Measurement Program for Occupational Exposure Source Term with in-situ Gamma spectroscopy in China's NPPs

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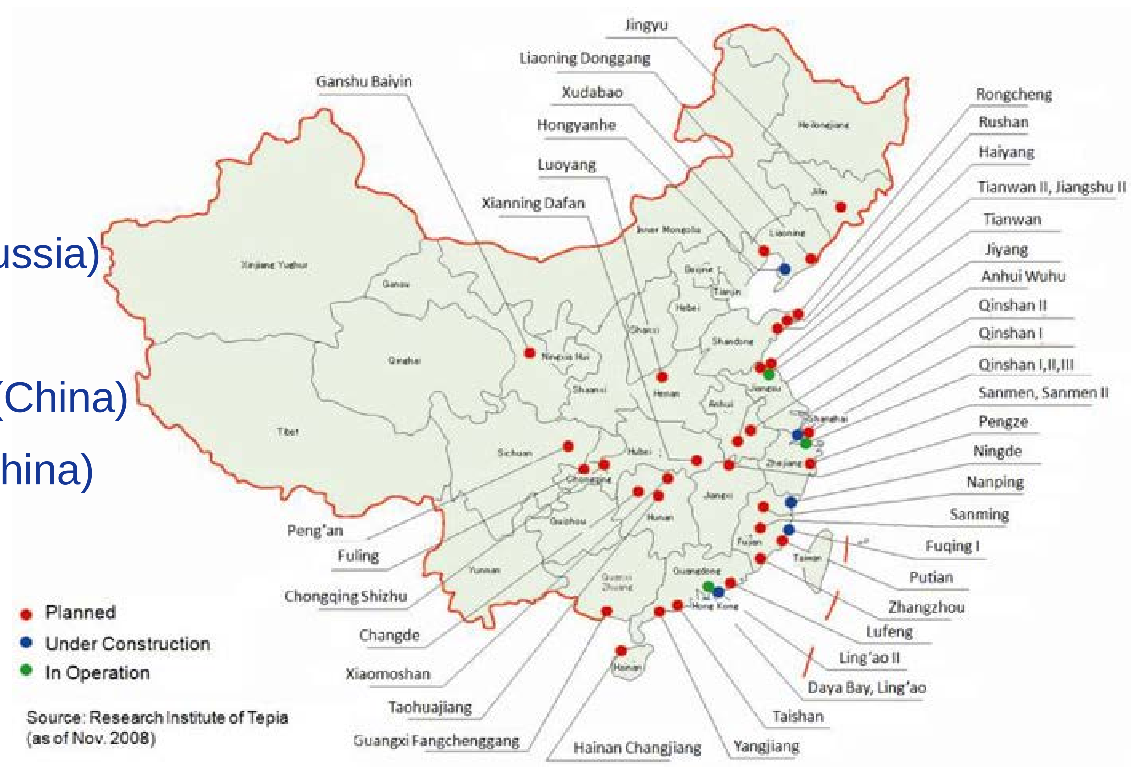
Outline

- Background
- Measurement program
- Methodology
- Selected results
- Conclusion

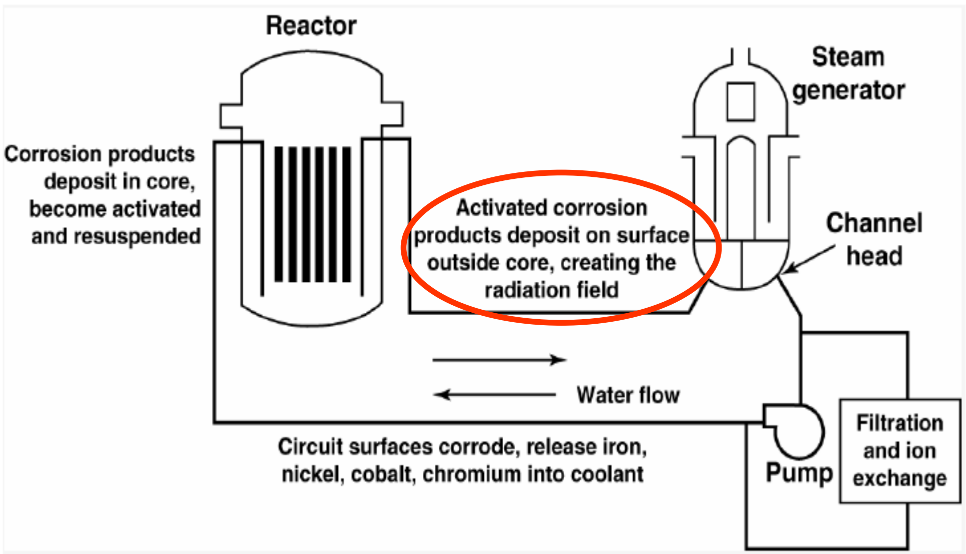
Background

- In recent years, China's nuclear power programme is undergoing a major expansion. As of March 2016, China has 33 nuclear reactors operating and 22 under construction.
- Different reactor types
  - PWRs
    - M310, EPR (France)
    - VVER1000(AES-910,Russia)
    - AP1000 (USA)
    - CNP300/600,CPR1000(China)
    - ACPR1400, Hualong (China)
  - PHWRs
    - Candu-6(Canada)
  - HTR-PM (China)
  - FNR-CEFR(China)



Background

- Activated corrosion products, deposited on the surfaces outside core, are the main contributors for external radiation field during the outage of NPPs.



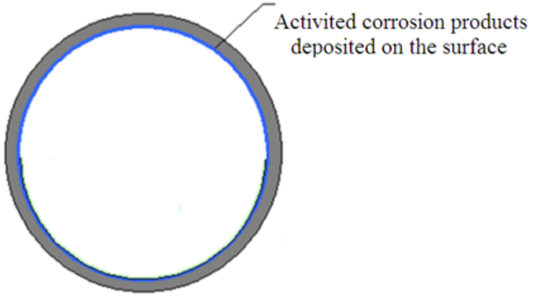
$^{58}Ni\ (n,p)\ ^{58}Co$

$^{59}Co\ (n,\gamma)\ ^{60}Co$

$^{54}Fe\ (n,p)\ ^{54}Mn$

$^{50}Cr\ (n,\gamma)\ ^{51}Cr$

$^{58}Fe\ (n,\gamma)\ ^{59}Fe$



- What (radionuclides)?
- Where?
- How much?
- Dose contribution?
- Difference among reactors?

- **Objective:**
  - Identification of radionuclides and their specific activities
  - Dose contribution for external radiation field

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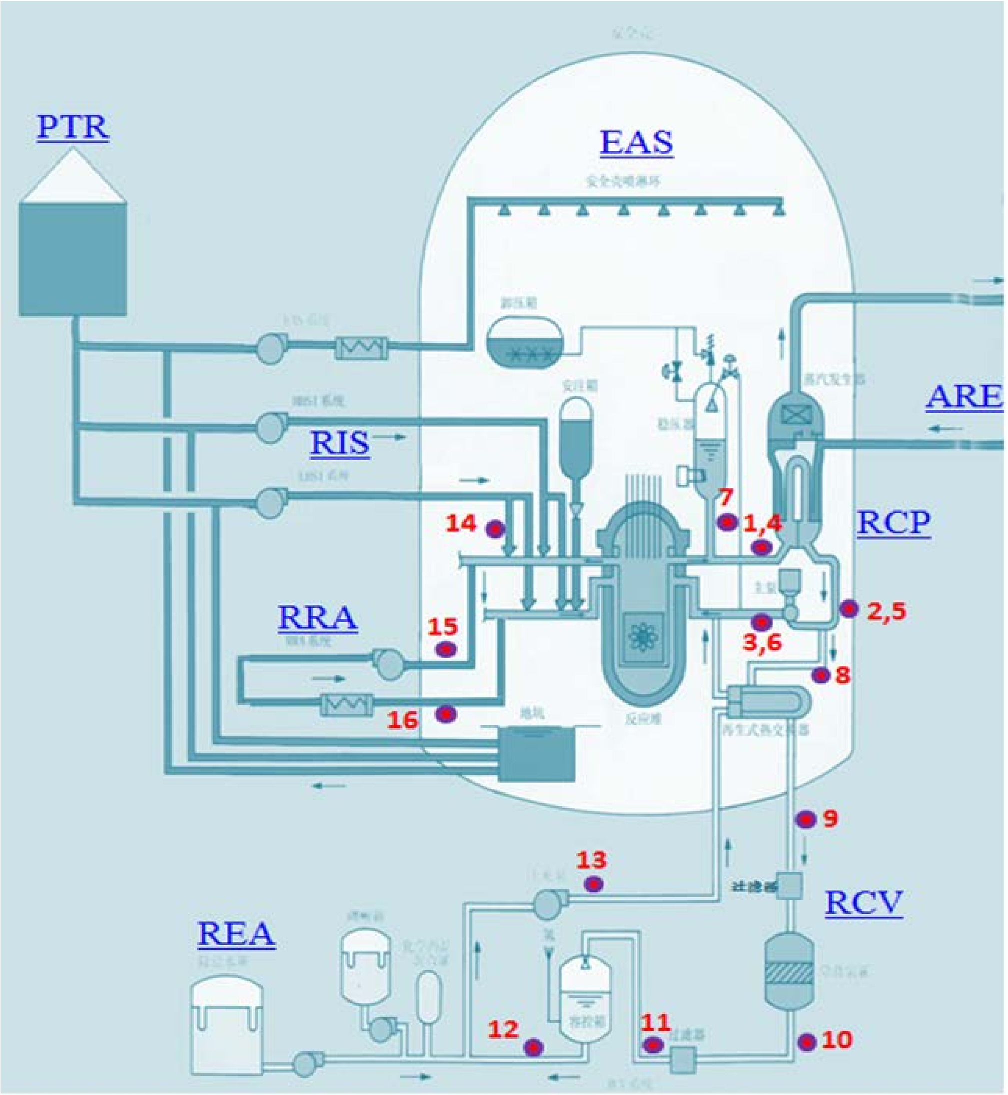
Measurement Program

Measurement locations for PWRs



☐Program for PWR

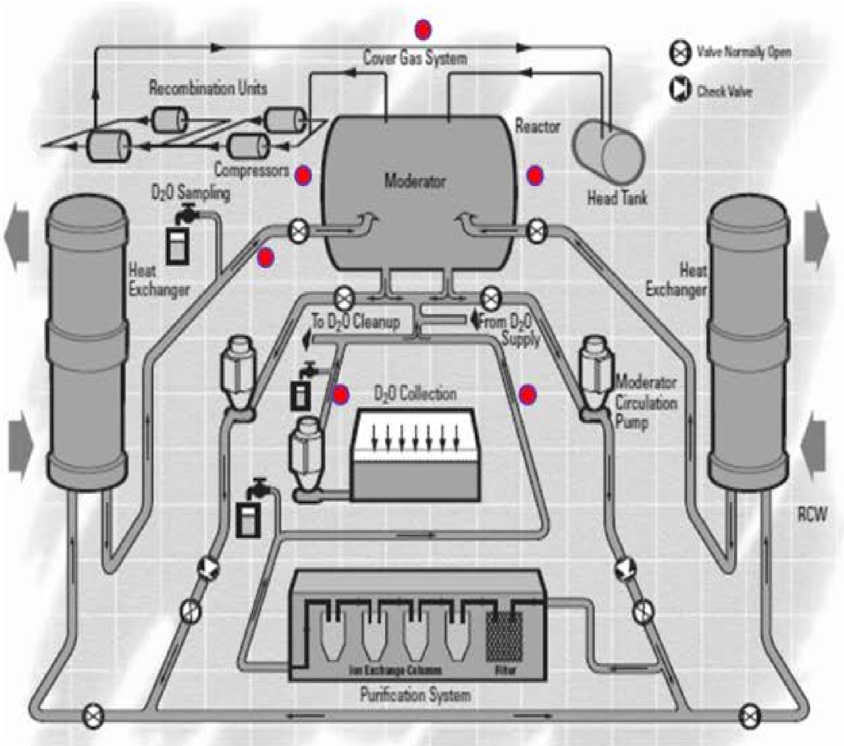
- ➢ Num. of locations: 18~20;
- ➢ Pipe status: Empty or Full
- ➢ Mea. Time: After Oxygenation

Survey locations

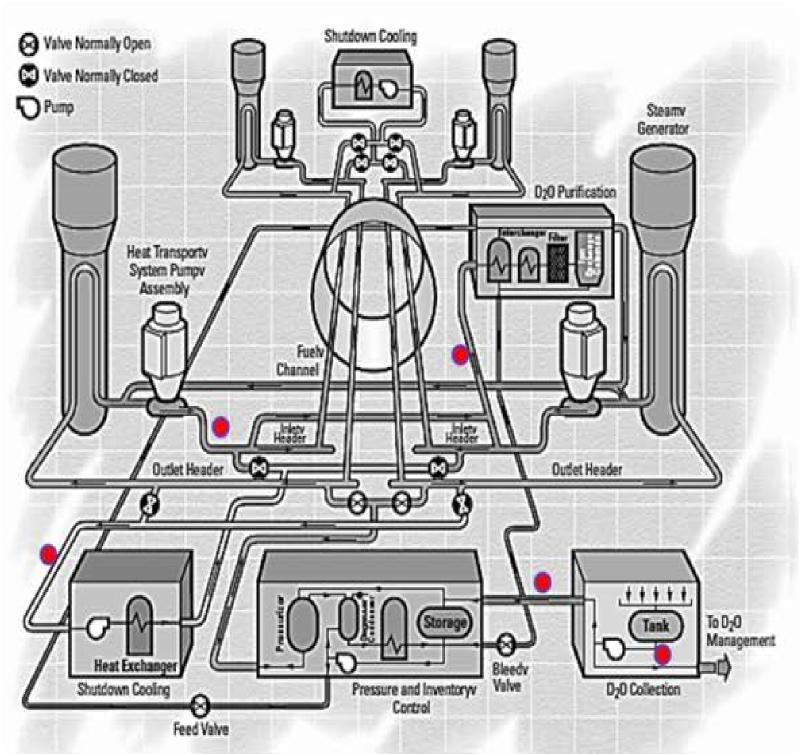
systems	Locations	priority
RCS (RCP)	Loop-1, hot-leg	Required
	Loop-1, cross-leg	Required
	Loop-1, Cold-leg	Required
	Loop-2, hot-leg	Required
	Loop-2, cross-leg	Required
	Loop-2, Cold-leg	Required
	Stabilizer pipe	Recommended
RHRS (RRA)	up-stream pipe before RHR pump	Recommended
	Connection pipe between PTR and RRA	Recommended
	down-stream pipe after RHR pump	Recommended
CVCS (RCV)	Before regenerative resin	Recommended
	Up-stream pipe before purification bed	Recommended
	Down-stream pipe after purification bed	Recommended
	After regenerative resin	Recommended
	Down-stream pipe of Volume Control Box	Recommended
	Before pump	Recommended
BRS (REP)	Upstream pipe	Optional

Measurement Program

❖ Measurement location for PHWR



慢化剂及其辅助系统



传热及其辅助系统

Measurement Program

20 measurement campaigns for 6 NPPs (since 2005)

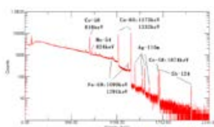
2015

Fuqing (FQ-101), LingAo(L113) — PWR(M310+)
Qinshan-1(Q1-116)
Fanjiashan (QF-101/201) — PWR(M310+)

2014

Tianwan (T106/T206)
Qinshan-3 (107/207/108) — PHWR(Candu6)

2012

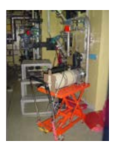


Qinshan-2 (301/302)
Qinshan-3 (205)

2010

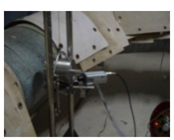
Tianwan (T104/T203) — PWR (AES-91)
Qinshan-2 (108/207)

2007



Qinshan-2(105/204) — PWR (CNP600)

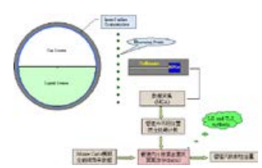
2005



The first mea. campaign in Qinshan-1 (108) — PWR (CNP300)

2004

To develop Sterm-HPGe



Source term characterization in China's NPPs

Outline

- Background
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Methodology

- Since the pipes are still in service for NPPs, in-situ gamma spectroscopy is almost the only available measurement method for radiological characterization of these deposited corrosion products, thanks to its non-destructive advantage.

- **Approach (gamma spectroscopy + proper data interpretation)**
  - Gamma spectroscopy
    - to identify radionuclides and their peak counts
    - Sterm-HPGe, Sterm-CZT developed by CIRP.
  - Hand-held dosimeter
    - to measure dose-rate (Radiagem-2000).
  - **Data interpretation:**
    - To calculate detection efficiency by using numerical calibration technique
    - To analyze dose-rate contribution by using Monte Carlo (MC) calculation

In-situ gamma spectroscopy

It consists of HPGe/CZT detectors, collimator, MCA, vehicle.

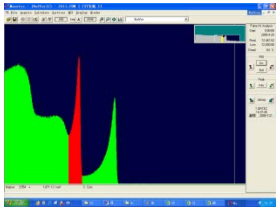
Sterm-HPGe

(GEM30P4, 2004)

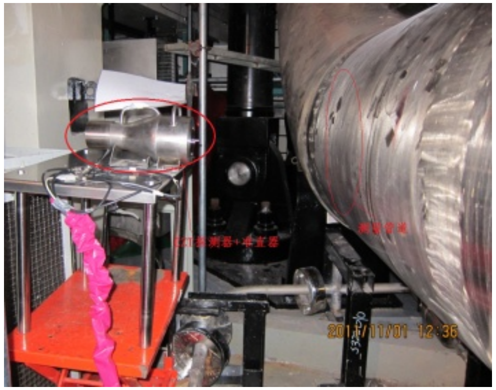
(GEM30P4, GX1020, 2011)

Sterm-CZT

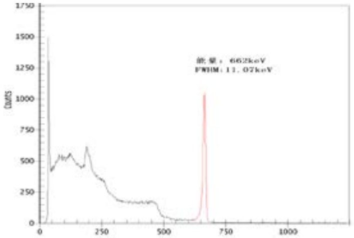
(CZT-500s,2005)



- Low resolution
- incomplete charge collection (left-tail peak)



(CPG-CZT, 2011)



- Improved resolution
- No left-tail
- Larger size

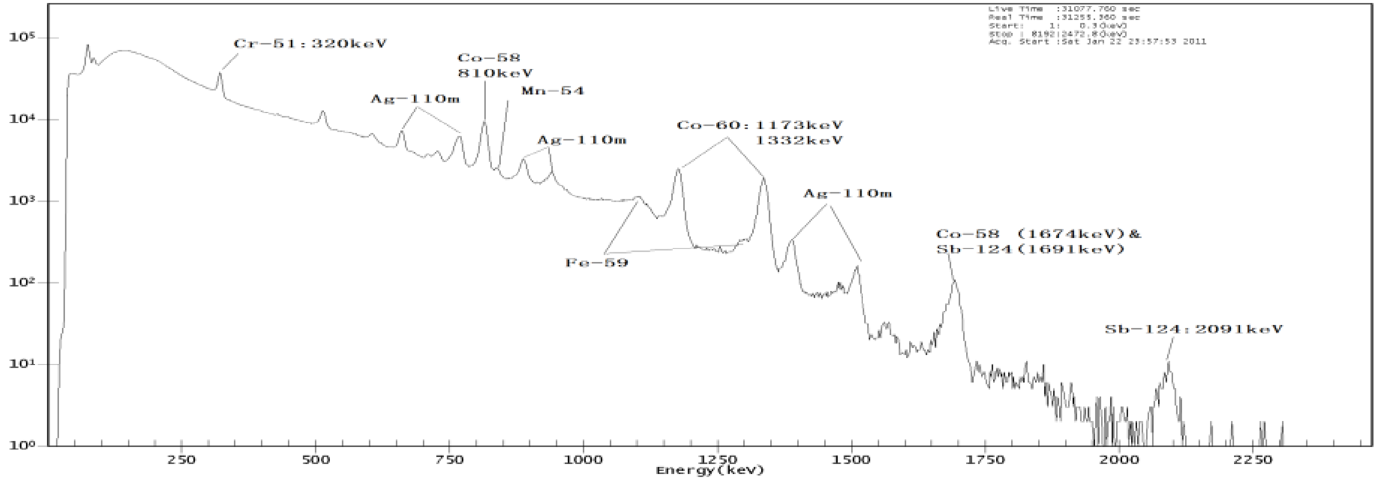
In-situ gamma spectroscopy

Table 1. Performance indicators of Sterm-HPGe and Sterm-CZT

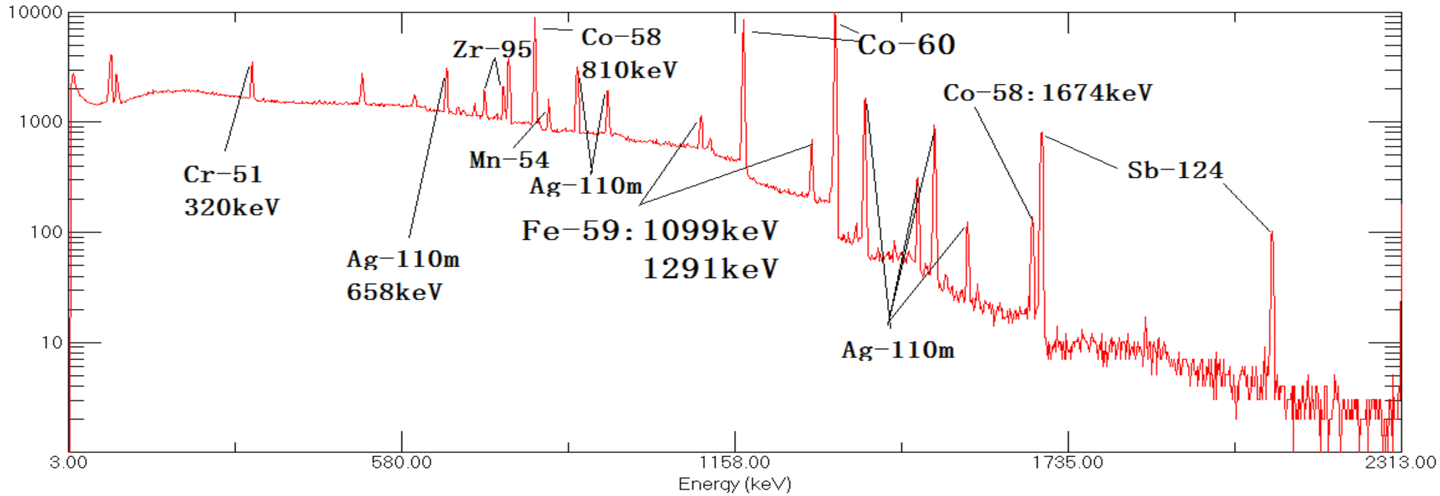
Main performance	Sterm-HPGe	Sterm-CZT
Detector	HPGe	CZT
Relative Efficiency	33%(GEM30P4, 2004) 10%(GX1020, 2011)	CZT500s (Ritec, 2005) 0.13%(eV CPG-CZT,10×10×10mm^3, 2011)
Energy range	60keV-3MeV, 3keV-10MeV	60keV-2MeV
Energy resolution	1.3keV@662keV (good)	12keV@662keV (moderate)
Measurable dose-rate	1μSv/h-200μSv/h (low)	10μSv/h-15mSv/h (higher)
	Other performance	
Radionuclide identify	All radionuclides can be identified	Almost all interest-radionuclides in NPPs
Typical Mea. time	~10 Mins.	0.5-3 hours
Typical MDA	10 Bq/cm^2	100 Bq/cm^2
Weight (including collimator)	40kg (Heavy)	15kg (Light)
Accessibility	Poor	Flexible
Work requirement	LN2 Cooling	-

In-situ gamma spectroscopy

- **Measured spectra by using Sterm-CZT and –HPGe (example)**



CZT

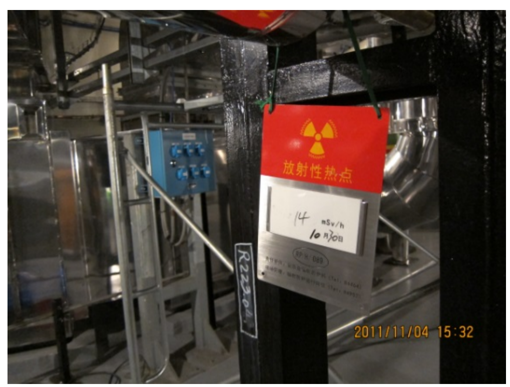


HPGe

In-situ gamma spectroscopy

- Although Sterm-CZT has limited energy resolution, it is more suitable to be used in narrow space or high radiation field than Sterm-HPGe.

Narrow space



High radiation field

Numerical efficiency calibration

- Full-energy peak detection efficiency is the key parameter for accurate measurement of radioactivity by using in-situ gamma spectroscopy.
- A so-called Sterm-MC software has been developed for numerical calibration purpose, combined with proper variance reduction technique to speed up the calculation.

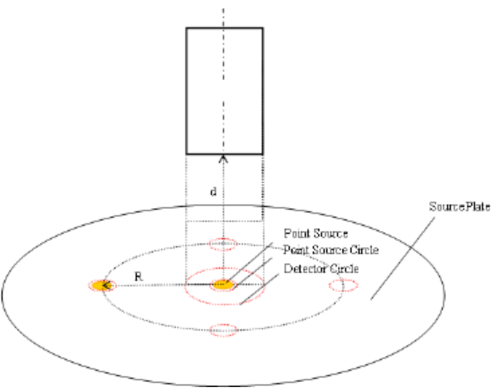
Table 2. Comparisons of two calibration methods

	Experimental calibration	Numerical calibration
Time	Time-consuming	Fast
Cost	Expensive	Cheap
Geometry	Limited geometry	More flexible
Others	Radiation exposure	Experimental validation needed

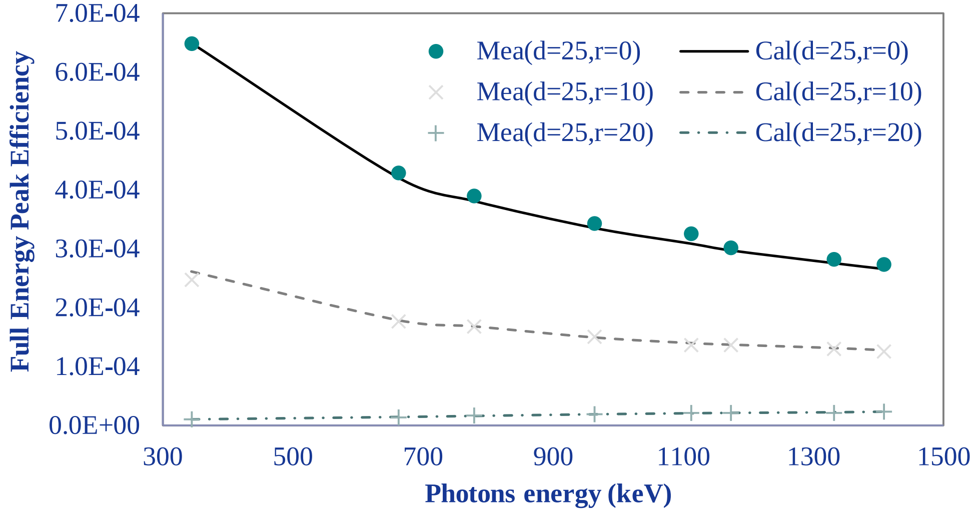
Sterm-MC
(based on Monte Carlo method)

Numerical efficiency calibration

Experimental validation

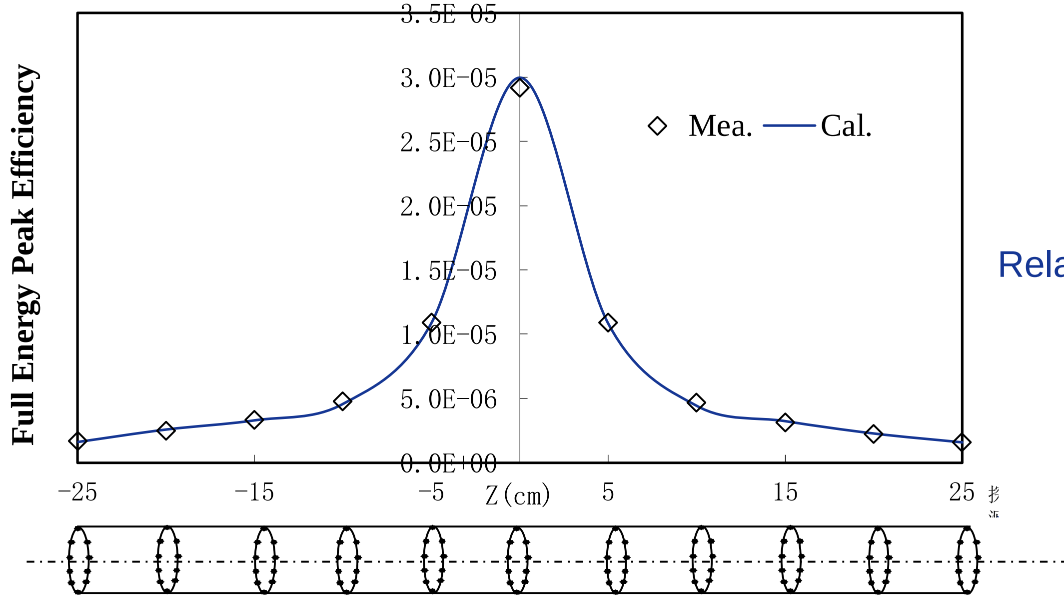


Point-source experiment



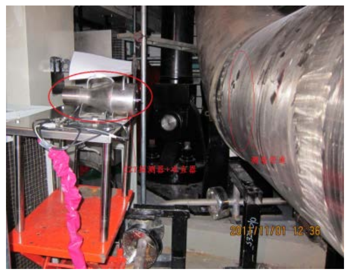
Relative deviation: ±10%.

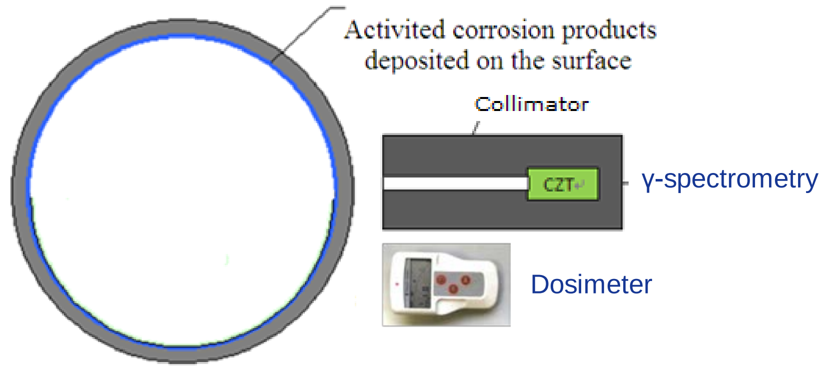
simulated surface source experiments

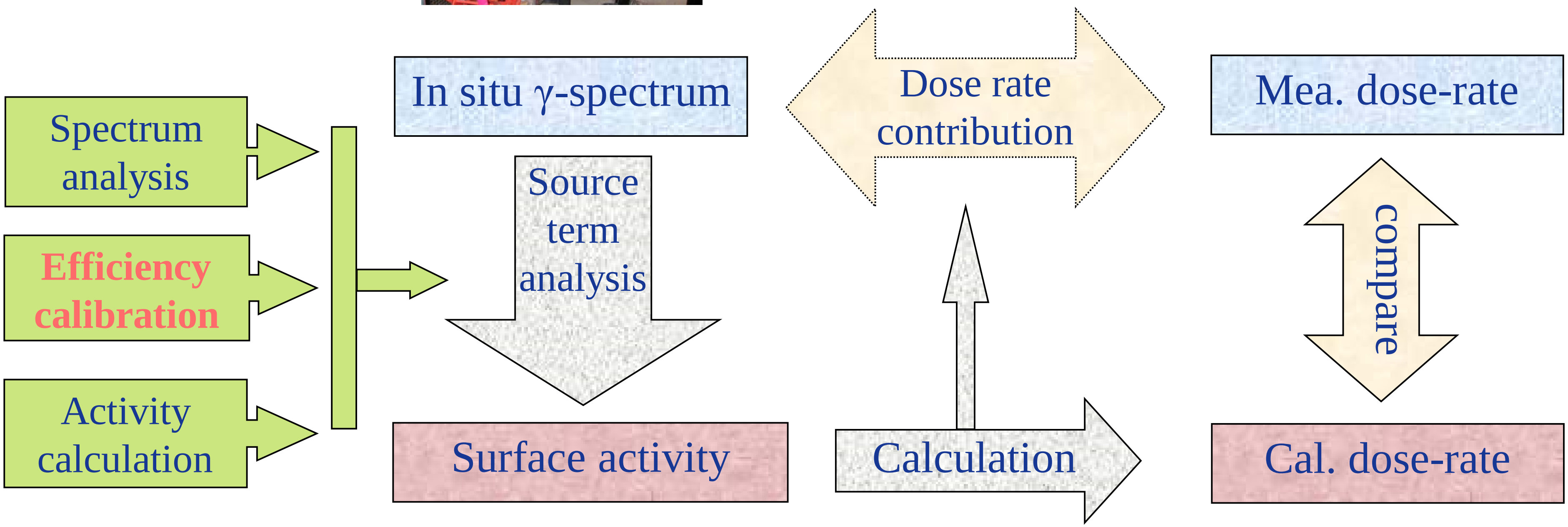


Relative deviation: ±15%.

Data interpretation

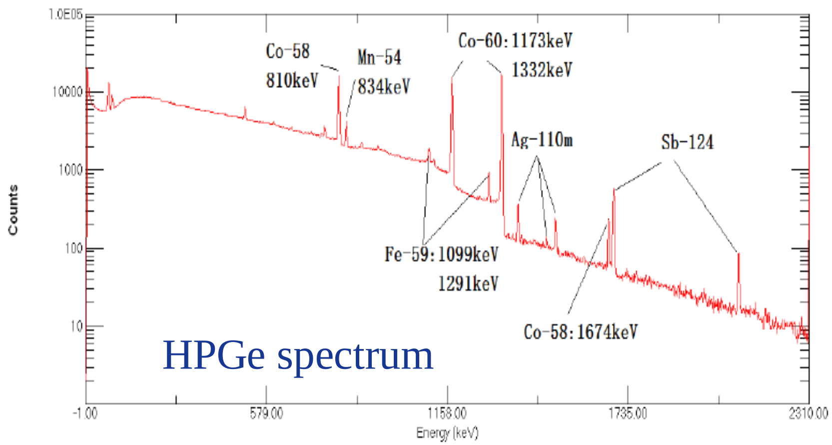




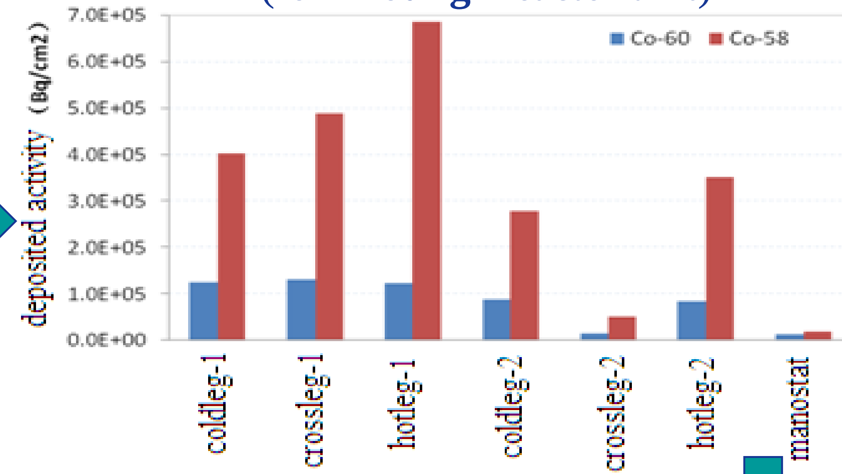


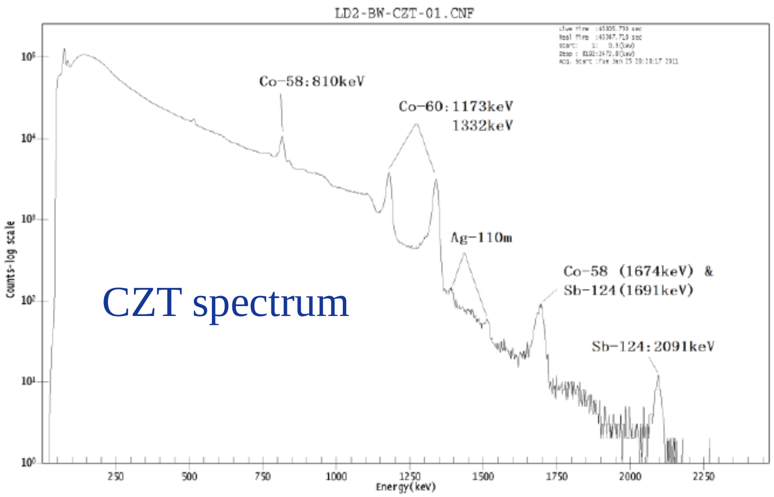
Data analysis framework of in-situ radiological characterization

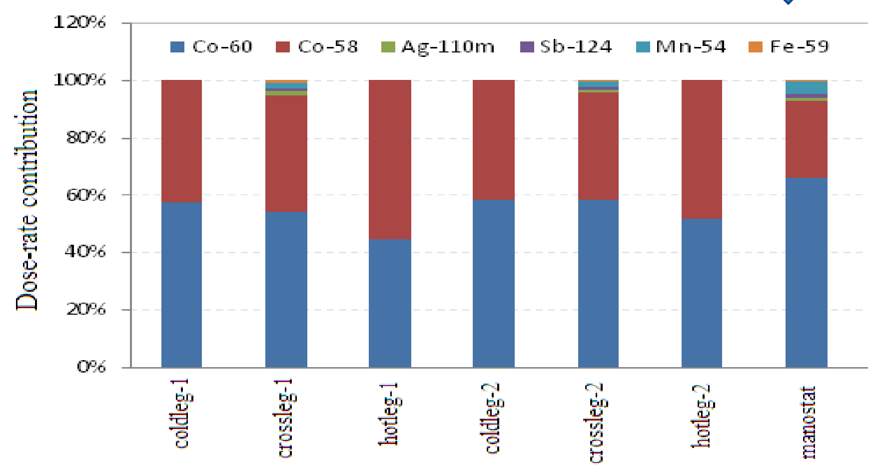
Data interpretation



Surface activity of RCS pipes
(for "**Young**" reactor unit)







Dose-rate contribution of radionuclides

Data interpretation

❖ Measured source term between Sterm-CZT and -HPGe

CZT

isotope	energy (keV)	activity (Bq/cm^2)	Ave. activity (Bq/cm^2)	Dose-rate contribution	Cal. Dose rate(μSv/h)	Measured dose rate （μSv/h）
^{60}Co	1173.2 1332.5	1.79E+04 1.37E+04	**1.58E+04**	80%	**31**	48.4
^{58}Co	810.8	1.98E+04	**1.98E+04**	20%		

HPGe

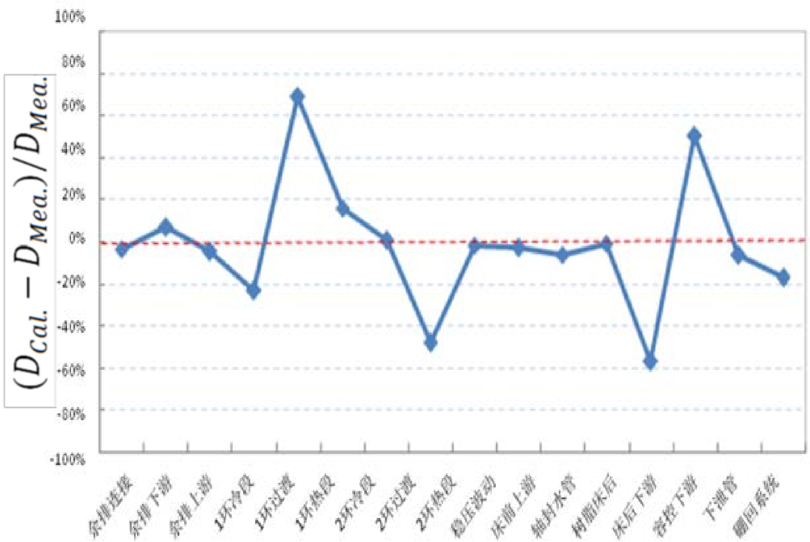
isotope	energy (keV)	activity (Bq/cm^2)	Ave. activity (Bq/cm^2)	Dose contribution	Cal. Dose rate(μSv/h)	Measured dose rate （μSv/h）
^{60}Co	1173.2 1332.5	1.81E+04 1.64E+04	**1.72E+04**	67%	**40**	48.4
^{58}Co	1674 810.8	3.35E+04 2.40E+04	**2.88E+04**	23%		
^{110m}Ag	1505 1384.3	1.76E+03 1.86E+03	1.81E+03	5%		
^{124}Sb	1691	2.98E+02	2.98E+02	1%		
^{59}Fe	1291.6 1099.25	9.58E+02 1.07E+03	1.01E+03	2%		
^{54}Mn	834.83	2.96E+03	2.96E+03	2%		

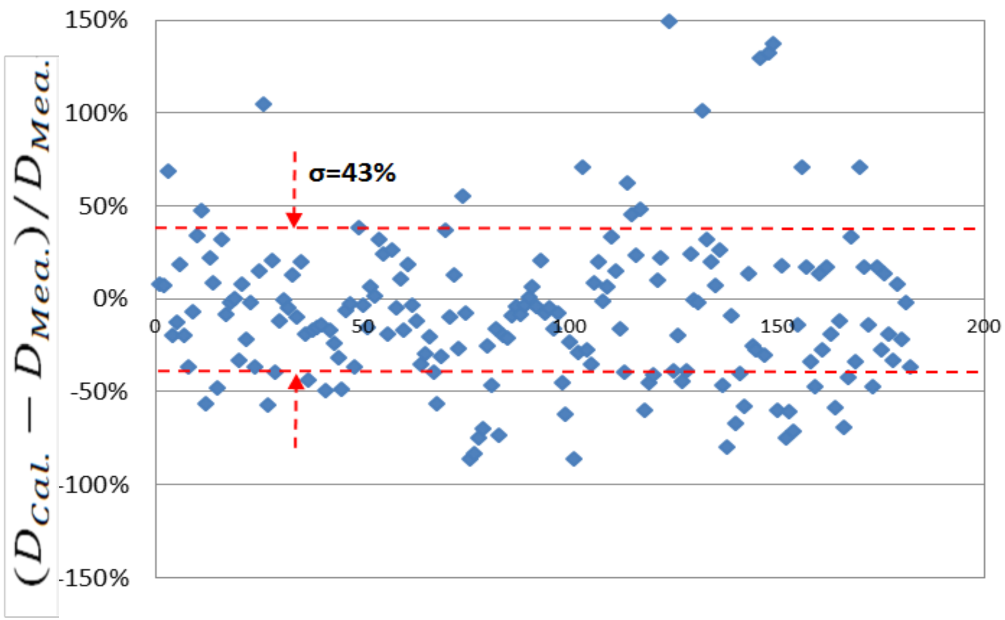
The differences of measured activity between Sterm-CZT and –HPGe are usually less than 30% for key radionuclides (e.g. Co-60, Co-58).

Data interpretation

Uncertainty estimation

- The overall on-site measurement uncertainty induced from different input-factors, such as detector's position/efficiency/spectrum analysis, is estimated as ~50% for key radionuclides.
- The standard relative deviation between calculated dose-rate and measured one is 43% based on a large number of measurement pipes (~190), which is accordance with the above estimated uncertainty (~50%)





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Radionuclides

- Almost all of the corrosion products indicated in ISOE report has been observed in QinShan-II NPP, except Fe-55 and Mn-56 for which the photons energy is too low or the half-life is too short.

Main contributors of Qinshan-II

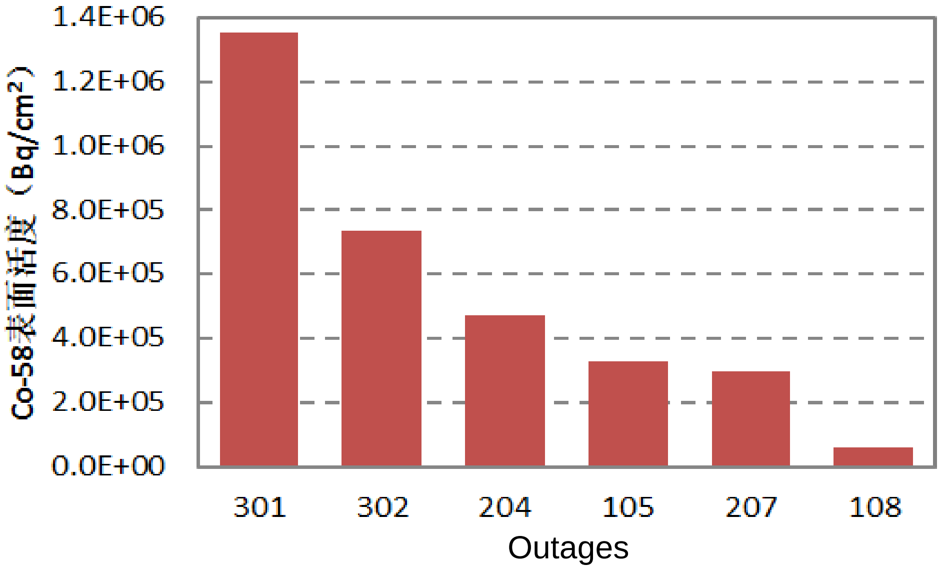
Main radionuclides	Co-60、Co-58、$Ag-110^m$、Fe-59、Mn-54、Zr-95、Zn-65、Nb-95、Cr-51、Sb-124
RCS (RCP)	Co-60、Co-58
RHRS (RRA)	Co-60、Co-58、$Ag-110^m$(later phase)
CVCS (RCV)	Co-60、Co-58、$Ag-110^m$(later phase)
BRS (REP)	Co-60、Co-58、$Ag-110^m$(later phase)

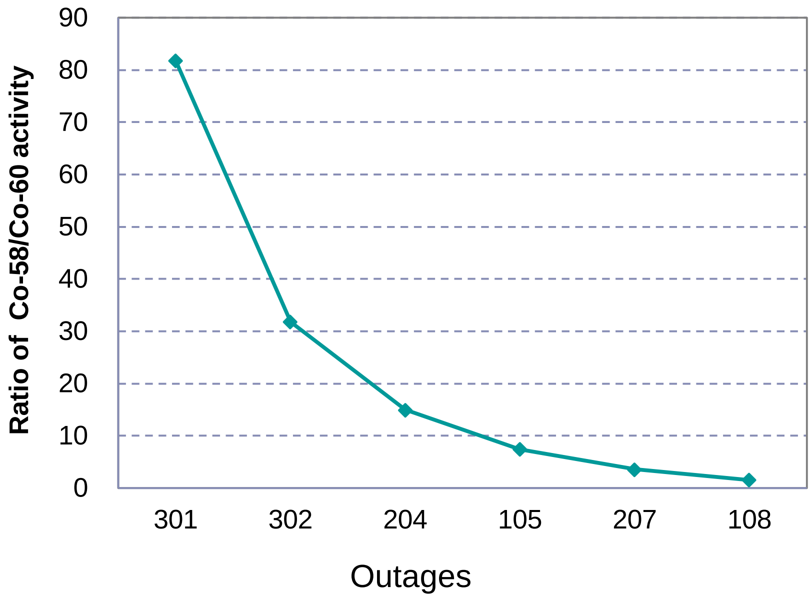
Compared with ISOE report

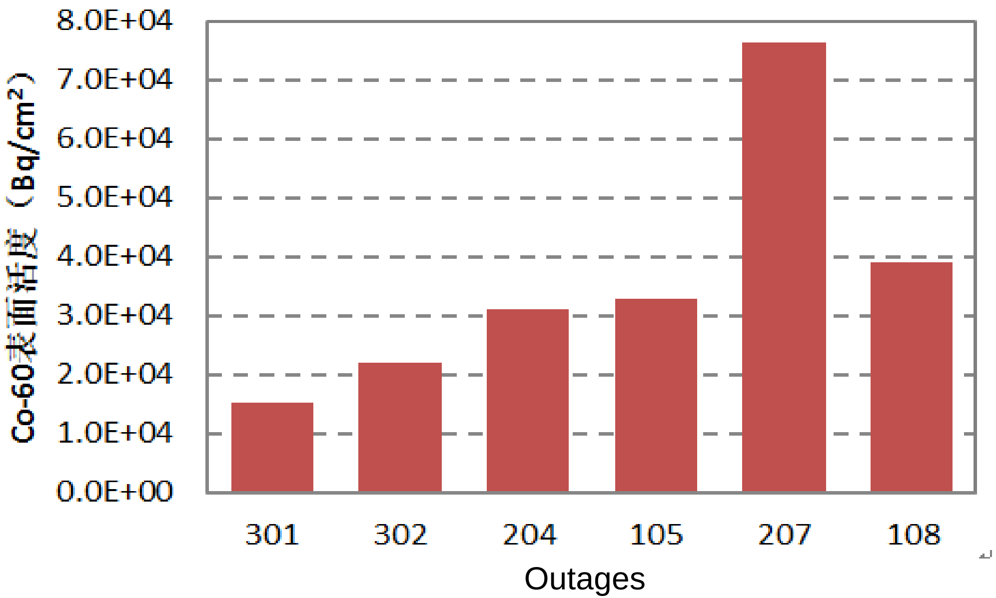
Radionuclide	Half Life	Activation Reaction	Major Source
^{51}Cr	27.702 days	^{50}Cr (n, γ) ^{51}Cr	Stainless steel and nickel based alloy
^{54}Mn	312.1 days	^{54}Fe (n,p) ^{54}Mn	Stainless steel and nickel based alloy
^{55}Fe	2.73 years	^{54}Fe (n, γ) ^{55}Fe	Stainless steel and nickel based alloy
^{56}Mn	2.578 hours	^{55}Mn (n, γ) ^{56}Mn	Stainless steel and nickel based alloy
^{58}Co	70.88 days	^{58}Ni (n,p) ^{58}Co	Nickel alloys
^{59}Fe	44.51 days	^{58}Fe (n, γ) ^{59}Fe	Stainless steel and nickel based alloy
^{60}Co	5.271 years	^{59}Co (n,γ) ^{60}Co	Stellite™ and cobalt bearing components
^{65}Zn	243.8 days	^{64}Zn (n, γ) ^{65}Zn	Natural zinc injection
^{95}Nb	34.97 days	^{95}Zr decay	Fuel cladding (Zircaloy, Zirlo™, etc.)
^{95}Zr	64.02 days	^{94}Zr (n, γ) ^{95}Zr	Fuel cladding (Zircaloy, Zirlo™, etc.)
^{110m}Ag	249.8 days	^{109}Ag (n, γ) ^{110m}Ag	Silver-Indium-Cadium Control rod wear, Helicoflex™ seals
^{124}Sb	60.20 days	^{123}Sb (n, γ) ^{124}Sb	Secondary start-up source, RCP bearings, impurities

Specific Activity (Bq/cm^2)

- Specific activity of Co-58 and Co-60 changes along with the NPP's operating ages (Qinshan-II).
  - Co-58: decreasing
  - Co-60: increasing

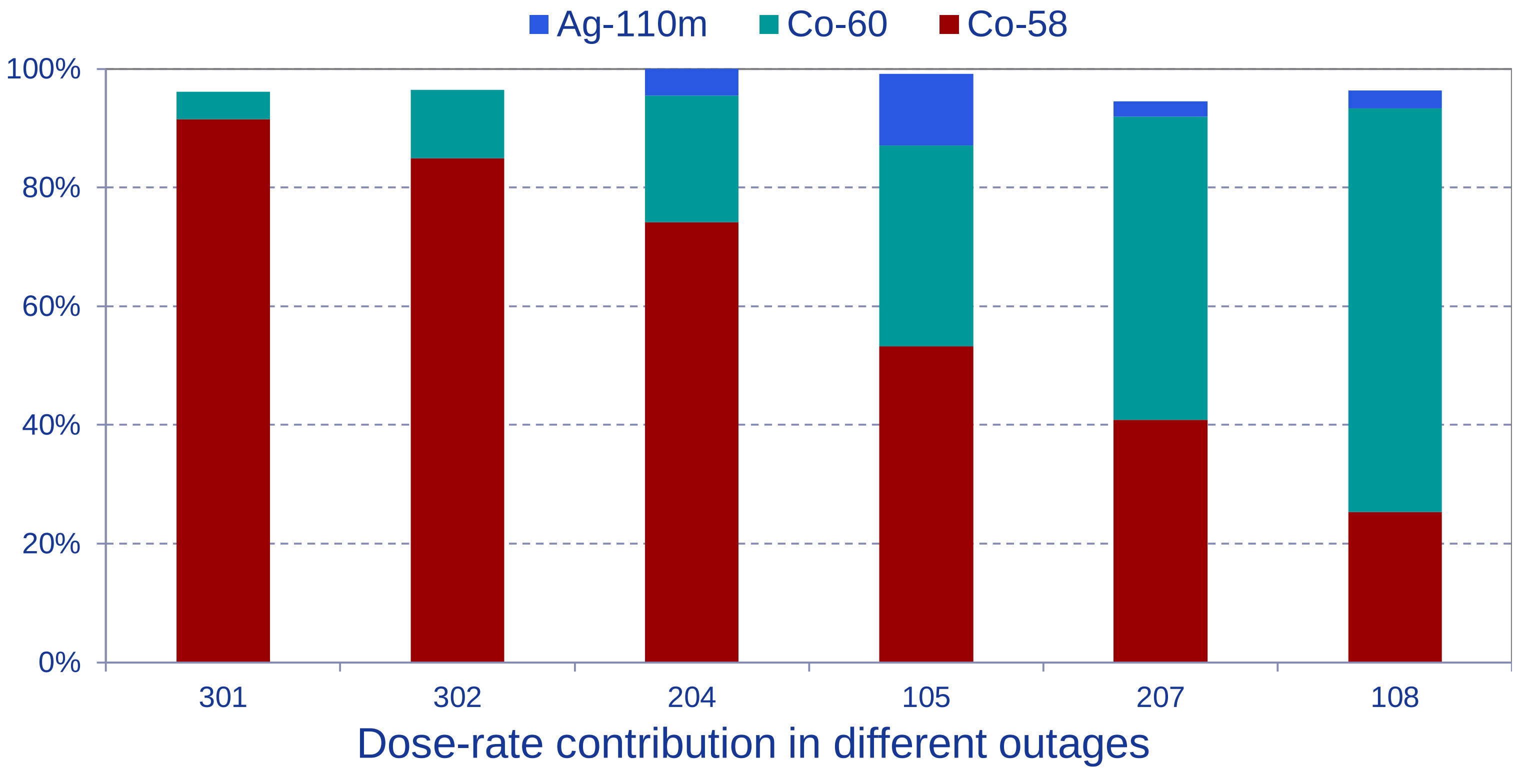






Dose-rate contribution

- Dose-rate contribution of Co-60, Co-58, and Ag-110m in different outages for Qinshan-II.
  - Co-58: ~90% at 1st outage, then decreases to ~20% at 8th outage.
  - Co-60: ~5% at 1st outage, then increases to ~70% at 8th outage.
  - Ag-110m: Major contribution for CVCS at 4th and 5th outages.



Conclusions

- Two in-situ gamma spectroscopy measurement systems, called Sterm-HPGe/CZT, have been developed based on numerical calibration technique.
- Since 2005, twenty measurement campaigns have been carried out for activated-corrosion source term characterization and dose assessment in China's nuclear power plants.
- The specific activity of corrosion products and their dose-rate contribution to external radiation field are analyzed. The measured results can also be used as inputs for future 3D dose simulation research for NPPs.
- More measurement program is now being planned.

谢谢大家！

Thanks for your attention