The Outlook for Nuclear Energy

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Provided as background information for the 23 July 2020 Seminar:
“Outlook for Nuclear Power in a Carbon Constrained World”
Outline

- Development of Nuclear Power prior to Fukushima
- Nuclear Power Post Fukushima: Status and Uncertain Outlook
- Challenges to a Robust Future Role of Nuclear Power:
  - Will SMR Offer Brighter Future for Nuclear Energy
- Nuclear Fusion: The ultimate solution?
History & Development of Nuclear Power

• Early optimism: “Too cheap to meter” (1953 USAEC)

• Soon, faced reality of a massive & complex industry

• It endured impact of a couple of major accidents

• Attempted Renaissance aborted each time
Development of Nuclear Power prior to Fukushima

• 1953: “too cheap to meter”, USAEC Chair
• Rising interest post 73
• Increasing const. delays, High inflation, and cost over-runs
• TMI 79
• Chernobyl 86
• Renewed interest post 2003:
  – Higher capacity factor; License extensions; Market in used reactor; money printing machines
• A Renaissance
Drivers of Revived Interest in Nuclear Power Prior to Fukushima (between 2003 & end of 2010)

- **Economics Competitiveness:**
  - Competed favorably with most other available base load power generation systems.

- **Low carbon base load power option**
  - Readily available to meet Climate Change challenge.

- **High level of Fuel Security for dispatchable Generation**
  - Fuel load for several years can be stored easily at little cost.

- **Good (relative) Safety Record, despite TMI and Chernobyl accidents**
  - Lingering questions/concerns remained of risks from future accidents at NPPs & NFC facilities (particularly the lack of verifiable & proven safe permanent waste disposal!!??)

- **Then Fukushima!!**

- TMI?
- $\ll 1 (0.7)$ calculated

Fatal cancers from Chernobyl in next 60 years (calculated) 7,500 in Belarus, Russia and Ukraine & 20,000 –30,000 worldwide (compared to 300 millions natural causes (@ 20% of total death) – This controversial / UNLIKELY – assumes LNT
The Fukushima Shock: What happened & why (11.03.2011)

- @ 14:46 **Earthquake** of Magnitude 9 (acceleration at site close to design); all reactors (1,2 &3) automatically shutdown!

- @15:45 **Tsunami** wave height at site: 14 M!!! ; (Design: 5.7 M, DG & Reactor at 10 -13 m. ➔ Historical record > 20 M!)

- **Flooded station** (D/G) ➔ Station Blackout (SBO)
  ➔ loss of coolant ➔ loss of decay heat removal

- **Core-melt** ➔ release of radioactivity & H from reactor vessel with steam being vented

- **H explosions** in 3 reactors (above 4% concentration)

- ➔ some **radioactive release** to atmosphere and sea ($^{131}$I and) $^{137}$Cs - ~ ½ of Chernobyl total release)

- **Stabilization** (Cold shutdown) took months !!!

- **Mitigation** on & off site: control & disposal of contaminated water, damaged SF, remediation of site, define exclusion zones, evacuation, rehabilitation, exposure control, health impacts & regaining confidence,

- **Full Story** so far: [The IAEA 2015 report](#)
Health impact of Fukushima: WHO, UNESCAR & IAEA
Assessment of risk to public from exposure to radiation from released radioactivity

WHO 2013 Report

- For general population inside & outside Japan, predicted risks are low & no observable increases in cancer rates above baseline are anticipated.

- “however, estimated risk for specific cancers in certain subsets of the population in Fukushima Prefecture has increased;

- it calls for long term continued monitoring and health screening for those people

UNESCAR 2014 Report & 2016 WP

- “No discernable increases in radiation related health effects are expected among members of public or their descendent”

- “The most important health effect is on social and well being related to the impact of the earthquake, tsunami & fear related to perceived risk of radiation”

The IAEA Encyclopedic report (2015), & updates

2018 Update:

- There were no acute radiation injuries or deaths among the workers or the public due to exposure to radiation resulting from FDNPS accident; Considering the level of estimated doses, the lifetime radiation-induced cancer risks other than thyroid are small and much smaller than the lifetime baseline cancer risks.

- Regarding the risk of thyroid cancer in exposed infants and children, the level of risk is uncertain since it is difficult to verify thyroid dose estimates by direct measurements of radiation exposure.

Lesson Learned

like Chernobyl, Profoundly Man made

• "In 2006 Japan revised standards for seismic resistance. … TEPCO needed to implement reinforcement. …could not exclude …Earthquake damaged critical reactor components."

• “NISA and TEPCO were aware of the need to improve safety before 2011

• “The accident was a profoundly man made disaster that could and should have been foreseen and prevented”

• “Its fundamental causes are to be found in the ingrained conventions of Japanese Culture”

Response varied

from political, to prudently cautious (Stress Tests), wait & see

• Initial impact of responses was mixed; But Renaissance stalled & combined with other factors, Nuclear Power is no longer a viable option in most OECD

• Decisions by few OECD countries has a powerful multiplier effect; impact will last for at least another decade.

• Germany’s Energywende: succeeded in increasing installed renewable capacity: from 11.4 → 112 GW (2002-2019)

• but at what cost? enormous overcapacity: 215 GW (Max. Consumption ~ 83 GW)
Uncertain growth outlook for Nuclear Power: Revival, then post Fukushima Brown-out

The role of nuclear energy, in the world’s energy transition?

Is it still indispensable as part of response to climate change?

If as Paris Agreement aims to keep rise in T below 1.5,

Then most likely: Yes

Is it likely to play an important role by 2050?

Not clear! but likely-to-may-be,

but must overcome major obstacles/challenges
Nuclear Power Today
Construction starts 1950 to 2019

As per 17 September 2019
Source: H.H. Holger, Adapted from IAEA - PRIS
Incremental nuclear power capacity additions (GWe) and nuclear electricity generation (TWh)

As per 17 September 2019
Source: H.H. Holger, Adapted from IAEA - PRIS
Construction starts & grid connections

As per 17 September 2019
Source: H.H. Holger, Adapted from IAEA - PRIS
Development of regional nuclear generating capacities

North America

Western Europe

Eastern Europe & CIS

Asia

As per 17 September 2019
Source: H.H. Holger, Adapted from IAEA - PRIS
Country specific nuclear shares in electricity generation, 2018

Source: IAEA - PRIS
Historical development of the global electricity generating mix and the share of nuclear power

1960+, Growth, 1979+ first brown-out, 2002+ revival, 2011+ another brownout, current fading in OECD) with new built mainly in China, Asia & developing countries
Status global nuclear power

Units in Operation: 450 399.7 GWe

- North America - 28.4%
- Europe - 30.4%
- OECD-Pac - 14.9%
- CIS - 10.0%
- Non-OECD Asia - 14.2%
- Latin America - 0.9%
- Middle East - 0.2%
- Africa - 0.5%

Units under construction: 52 52.7 GWe

- North America - 4.2%
- Europe - 13.0%
- OECD-Pac - 15.2%
- CIS - 17.9%
- Non-OECD Asia - 37.8%
- Middle East - 10.2%
- Latin America - 2.6%

As per 17 September 2019
Source: H.H. Holger, Adapted from IAEA - PRIS
Number of Power Reactors by Country and Status

Source: IAEA – PRIS, 2019
Industry Trends over last 10 years -

- Trends of First Connection
- Trends of Construction Starts
- Trends of Permeant Shutdowns

NOT A ROBUST INDUSTRY
Newcomers to nuclear power

Sources: H.H. Holger, adopted from IEA, IAEA, WNA, 2018
Reactor newbuild is likely to proceed to construction and/or commissioning by 2030.

The reactor newbuild faces major obstacles moving into construction and/or commissioning by 2030.

The obstacles to the reactor newbuild moving into construction and/or commissioning are massive, and are unlikely to be overcome by 2030.
Outlook for Nuclear Power (post Fukushima brown-out) covering periods 2030 through 2050

Includes changes of IAEA’s High & Low Projections (2011-2019)
Global nuclear power projections (IEA, IAEA, WNA

- Projected installed capacity

Age structure of the global fleet of the nuclear power plants
298 NPPs or 65% of the global fleet is 30 years or older

Sources: IEA, IAEA, WNA
IAEA – 2019 global nuclear capacity outlook
HIGH projection

Capacity projected in 2019 for 2050: 715 GW versus 1415 GW in 2010 projection

Year of projection:
- 2010
- 2011
- 2012
- 2013
- 2014
- 2015
- 2016
- 2017
- 2018
- 2019

Source: H.H. Holger Adapted from IAEA RDS-1, 2005-2019
LOW capacity projected in 2019 for 2050: 371 GW versus 520 GW in 2010 projection

Source: H.H. Holger Adapted from IAEA RDS-1, 2005-2019
Electrical generating capacity, by region, GWe

Source: IAEA RDS-1, 2019
What lies behind the huge differences between low and high projections?

Increasing challenges facing newly built NPPs, from:

- **Economic competitiveness of NP is being challenged from:**
  - alternative power technologies, mainly from Renewable with rapidly falling prices, helped by favorable environment of incentives/subsidy policies, & low Gas & Coal prices, specially in OECD
  - excessive cost overruns due to regulation, GIII+ FOAK construction delays
  - Almost impossible for private business to consider new NPP projects without strong Government support, which is non existent in almost all OECD (few exceptions like UK)

- **Three S-Challenges/concerns remain strong head wind against expansion of Nuclear Power (in particular for new - countries):**
  - Safety: to minimize the risk of release of radioactivity from operations, accidents of NFC
  - Security; to protect and secure radioactive material and NFC facilities
  - Safeguards, (Non-proliferation): from diverting technology and material to military purpose

- **The 3-S challenges are interconnected & impact economic competitiveness;**
  Often Safety and Security are discussed and used interchangeably
Safety of current generation of NPP

- How likely is a large core-damage accident?
  - Core-damage frequency (CDF): a few $\times 10^{-5}$ / year
  - Probability of a large release: a few percent of CDF $\approx 10^{-6}$ / year

- What limits the core-damage frequency to a few $\times 10^{-5}$/year?

- Can we do better? How?

What could cause a given NPP to fail to achieve these safety levels?

Weak Safety Culture

- 1979: Three Mile Island (US)
  - Poor operator training
  - Insufficient sharing of information and learning from experience

- 1986: Chernobyl (USSR)
  - Top-down management created an atmosphere where a questioning attitude brought punishment
  - A weak regulatory agency – analysis not required before performing an off-normal experiment

- 2011: Fukushima (Japan)
  - Inability of safety concerns to be acted upon at higher levels within the operating company
  - Government interference with nuclear operations
  - A weak regulatory agency deferred to the operating company

Source: Bob Budnitz, Erica, Sicily, August 20, 2016
The Drivers of Nuclear Power Safety

- Three MAIN drivers for a Nuclear Safety Centre
  1. Safety culture at all levels and for all stakeholders (no exemptions)
  2. An international nuclear safety regime which needs further strengthening (international regulator): Examples from other fields:
     - Civil Aviation: the ICAO Template
     - Climate Change Template (from UNFCCC to Paris Climate Agreement)

  1. Better appreciation of, and response to, the perception of risks among the public & decision makers

- These drivers - if not strengthened & improved, will constrain prospects of NP
  - Nuclear safety concerns, & cost, continue to impede political & public acceptance of NP
  - Risks from potentially catastrophic accidents cannot be dealt with probabilistically in isolation nor equated to natural catastrophic events with similar risk magnitude
  - Comparative risk/benefits assessments of different generating options covering all externalities

• Technology innovation - necessary but insufficient
• Perceptions matter (cannot be changed by stating technical facts or education
  - Including perceptions about HLW and spent fuel management
Future expansion into “newcomer” countries: Concerns & Prerequisites

• **Safety culture is the major concern**!
  (... and this includes security and non-proliferation concerns too!)

• **Prerequisites:** For nuclear power to be deployed successfully in countries without a current commercial nuclear program, several cultural attributes must be present.:
  – A political culture that can make a long-term commitment,
  – provide for an independent regulatory agency with both authority & resources
  – Equally crucial are a set of social-culture issues including:
    • freedom from corruption, holding safety as paramount, a commitment to transparency in management practices and communication, and a strong continuity of institutions.

• **Public Acceptance**

• Without these, a nuclear-power program is less likely to achieve an adequate safety record

• Should monitor NP development in new comer countries over 1-2 decades, UAE, Turkey, ....

Credit: Bob Budnitz, Erica, Sicily, August 20, 2016
Long Term Disposal of SF & HLW:

Nuclear power is the only large-scale energy-producing technology that is required to take full responsibility for all its waste and fully costs this into the product.

- Most nuclear utilities are required by governments to put aside a levy (e.g. 0.1 cents per kilowatt hour in the USA, 0.14 ¢/kWh in France) to provide for the management and disposal of their waste.
- The current & future size of the problem of HLW & SF
- Interim & Final solutions
- Disposal for x000 years in underground repositories, retrievable and terminal
- Extensive RDD and technical solutions are feasible but NIMBY!
- Finland, Sweden & France most advanced with construction license submitted (granted in 2015 in FIN)
OECD countries: Nuclear power continues to face problems on:

- **Economic grounds**
  - High upfront investments in mostly liberalized markets
  - Poor track record regarding on time and on budget construction completion
  - Massive reduction in cost of Re and continued supporting policy incentives
  - Costs of system integration of intermittent renewables externalized
  - Cheap natural gas (LNG) & shale gas in North America
  - No compensation for nuclear 24/7 capacity availability
  - No recognition of nuclear climate and other environmental benefits
  - Low growth or stagnating electricity demand

- **Rising public opposition & politics in the aftermath of FDNP accident,**
  - remaining concerns about safety of NP & lack of demonstrable progress on HLW Disposal acceptable solutions ==> affecting prospects of NP
  - ROK is latest country to announce a nuclear cap/phase-out following Germany, Switzerland, etc.
  - Other countries (e.g., France, Sweden) cap directly or indirectly market share of nuclear power
  - Phase-out politics frustrate NPP staff and potentially could affect nuclear operating safety

- **Knowledge depreciation**
  - Only UK, Poland, Chec, France, Finland, few others remain viable for now
Recent developments II (WNI, WNA, IAEA, ..

• Non-OECD Countries
  – Prospects remain relatively bright in Asia and newcomer countries
    • In addition to China, India, Pakistan, Russian Federation, several Latin American, African and Middle Eastern Countries (e.g. UAE, KSA, Iran, Egypt, Turkey)
  – Nonetheless, public apprehension and signs of organized opposition is also becoming visible and rising in developing economies (within ongoing programs and new comers) – Future of NP dependent on China & India, and Russia

• Waste: World 1st permanent HLW Waste repository received construction permit! (FIN), Good step but Jury will take a long time, as we need more examples of such technology solutions

Would Climate change challenge bring renewed interest in Nuclear Power, in particular small modular reactors (SMRs) – the new lease on life for nuclear power! For now “All Renewable” overshadowing potential roles of Nuclear & Decarbonized O&G
Will SMRs save the day?

Drivers & Expected Advantages
Driving Forces for SMRs

Scalability of Power

Enhanced Safety

Modularity, Constructability

Flexibility of Utilization

Images courtesy of US-DOE, NuScale, KAERI, CNEA, mPower & CNNC
Key expected advantages

**Economic**
- Lower Upfront capital cost
- Economy of serial production

**Modularization**
- Multi-module
- Modular Construction

**Flexible Application**
- Remote regions
- Small grids

**Smaller footprint**
- Reduced Emergency planning zone

**Replacement for aging fossil-fired plants**

**Potential Hybrid Energy System**

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**Better Affordability**

**Shorter construction time**

**Wider range of Users**

**Site flexibility**

**Reduced CO₂ production**

**Integration with Renewables**
About 40 SMR design teams world-wide
SMRs Under Construction Now

• About 40 SMR design teams world-wide working on:
  – Evolutionary
  – Revolutionary

• Under Construction Now
  – Argentina:
    • 27 MWe integral PWR
  – China
    • 105 MWe pebble bed high temperature gas reactor
  – Russia
    • 70 MWe integral PWR (ship)
    • 50 MWe integral PWR (icebreaker)

• Design Types for immediate & Near Term Deployment
SMRs Estimated Timeline of Deployment

Immediate Deployable
- CAREM
  - Argentina
- HTR-PM
  - China
- KLT-40S
  - OKBM Afrikantov, Russia
- HTR-PM
  - INET, China

Near-term Deployable
- ACP100
  - China
- SMART
  - Republic of Korea
- NuScale
  - USA

Mid to Longer-term Deployable
- UNITHERM
  - Russian Federation
- HTMR100
  - South Africa
- SMR160
  - United States of America

Under Construction
- CAREM-25
  - CNEA, Argentina
- KLT-40S
  - OKBM Afrikantov, Russia
- HTR-PM
  - INET, China

Certified or at Advanced Design Stage
- SMART
  - KORLI, Republic of Korea
- RITM-200
  - OKBM, Russia
- PRISM
  - GE-Hitachi, USA
- PBMR-400
  - PBMR, South Africa
- BREST300-OD
  - PNIIET, Russia
- 4S
  - Toshiba, Japan
- ACP100
  - CNNC, China
- NuScale
  - NuScale Power, USA
- mPower
  - BE&W, USA
- GTHTR300
  - JAEA, Japan
- SVBR-100
  - AKME Engineering, Russia
- ABV-6M
  - OKBM, Russia

Conceptual Design for Future Deployment
- AHWR300
  - BHEL, India
- Flexblue
  - DCNS, France
- IRIS
  - IRIS International Consortium
- DMS
  - Hitachi-GE, Japan
- IMR
  - MHI, Japan
- VVER-300
  - OKBM Gidropress, Russia
- Westinghouse SMR
  - Westinghouse, USA
- SMR160
  - Holtec, USA
- VK-300
  - NIKIET, Russia
- Th-100
  - STL, South Africa
- SC-HTGR
  - AREVA, France
- G4M
  - Genshi Energy, USA

Timeline:
- 2005
- 2010
- 2015
- 2020
- 2025
- 2030
- 2040
- 2050+

MR5-NEP-NEP-709-Feb2016
# Power Range of SMRs

<table>
<thead>
<tr>
<th>Power Range MW(e)</th>
<th>Reactor Designs</th>
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<tr>
<td>&gt; 301</td>
<td>IMR, AHWR 300, VVER 300, GTHTR300, IRIS, DMS, GT-MHR, EM², BREST OD 300, SC-H1GR</td>
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<tr>
<td>251-300</td>
<td>Westinghouse SMR, FUSI, MHTR-1, ThorCon, LFTR</td>
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<td>201-250</td>
<td>mPower, SMR-160, PDMR-400, IMSR, Flexblue</td>
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<td>151-200</td>
<td>CAP150, HTTR-PM, MSTW, Mk1 PB-FHR, SmAHTHR</td>
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<tr>
<td>101-150</td>
<td>ACP100, SMART, MIHTR-100, SVBR100, ACPR50S</td>
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<tr>
<td>51-100</td>
<td>CAREM25, NuScale, KLT-40S, H1MR-100, G4M</td>
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<td>0-50</td>
<td>Reactor Designs</td>
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Concluding Remarks

- **Nuclear Power continues to face challenges (3S);** very likely to continue slow growth—@ significantly reduced rate for next 10 years at least; *Mostly outside OECD – in Asia*
- **NP is complex technology. NO technology is w/o risks,** but without new approach, it will be difficult to convince public to accept relative benefits far outweigh perceived risk;
- **Phasing out NP in OECD is political GAMBIT!**; It may be a mistake, but OECD can afford it

- **Dim outlook in OECD, with head wind from euphoric-support embracing all Re electricity**

- **For NP to make a major contribution to mitigation of climate change and meeting SD goal 7,** it must **overcome rising aversion to NP:**
  - prove economic competitiveness of some G III+, G-IV & SMR, under market, & local environments
  - demonstrate practical solutions to HLW disposal (Finland, Sweden, France,..)
  - strengthen nuclear safety, all levels, including culture and the international safety regime,
  - develop effective strategies to improve public and decision makers’ understanding of benefits vs. perception of associated risks,
  - Resolve the obstacles to full implementation of NPT, including start of disarmament of all NWS, INFCCs..

- **G-IV, SMR (Revolutionary) nuclear technologies offer a possible path for bright future**
  - Would nuclear fusion finally turn the corner, with ITER? In 2 decades?