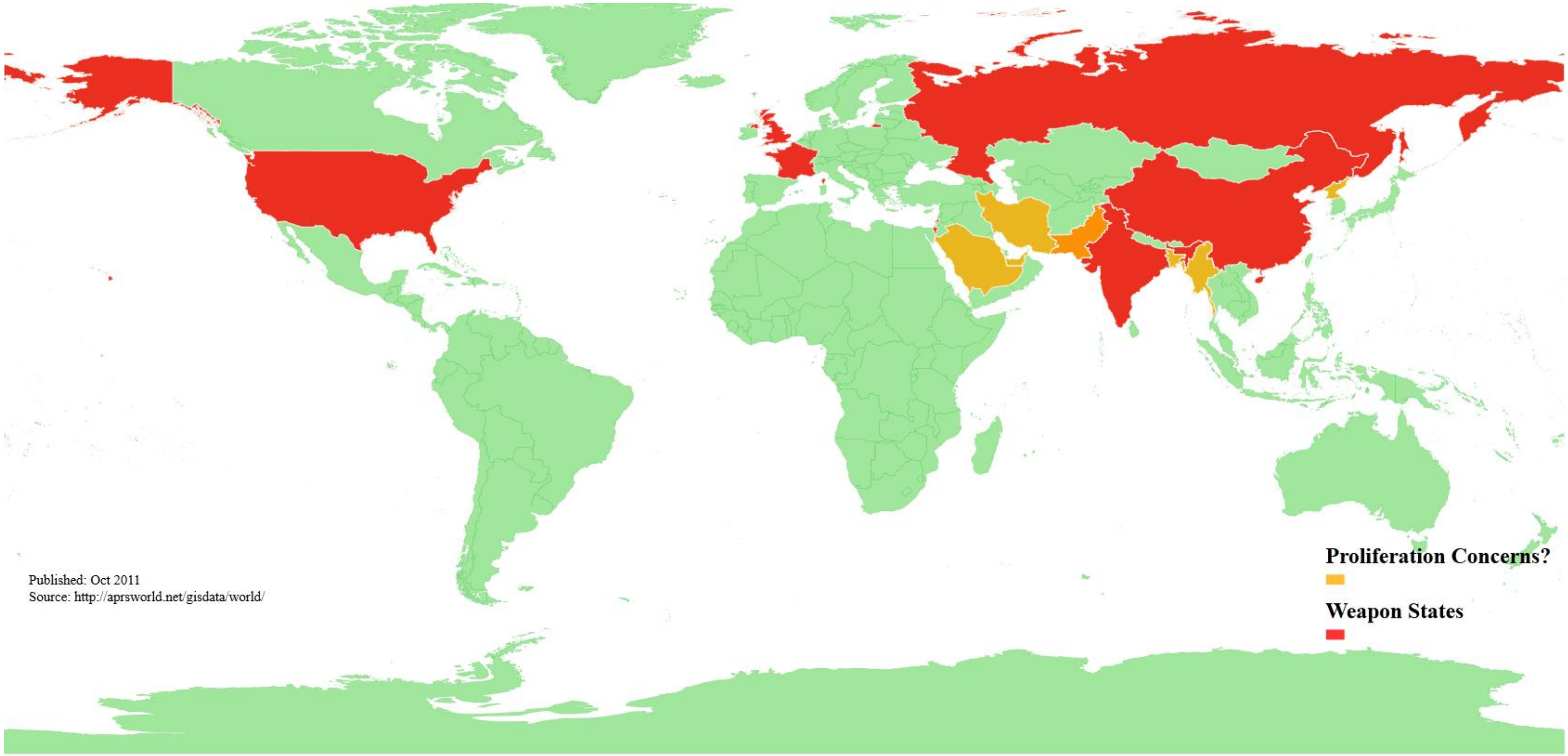


Source: IRSN 2007

Annually the classification of these events leads to the analysis of approximately:

- 200 outstanding events (244 in 2006);
- 100 events retained in the framework of national lessons learned feedback;
- 20 precursor events;
- 2 to 3 in depth analysis.

Perceptions: Proliferation

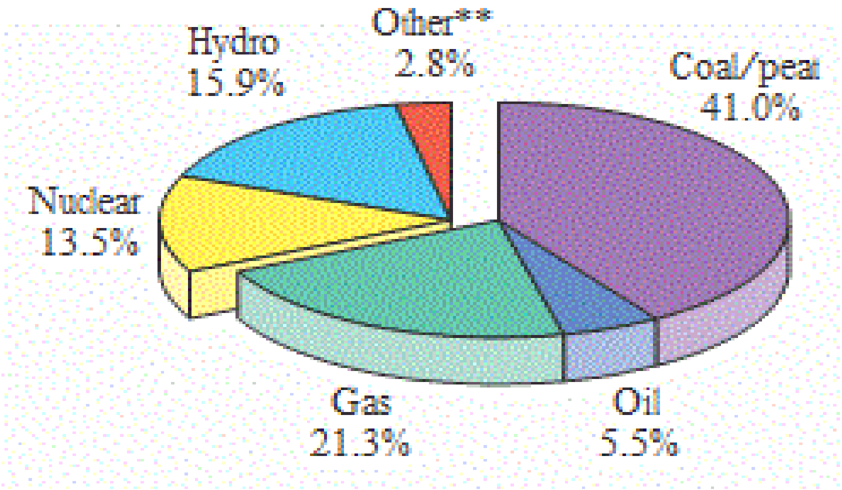


- NPT Signatories but poor record keeping
- IRAN
- Pakistan and North Korea
- Terrorist and the Bomb

Performance

- Currently Operational – 432 plants with net installed capacity of 366 GW
- Types of reactors operational : LWR, BWR & PHWR
- Planned additions – 65 plants with 65 GW
- Total electricity production till 2009 : 64,600 TWh
- Active FBR programs: India, China, Russia & Japan(?)
- Two major accidents according to International nuclear event scale (INES) - Fukushima & Chernobyl

Global Electricity Scenario



Total in 2008 : 20181 TWh

** Other : Solar,Geothermal,Wind,Waste

- **Nuclear energy contributes 13.5% of current global power**
- **If the share of nuclear energy is to remain the same in 2030 , we need~ 4100 TWh from nuclear . This means ~ 950 plants**
- **~ 150 of the currently operational plants will age by 2030**

Source : EIA, 2010

Life Cycle CO_2 Emissions : Comparison

Energy Source	Lifecycle CO_2 emissions (g/ kWh)
Coal	1000
Oil	800
Natural gas	400-500
Wind	7-124
Solar	13-730
Nuclear	2-60

V S Arunachalam and Fleischer, MRS Bulletin, 33, 2008, pp.264-276

2030 - WHAT IF?

No new reactors & 150 reactors age by 2030

- Only 232 reactors generating ~ 1467 Twh/year
- If nuclear had maintained same proportion of total electricity 4100 Twh/year
- If this gap is supplied by fossil fuel say coal, life cycle emissions are ~ 2633 MT of CO_2

World Energy Resource Base

Source	R/P RATIO	Energy potential
Coal	118	3769 billion TOE
Oil	46.2	189 billion TOE
Natural Gas	58.6	200 billion TOE
Oil Shale		22529 billion TOE
Solar		262.9 Ewh/year
Wind		17.5 Ewh/year
Uranium		53,663 Te
Breeder		2,000,000 TWy

John P Holdren and WNA Market Data

GENERATION 4 Program (i)

Gen 4 reactors promise improvements

- Fast Breeder Reactor
- Supercritical-Water-Cooled Reactor
- Very High Temperature Reactor
- Gas-Cooled Fast Reactor
- Lead-Cooled Fast Reactor
- Molten Salt Reactor

GENERATION 4 Program (ii)

The Gen 4 program aims at new reactor designs that offer more attractive

Safety and security

Passive and Inherent safety features
e.g., FBR, AHWR

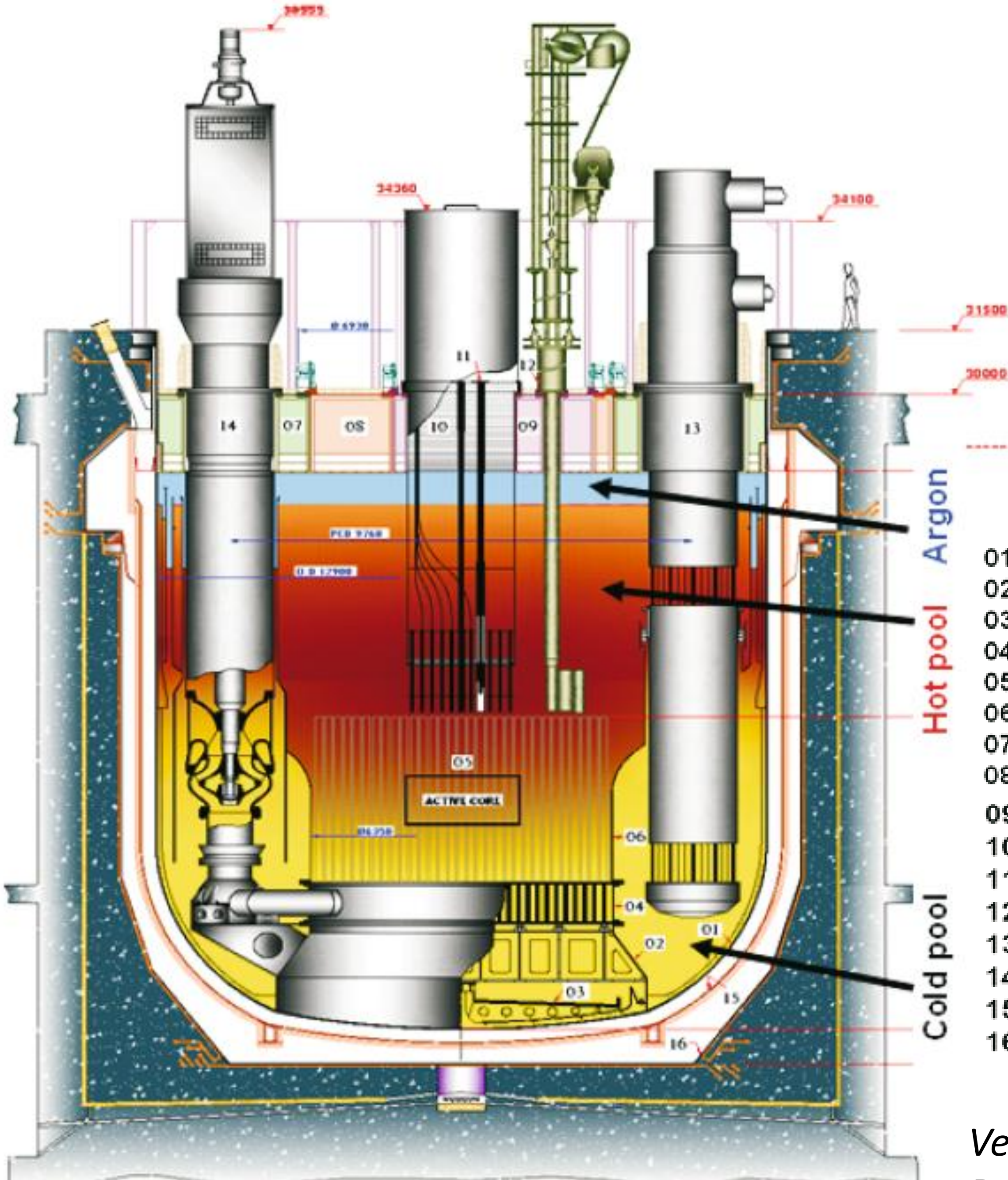
Efficiency

e.g., SCWR

Proliferation resistance

e.g., FBR, SCWR, AHWR etc through use of thorium in place of uranium and burning of Pu

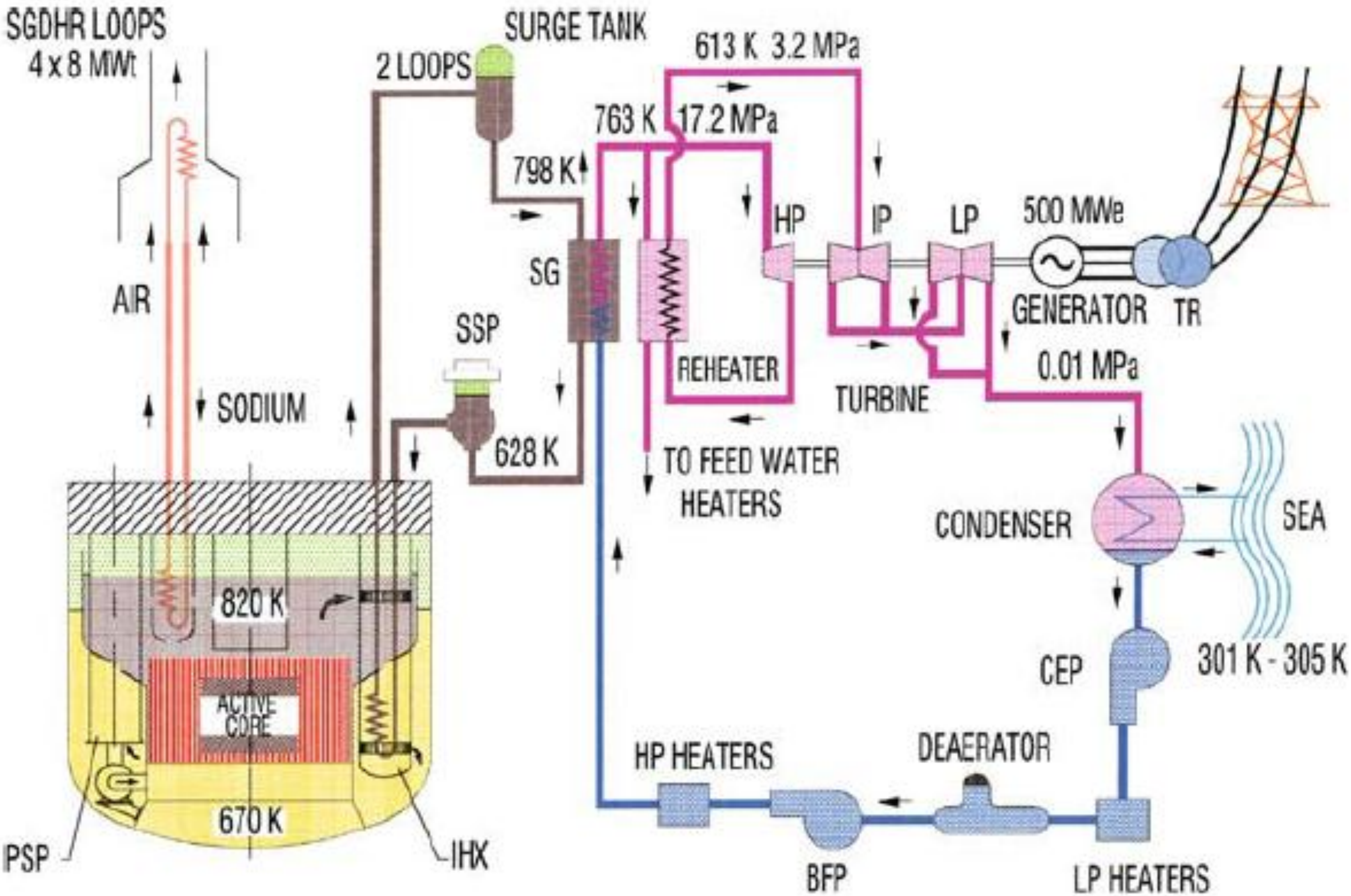
Prototype Fast Breeder Reactor, Kalpakkam, India



01. MAIN VESSEL
02. CORE SUPPORT STRUCURE
03. CORE CATCHER
04. GRID PLATE
05. CORE
06. INNER VESSEL
07. ROOF SLAB
08. LARGE ROTATABLE PLUG
09. SMALL ROTATABLE PLUG
10. CONTROL PLUG
11. CONTROL & SAFETY ROD MECHANISM
12. IN-VESSEL TRANSFER MACHINE
13. INTERMEDIATE HEAT EXCHANGER
14. PRIMARY SODIUM PUMP
15. SAFETY VESSEL
16. REACTOR VAULT

Velusamy et al, Sadhana Vol. 35, Part 2, April 2010, pp. 97–128.

FBR: The Thermal loop

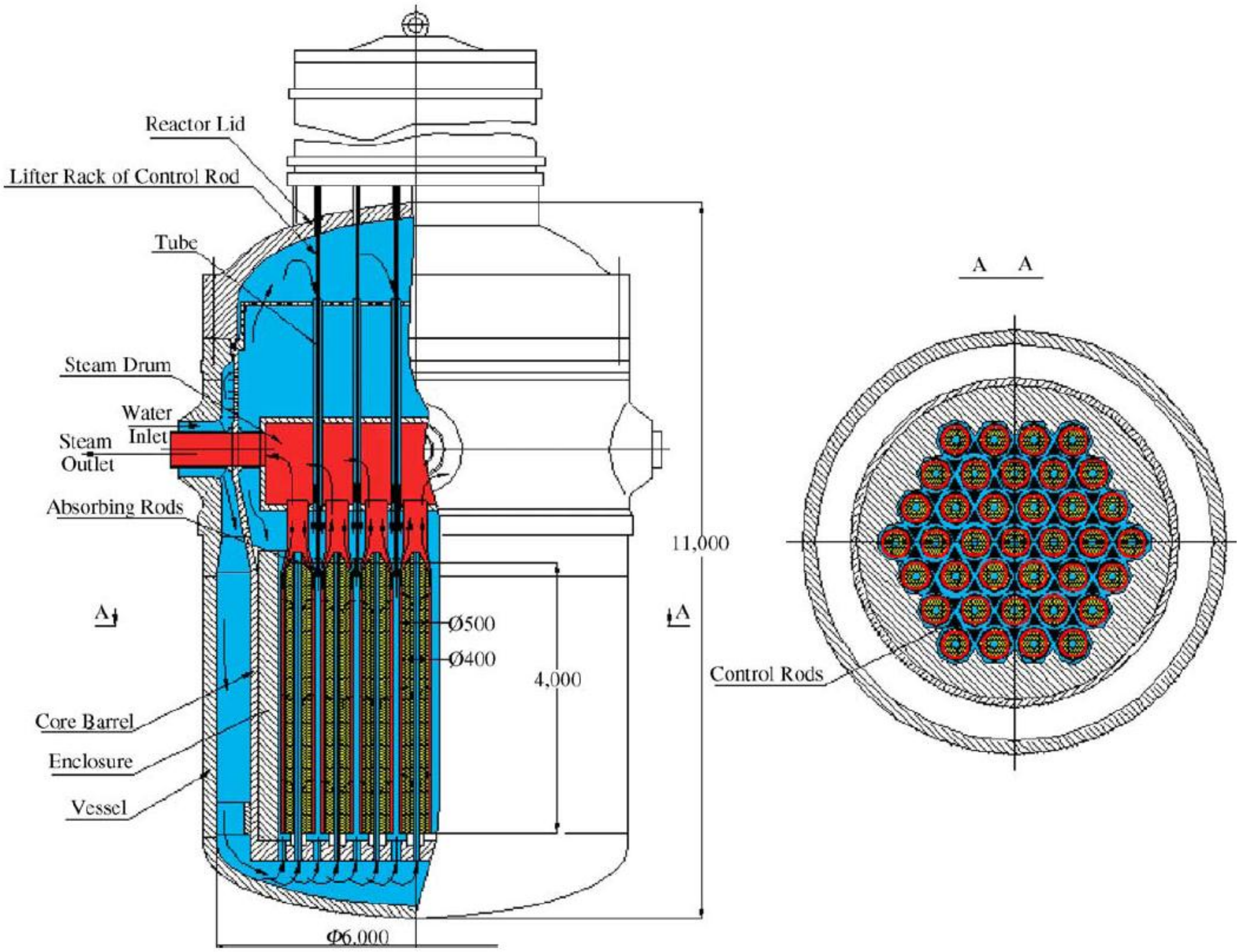


Velusamy et al, Sadhana Vol. 35, Part 2, April 2010, pp. 97–128.

PFBR, India (500 MWe) UNDER CONSTRUCTION

Power	1250 MWt
Fuel	MOX (~15 Te DU + ~2 Te Pu)
Pu enrichment	(21 %/ 28 %)
Coolant circuit	pool type
Peak heat rating	450 w/cm
Refuelling interval	180 full power days
Core fraction replaced	one third
Peak burnup	100 GWd/t
Thermal Efficiency	40%

Promises : Supercritical Reactor



Tsiklauri et al 2005, Nuclear Engineering and Design, volume235 pp.1651–1664

Typical SCWR Parameters

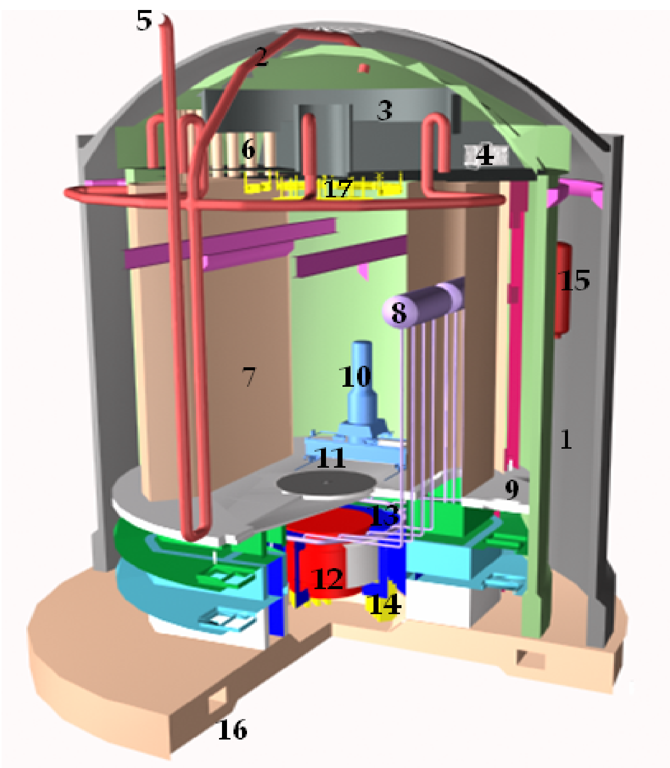
Power (MWe)	Up to 1500
Pressure (MPa)	25
Inlet Temp. (oC)	Up to 350
Outlet Temp. (oC)	Up to 625
Efficiency	Up to 50%
Burnup (thermal option)	Up to 60GWd/tHM
Burnup (fast option)	Up to 120GWd/tHM
Spectrum	Thermal or Fast
Fuel	UO2, MOX, thorium
Fuel Cycle	Once through or Open
Pressure Boundary	Pressure tubes or pressure vessel
Coolant	Light water
Moderator	Light water or ZrH_2 (PV) or heavy water (PT)

Adapted From "SCWR: OVERVIEW" by H. Khartabil, AECL, Canada

CSTEP

Promises : AHWR

ADVANCED HEAVY WATER REACTOR



1 Secondary Containment
2 Primary Containment
3 Gravity Driven Water Pool
4 Isolation Condenser
5 Passive Containment Isolation Duct
6 Vent Pipe
7 Tail Pipe Tower
8 Steam Drum
9 100 M Floor
10 Fuelling Machine
11 Deck Plate
12 Calandria with End Shield
13 Header
14 Pile Supports
15 Advanced Accumulator
16 Pre - Stressing Gallery
17 Passive Containment Cooler

- **BASIC DATA**

FUEL : U-233/THORIUM MOX + Pu-239/THORIUM MOX

COOLANT : BOILING LIGHT WATER

MODERATOR : HEAVY WATER

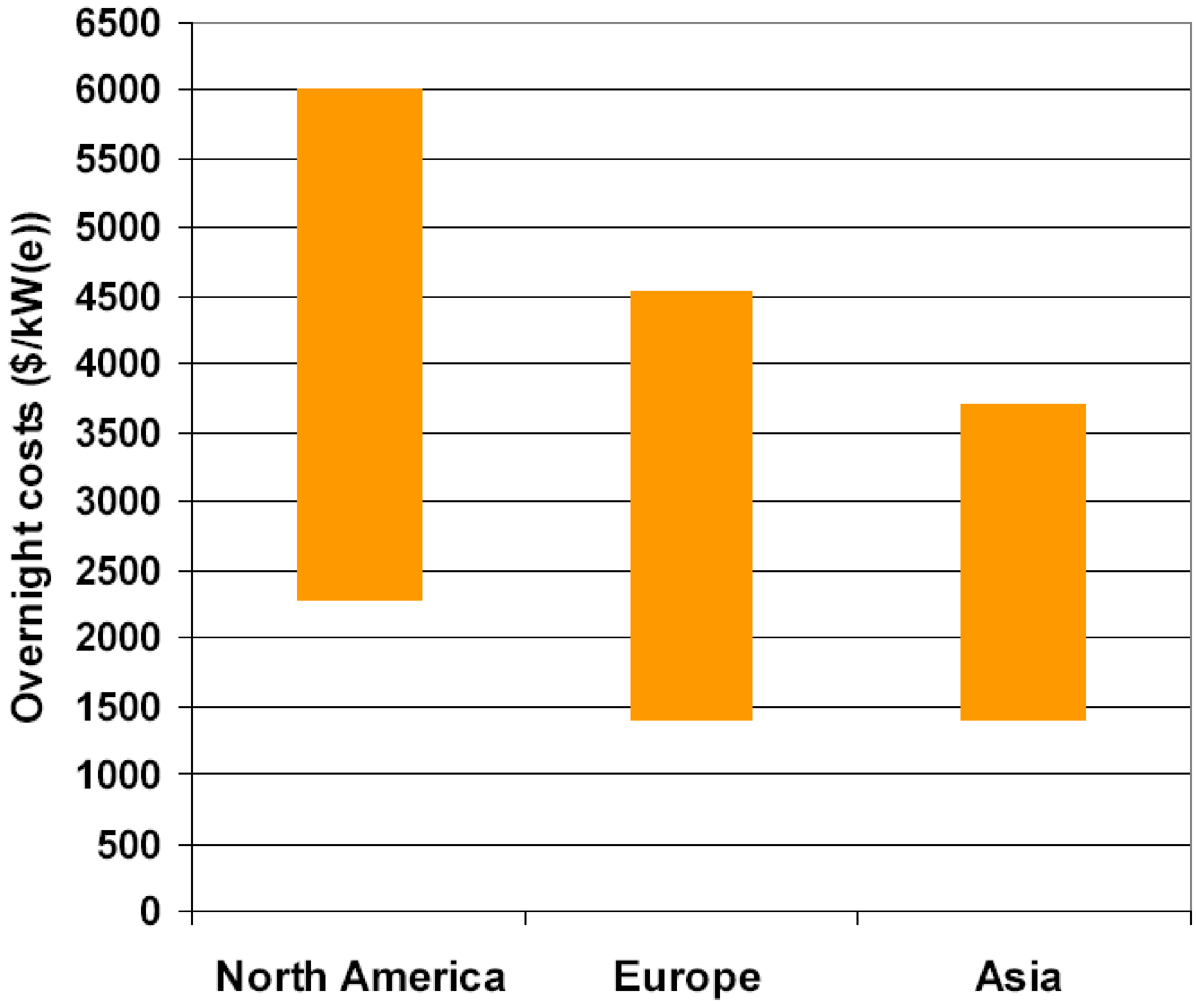
POWER : 300 MW(e)
920 MW(t)

- 65% power from Th
- Passive heat removal from core by natural circulation
- No pumps used
- Neg. void coefficient
- Double containment
- Use of LEU in place of Plutonium eases waste management

Promises in Materials

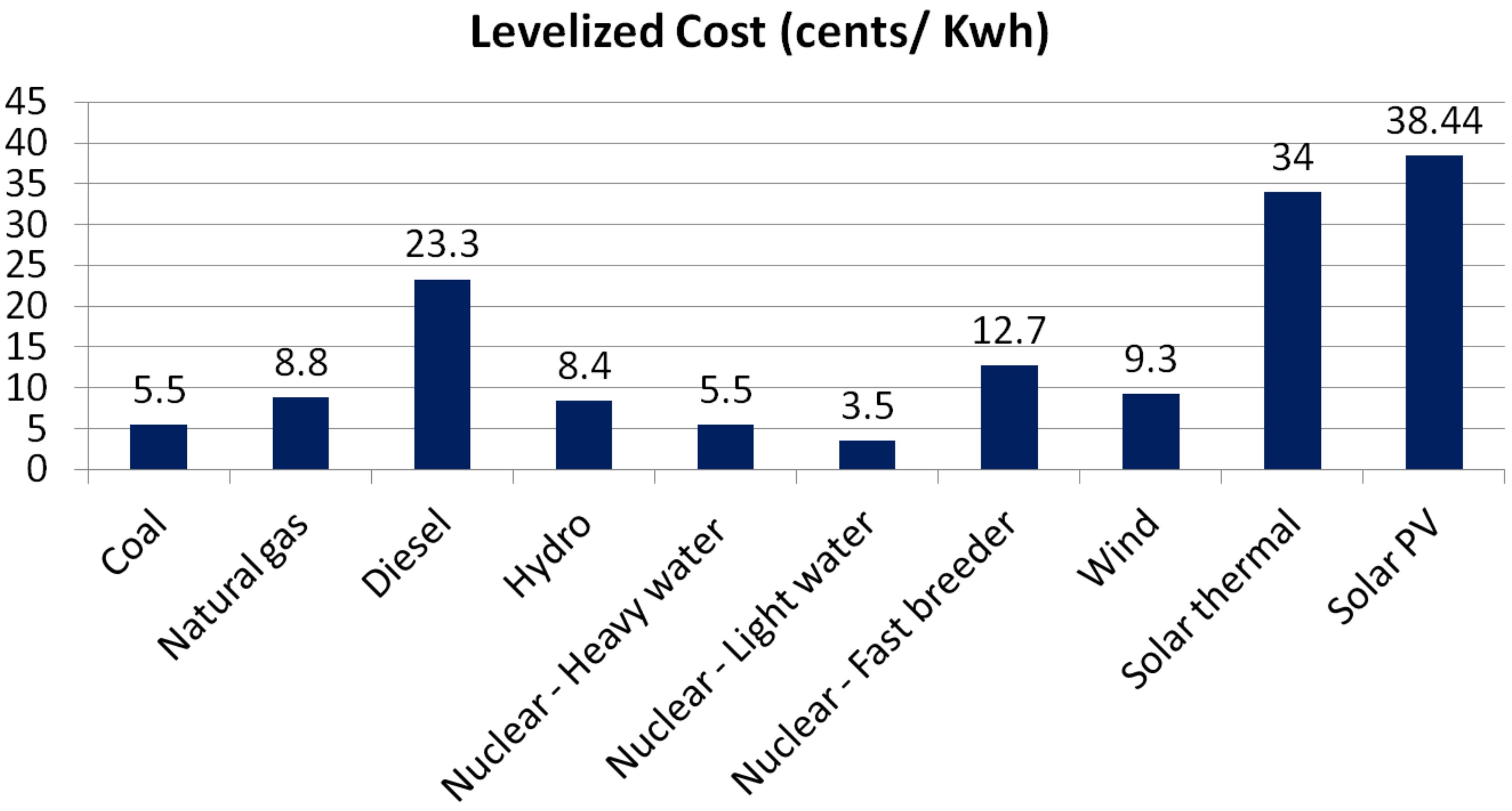
- Thorium : Higher burn-up and less Pu waste
- Zircaloy claddings are known to be responsible for hydrogen explosions. Ni-based alloy could avert this.
- Development of alloys resistant to corrosion and stress corrosion cracking: Development of strong ODS alloys.
- Sodium coolant can eliminate void problems
- SiC coating for fuels will avoid sharp temp gradient
- Graphite coated micro-fuel spheres to prevent fission product leakage.

Minimum and maximum estimates of overnight costs* for new nuclear power reactors, by region: 2007–2008. (* estimate predates financial crisis of 2008)



NUCLEAR POWER COST ESTIMATES, IAEA 2009

Economics – Levelized Cost Estimates



Source : prior to financial crisis of 2008 CSTEP, CERC & NPCIL

NUCLEAR POWER : SAFETY, SUSTAINABILITY & AFFORDABILITY

- **Safety**
  - No station blackout
  - No cooling failure
  - Managing accidents
  - Modeling, Simulation and AI systems
  - Training, Training, Training

- **Sustainability**
  - Improving efficiency : new reactor systems
  - Non-proliferation
  - Handling waste

- **Affordability**
  - New financing models
  - Scalability
  - Regional, National and global power grids
  - Hybrid grids ; saving energy resources
  - Self-stabilizing reactors that can control fission when temperature rises (Dounrey)

Learning to Live with Complex Systems