China's Nuclear Energy Development and Spent Fuel Management

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Content

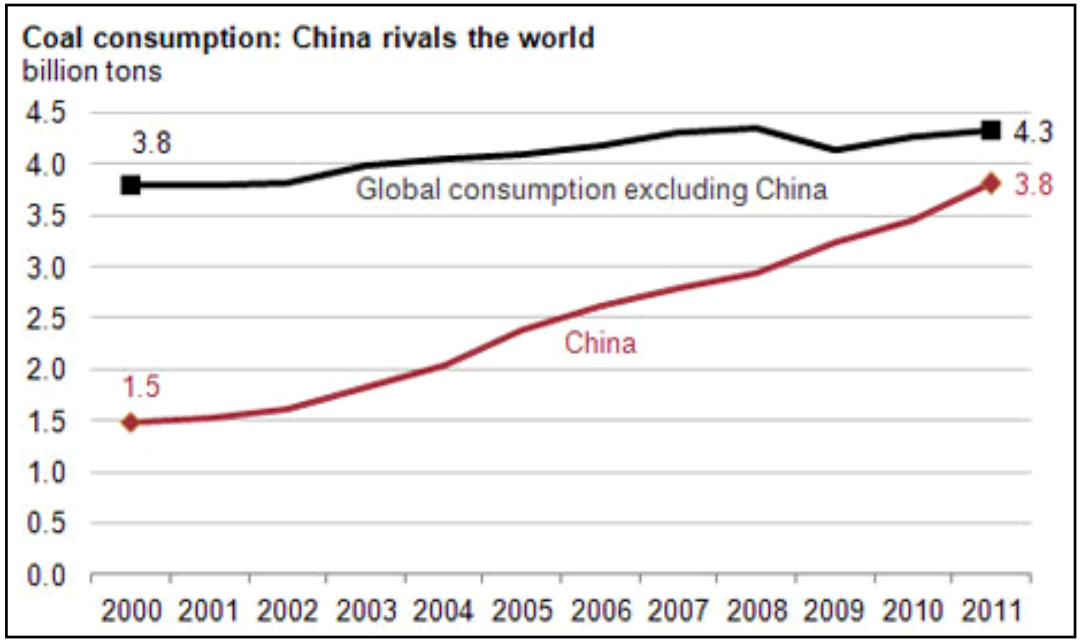
1. China's energy situation
2. Nuclear development and policy
3. Technical issues reactor and SF storage
4. Reprocessing issue

Part 1, China's energy situation

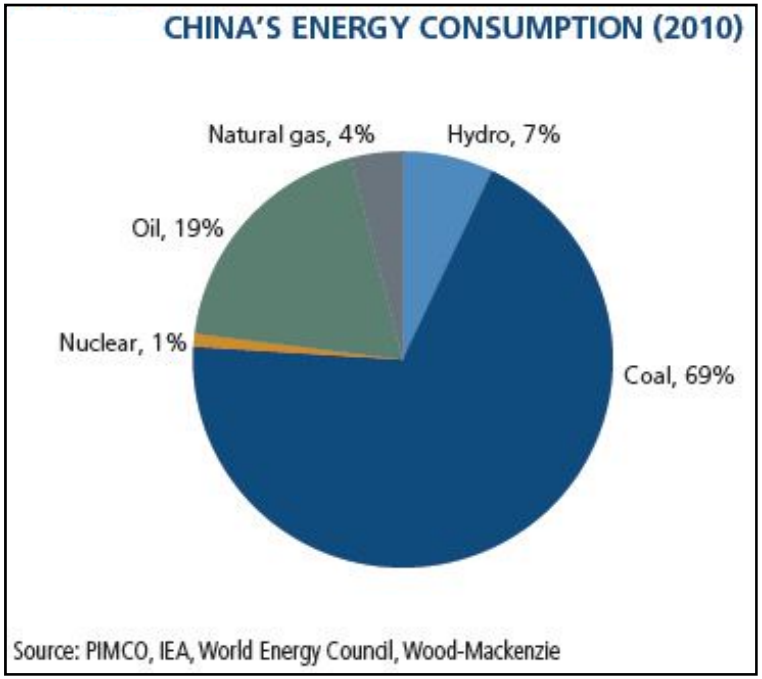
1. **China's energy situation**
   - primary energy and electricity production in China
   - problems caused by coal dominated energy
   - China's energy policy
2. **Nuclear development and policy**
3. **Technical issues of reactor and SF storage**
4. **Reprocessing issue**

Energy mix of China

- In 2010, China overtook US as world's largest energy consuming country
- Coal is the dominant and rapid increasing energy source (~70% of primary energy)

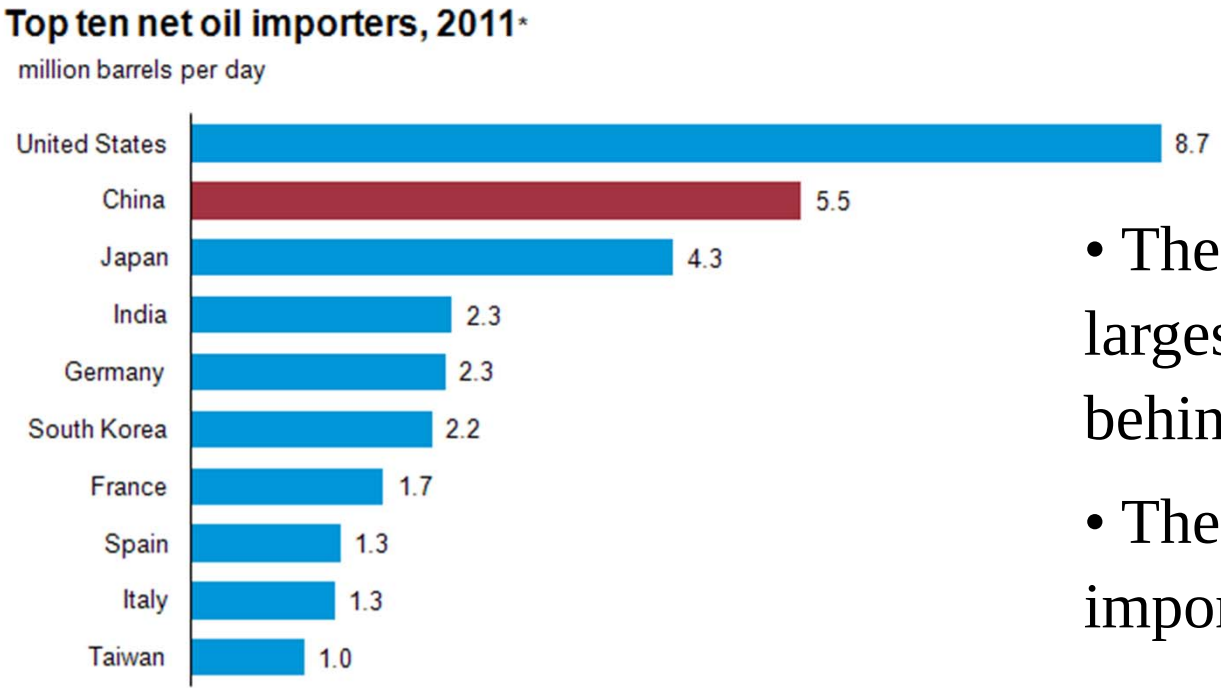


http://www.guardian.co.uk/environment/2013/jan/30/china-burns-half-coal-worldwide



Energy mix of China

Oil is the second largest primary energy in China (~19% of primary energy)



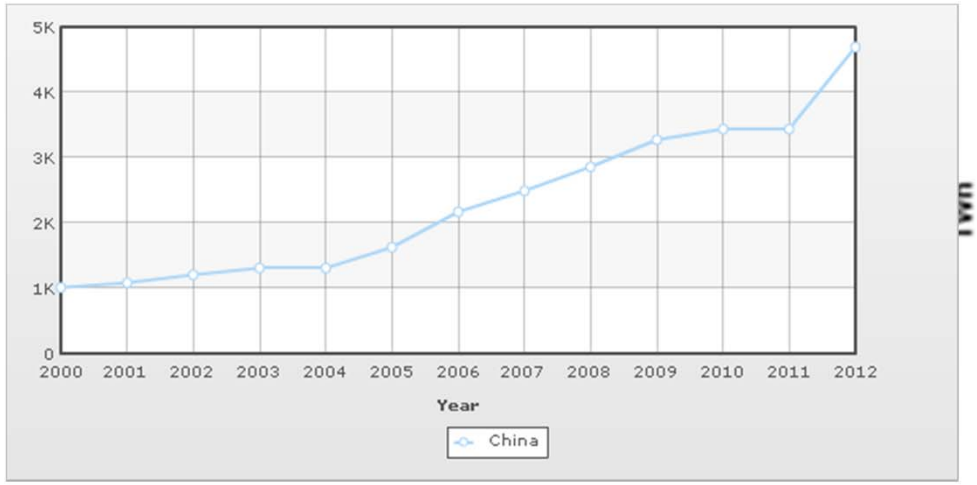
*Estimates of total production less consumption. Does not account for stockbuild.
Source: U.S. Energy Information Administration *Short-Term Energy Outlook (August 2012)*

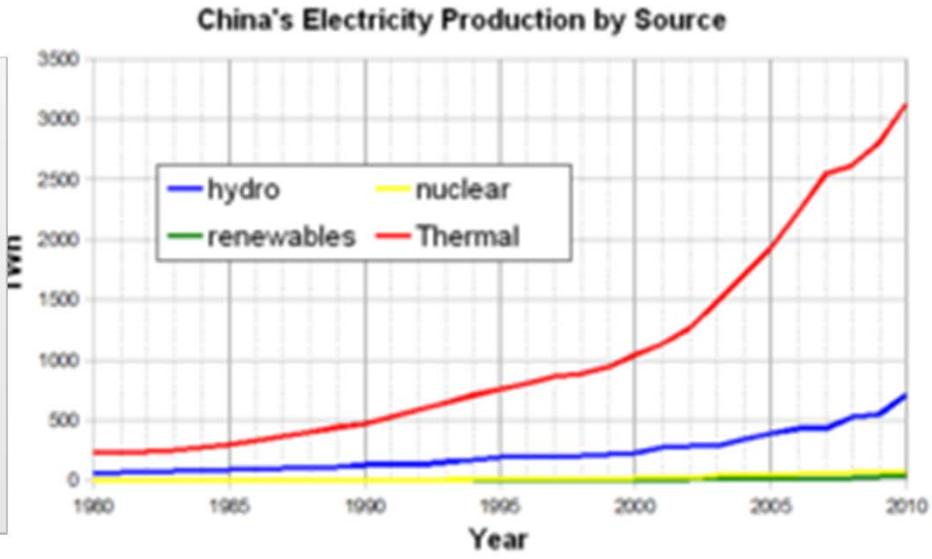
- The world's second-largest consumer of oil behind the United States
- The second-largest net importer of oil as of 2009.

Electricity production

- Eletricity pruoduction increased dramaticly in recent years (total capacity of 1.14 TWe, ~4.94 trillion KWh in 2012)
- Electricity production relies heavily on thermal power stations (~80% by coal)

China's electricity consumption (TWh)





Source: http://www.indexmundi.com/g/g.aspx?c=ch&v=81

Problem caused by coal dominated energy

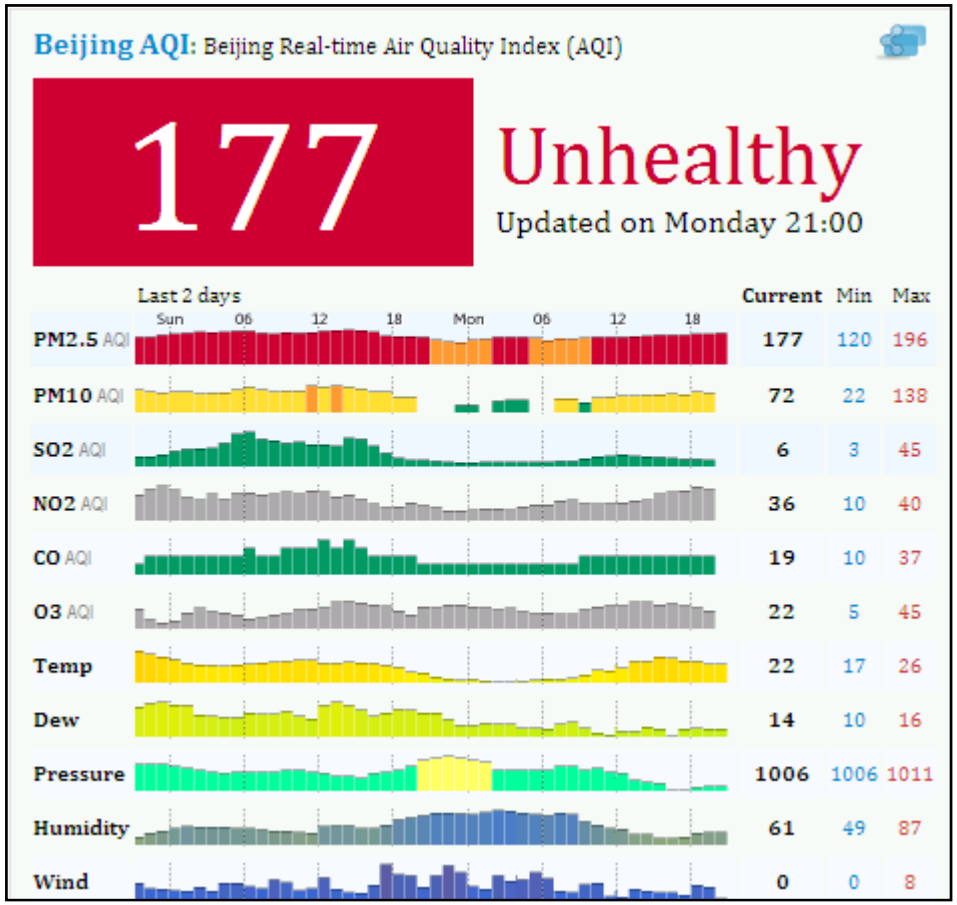
- **Enormous pressure to transportation system**
  - 1/3 of primary energy used for transportation
  - 1/2 of rail transport capacity spent on shipping coal around
- **Challenge to the CO_2 emission-cut promises**
  - largest contributor to CO_2 emissions
  - to lower its CO_2 emissions per unit of GDP by 40-45% by 2020 compared to the 2005 level
- **High human cost for coal mining**
  - >3000 people killed in coal mines every year in China (51051 killed in total from 2000 to 2009)
  - death toll is ~160 times higher than US (318 killed in 2000-2009)

Problem caused by coal dominated energy

- **Heavy pollution**
  - acid rain, dust and soot
  - Air quality PM 2.5 (small particulate matter of 2.5 microns in diameter or less that are easily absorbed into the lungs) became hotspot issue in China
    - Beijing air pollution levels soared off the charts as a wave of heavy haze engulfed the city in the spring of 2013
    - An area of >1 million km^2 in north-east China is covered in thick haze

Air Quality Index

AQI of different cities at the same time:



Source: http://aqicn.org

Energy situation in China

- **Though energy consumption is large in absolute terms and energy mix is bad**
- **consumption per capita is very small**

electricity consumption per capital in 2012

US	11920 KWh
Korea	8228 KWh
Japan	7568 KWh
China	2559 KWh

- **Sharp increase of energy consumption is inevitable**

Energy policy in China

- Jan. 2012, as part of its 12th Five-year Plan (2011-2015), China published **"12th Five-year Plan on Greenhouse Emission Control"**
  - 11.4% of primary energy consumption from non-fossil sources in 2015 and 15% in 2020. (up from 8.3% in 2010)
  - To foster hydro, wind, solar and biomass energy

	Installed capacity 2010	Planed target 2015	Planed target 2020
Hydopower	216 GW	260 GW	420 GW
Wind	31 GW	100 GW	200 GW
Solar	0.8 GW (PV only)	21 GW	50 GW
Biomass	5.5 GW	13 GW	----

Part 2, Nuclear development and policy

1. China's energy situation
2. Nuclear development and policy
   - nuclear development before Mar. 2011
   - response to Fukushima accident
   - post-Fukushima accident: situation and policy
3. Technical issues of reactor and SF storage
4. Reprocessing issue

Nuclear energy development

- **Construction of NPP started in mid-1980's**
- **Moderate development (before 2004)**
  - First NPP in commission in 1994
  - Slow progress in the next 10 years (8 units, 6.1 GWe in operation by the end of 2003)
- **Positive development (2004~2011)**
  - 5 new units, 4.2 GWe in operation (totally 13 units, 9.8 GWe by Mar. 2011)
  - 26 units (26.2 GWe) under construction, 32 units further approved by the state at end 2010

Nuclear energy development

- **Positive development (2004~2011)**
  - Ambitious nuclear plans proposed by different authorities

Time	Organization	in operation in 2020 /GWe	under construction in 2020 /GWe
Oct. 2007	National Development and Reform Commission	40	18
Mar. 2008	National Energy Administration	>50	
Jun. 2008	State Council	86	16
Jan. 2011	State Council Research Office	70	30
Jan. 2011	China Daily	86	

Response to Fukushima Accident (FA)

Mar.16, 2011	• approvals for new NPPs suspended • start safety inspections of all reactors in operation and under construction, as well as fuel cycle facilities
May 2012	• new safety plan for nuclear power approved in principal
Oct. 2012	• approvals for new NPPs recommenced • **nuclear policy changed to "steady development with safety"**
Oct. 24, 2012	approval of new "Nuclear Safety and Development Plans" by State Council: • by 2015, only costal projects to be approved; inland on hold • adhere to Gen III nuclear safety standards for new projects • **40 GWe installed in 2015, 58 GWe in 2020**

NPP construction after FA

- **4 units (3.6 GWe) came in operation after FA**

Ling'ao phase II, Unit 2	1000 MWe	Aug 7, 2011
Qinshan phase II, Unit 4	600 MWe	Feb 28, 2012
Ningde unit 1	1000 MWe	Apr 18, 2013
Hongyanhe unit 1*	1000 MWe	Feb 17, 2013

  - by May 2013, 17 units (approx. 13.9 GWe) in operation

*: date of first connection to grid

Nuclear energy development

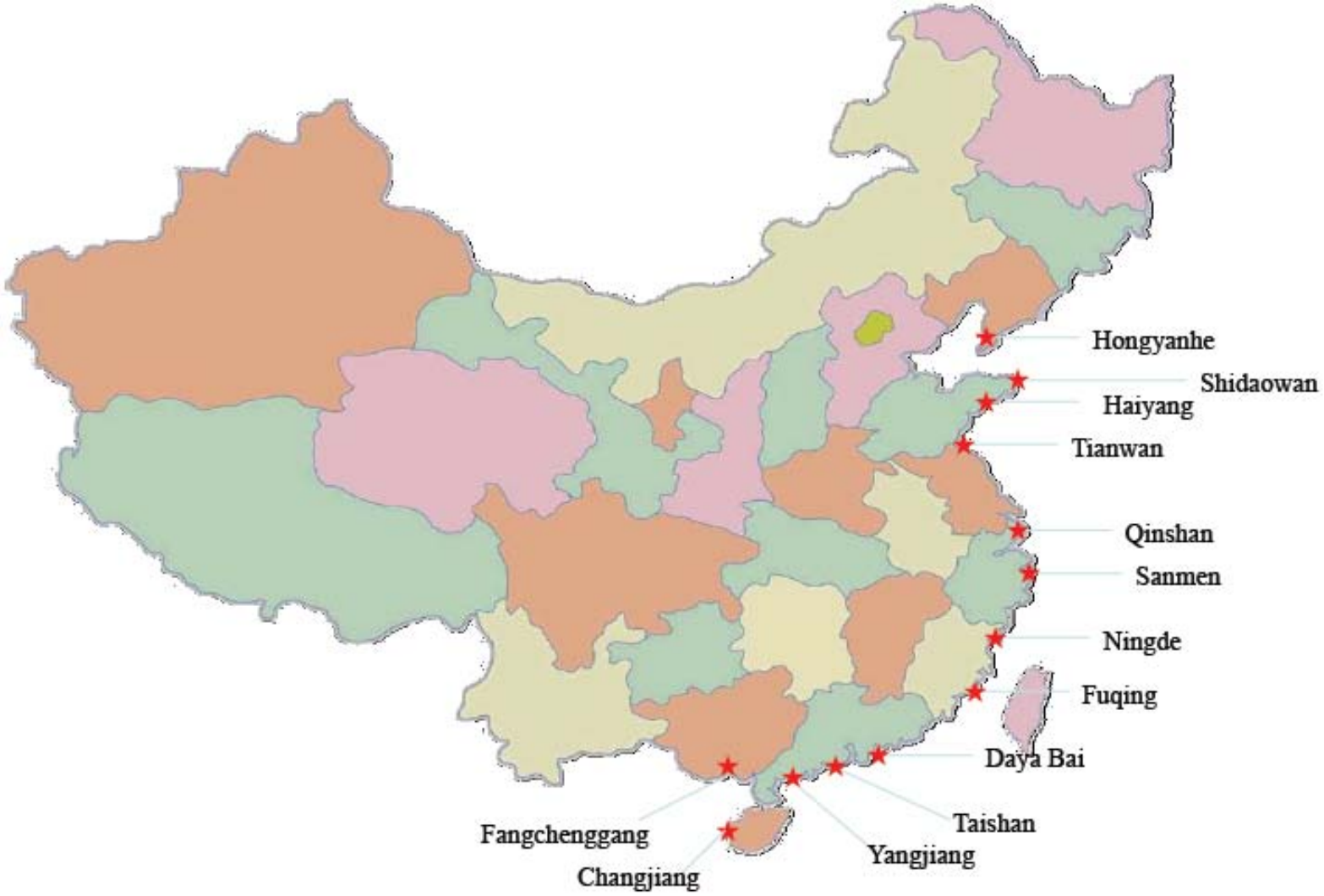
- **Post-FA and future**
  - By Dec 2012, 31 nuclear units under construction (~ 31.6 Gwe)
    - *20 self-reliant design PWR (including Ningde #1 and Hongyanhe #1 which are now in operation)*
    - *4 AP1000*
    - *2 EPR*
    - *1 HTR-PM*
    - *2 units with CP but not start construction*
  - **Slower a little bit, but still steady and aggressive**

source: T. W. Yan, 2012

Nuclear reactors in operation

#	Unit	Net capacity /MWe	Type	First com'l operation	CF in 2011/%	2011 unp. scram
1-2	Daya Bay 1&2	900*2	PWR (French M310)	1994	99.98 /86.56	0
3	Qinshan Phase I	300	PWR (CNP-300)	1994	88.04	0
4	Qinshan Phase II, 1	600	PWR (CNP-600)	2002	73.17	1
5	Qinshan Phase III, 1	650	HWR (Candu 6)	2002	92.53	1
6	Ling'ao Phase I, 1	1000	PWR (French M310)	2002	91.39	0
7	Qinshan Phase III, 2	700	HWR (Candu 6)	2003	91.02	1
8	Qinshan Phase II, 2	600	PWR (CNP-600)	2004	90.95	0
9	Ling'ao Phase I, 2	1000	PWR (French M310)	2004	94.05	0
10-11	Tianwan 1&2	1000*2	PWR (VVER)	2007	86.55 /87.05	0
12	Qinshan Phase II, 3	650	PWR (CNP-600)	2010	86.64	0
13	Ling'ao Phase II, 1	1000	PWR (CPR-1000)	2010	72.06	2
14	Ling'ao Phase II, 2	1000	PWR (CPR-1000)	2011	99.58	7
15	Qinshan Phase II, 4	600	PWR (CNP-600)	2012	N/A	N/A
16	Ningde I	1000	PWR (CPR-1000)	2013	N/A	N/A
17	Hongyanhe I	1000	PWR (CPR-1000)	2013	N/A	N/A

NPP sites in China



Four Bases of present NPPs in China

Four NPP bases at present:

- Tianwan
  2 units in operation
- Qinshan
  7 units in operation
- Ningde
  1 unit in operation
- Daya Bay
  6 units in operation

Source: www.world-nuclear.org

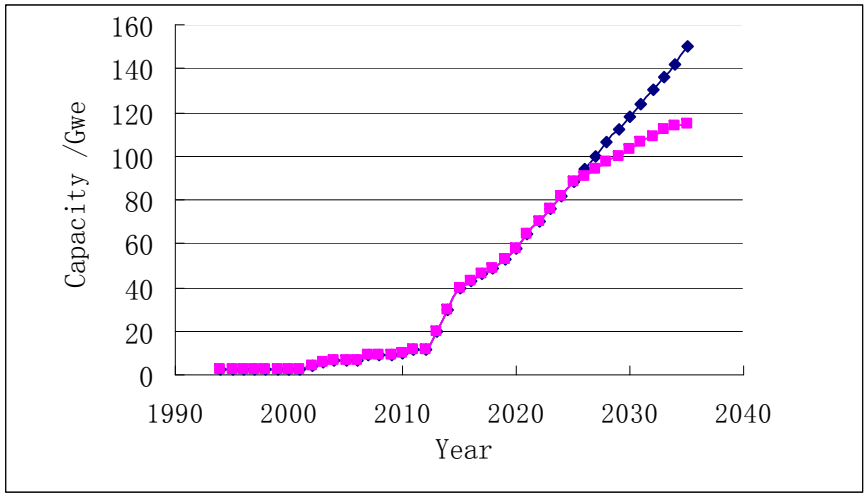
Schedule of NPP construction

Year/units	FCD	NI installation	CFT	HFT	FFL	Critically	Commercial operation
2007	1						
2008	6						
2009	9	2					
2010	10	6					
2011		10	1				
2012		8	7	5	2	2	2
2013			9	10	10	9	7
2014			9	9	10	11	9
2015				2	4	5	7
2016							4

source: T. W. Yan, 2012

Estimation of nuclear energy increase

- **By now, 13.9 GWe in operation and 26.6 GWe under construction**
  - According to the latest official plan, 40 and 58 GWe will be in commercial operation in 2015 and 2020 respectively
  - including 0.2 GWe of HTR-PM and 1.2 GWe of CANDUs

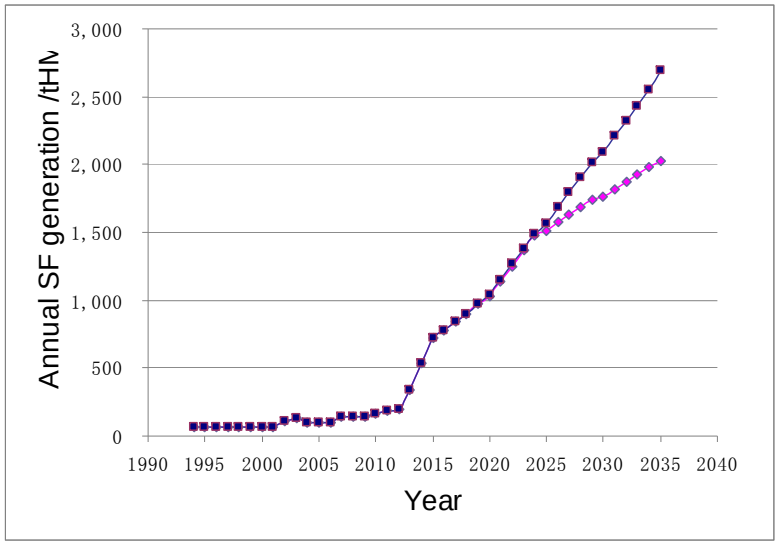


Estimation of PWR capacity in China

Year	high case /GWe	low case /GWe
2011	11.3	11.3
2020	58	58
2025	88	88
2030	118.0	103
2035	150	115

Estimation of SF generation

- **Estimation of SF according to**
  - Operational parameters of reactor: Bu, thermal effectivity and load capacity
  - Only PWRs are considered in the calculation



Estimation of annual SF generation in PWRs

Table: inventory of SF discharged from PWRs

year	high case /tHM	low case /tHM
2012	2004	2004
2020	8136	8120
2025	14999	14871
2030	24494	23257
2035	36697	32884

Part 3, technical issues of reactor and SF

1. China's energy situation
2. Nuclear development and policy
3. **Technical issues of reactor and SF storage**
   - reactor models in China
   - SF on-site storage for different reactor models
   - estimation of SF generation and storage capacity
4. Reprocessing issue

Reactor models in China

- **PWR is and will occupy the mainstream status at present and in future**
- **15 PWRs in operation at present** 17 in total
  - Self-designed PWRs in Qinshan phase I and II (5 units /2.7GWe)
  - French-made M310 PWR in Daya Bay and Ling'ao Phase I (4 units/ 4GWe)
  - Russia-made VVER in Tianwan (2 units, 2 GWe)
  - CPR1000 in Ling'ao Phase II, Ningde and Hongyanhe (4 units / 4GWe)
- **Meanwhile, 2 CANDU reactors in operation**
  - 2 CANDU reactors in Qinshan Phase III with 1.2 GWe in total

Reactor models under construction

- **Gen III PWRs under construction**

  Twelve AP1000 units (constr. and planned)

  Two EPR units

EPR Taishan site
(Oct. 2011)

AP 1000 Haiyang site
(Sep. 2012)

AP 1000 in Sanmen site
(Sep. 2012)

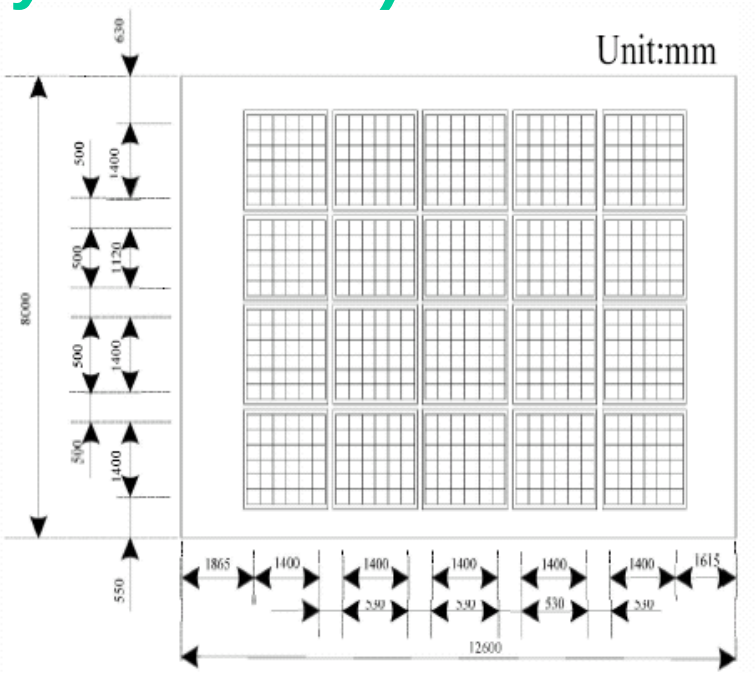
Other reactor models

- **CPR1000**
  - 4 in operation, >20 units under construction or planned
  - Design based on French M310 reactor
- **VVER**
  - 2+2 units in Tianwan, imported from Russia
- **HTR-PM** (High Temperature Reactor-Pebble bed Modules)
- **CANDU**
  - 2 units in operation in Qinshan Phase III

SF storage at reactor

M310/CPR1000

- Gen II reactor, widely in operation and under construction
- For M310, two pools, each includes 690 asseb. (4.4 yr of disch.)



Cross section of SF pool (K.Wang, et al. 2011)

Parameters	Value
Size of pool	12.6m*8.0m
Depth of water	12.5 m
Max. number of assemblies in pool	690 assemblies
Grid flow area	1.50 m^2
Heat load of exchanger	4.2 MW

SF storage at reactor

AP 1000

- **Most common reactors of Gen III in China**
  - SF stored in auxiliary building
  - Up to 889 assemblies submerged beneath ~25 feets water in Spent Fuel Pool (SFP). 10 yr of discharge plus one core
  - For the first 72 h after loss of cooling, simple or no actions are required

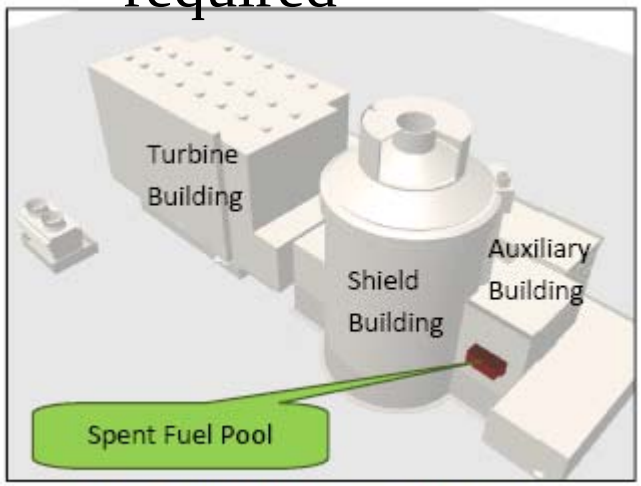
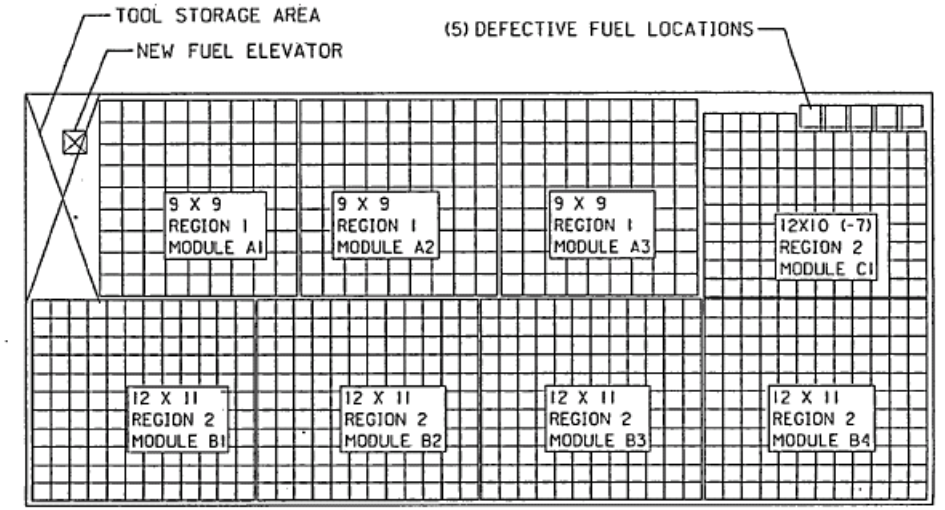


Figure 1: AP1000 Plant Layout of Spent Fuel Pool



SF storage at reactor

CANDU 6

- **Two units in operation ~1.2 GWe totalled**
  - ~5,000 SF bundles discharged per year in per unit
  - SF bundles firstly stored in pools for cooling after discharge
  - Each SFP includes 37,728 bundles (~7.6 years of SF bundles discharged)
  - First two MACSTOR-400 modules finished construction on Aug 2009.

SF storage at reactor

CANDU 6

- **MACSTOR-400 dry storage module**
  - 24,000 SF bundles in one module 4.8 yr of discharge
  - SF cooling by natural convection
  - Plans to construct 18 modules at a rate of 2 modules every 5 years

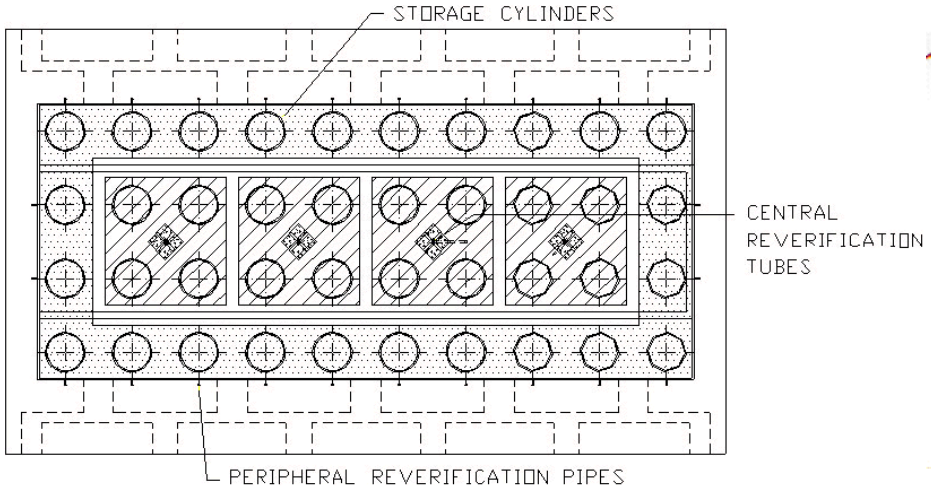
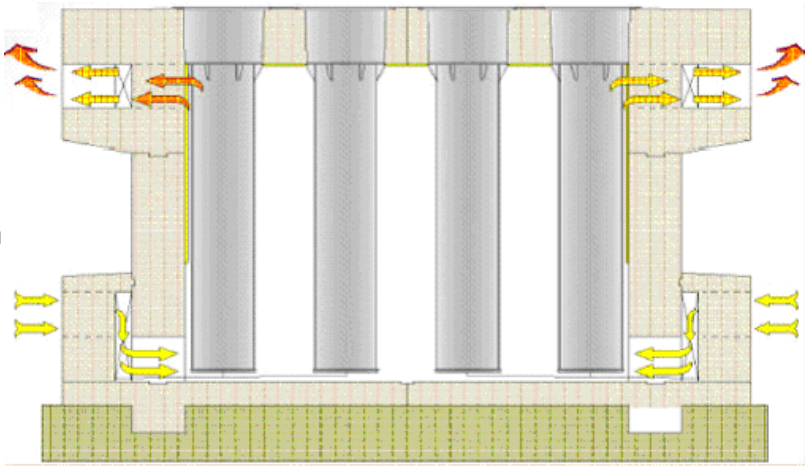


Diagram of the MACSTOR system

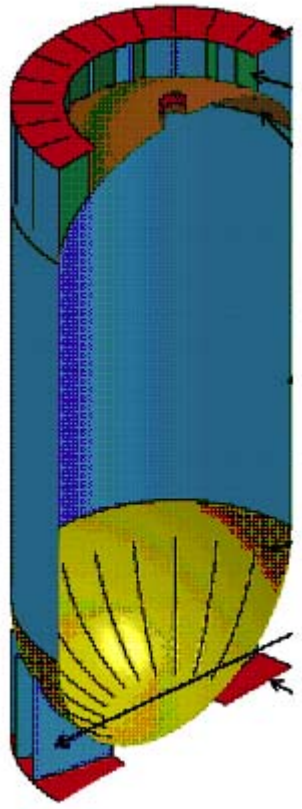


Passive heat transfer in MACSTOR-400

SF storage at reactor

HTR-PM

- **200 MWe, start construction on Dec. 2012**
- **Dry storage of spherical SF assembly**
  - Cask of 4.18 m high and 1.74m of inner diameter
  - 40,000 assemblies in a cask, 280 casks in facility. enough to hold lifetime dischare
  - Average burnup of 90 GWd/tU
  - Max. thermal power of SF in cask: 27.1 KW 1.43KW after 5 years
  - Forced ventilation for the first 30-60 months



SF storage capacity at reactor

- **No urgent requirement to remove SF from NPPs**
  - Initial designed capacity of SF for ~10a
  - Higher burnup, reload cycle extension and high-dense pack storage enlarge the AR storage capacity to ~20a
  - Financial benefits from delay of SF removal

Part 4, reprocessing issues

1. China's energy situation
2. Nuclear development and policy
3. Technical issues of reactor and SF storage
4. **Reprocessing issue**
   - away-from-reactor storage of SF
   - reprocessing policy
   - activities for reprocessing development
   - challenge and trend

SF storage away-from-reactor

- Daya Bay is the only NPP had the experience of SF shipping out
  - First shipping in 2003 to Gansu province
  - At a rate of 2 casks (104 assemblies) per year
- A centralized SF pool in operation
  - SF pool in the pilot reprocessing facility in Gansu province
  - With capacity of 550 tHM, start operation in 2003[1]
  - Possible to be extended to 1300 tHM[2]
  - Maybe almost full as roughly estimate

[1] China Nuclear Industry, Vol. 45
[2] G.Q. Deng, 2010

Reprocessing policies

- Reprocessing for military use started in 1960's and ended in 1980's
- Set the guideline of closed cycle to reprocesing and reuse fissile materials
- Possible reasons
  - To save uranium resource and manage SF
  - To improve nuclear chemical engineering technology and personnel cultivation
  - To stimulate related technologies and industries (materials, mechanics, contrology and etc.)

Attempts at commercial reprocessing

- Reprocessing Pilot Plant (RPP)* for SF from power reactor
  - **400 kgHM/d for head and end end, 300 kgHM/d for chemical separation part (overall capacity of ~50 tHM)**
  - **Possible to be expanded to 100 tHM/a in future**
- History of RPP construction
  - **1986: site of RPP decided in Gansu province**
  - **1987: project approval and start to design**
  - **1998: comprehensively start of construction**
  - **2010: integral active test completed successfully**

Source: G. Q. Deng, 2010

Attempts at commercial reprocessing

- To deal with the rapid increaseing of SF from NPPs, a large scale commercial repro. plant is considered.
- Technical features of large scale repro. plant
  - **capacity of 800 tHM/a**
  - **based on the proven PUREX process**
  - **vitrification of HLLW**
  - **U and Pu co-precipitate to reduce risks of proliferation**
- The projected hot test of large scale repro. plant would be ~2025
- Construction based on intern'l cooperation and domestic R&D

Source: G. Q. Deng, 2010

Progress on intern'l cooperation

- 2007, CNNC signed with the AREVA to study the feasibility of constructing a reprocessing-recycling plant [1]
- Apr. 25, 2013, letter of intent signed in the presence of French and Chinese presidents [2]
  - technical specifications set out, but no details released
  - capacity of 800 tHM/a confirmed

[1]: AREVA PRESS RELEASE, Nov.6, 2007

[2]: www.world-nuclear-news.org/WR_China_approaches_reprocessing_commitment_2604131.html

Challenge to China's reprocessing

- China has to face some challenges for its development of SF reprocessing
  - **Due to the high complexity of the reprocessing, it is a long way to fully master reprocessing technologies**
  - **Multiple reactor models such as M310, CPR, VVER, AP1000, EPR and etc. make reprocessing more difficult, especially for the head end process**
  - **Extension of SP storage capacity is necessary, due to the sharp increase of SF inventory.**

Trend of reprocessing in China

- Choice of closed fuel cycle will not be changed, at least in the short term, though the worries on SF storage are low
- More investments and progresses on China's reprocessing might be seen by the means of intern'l cooperation and domestic R&D
- Even so, the construction of large scale reprocessing plant might still be behind present schedule
- Dry storage of PWR SF is being attracting more and more attentions and will actually happen anytime soon

Thank you

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