International Workshop on Age-Related Degradation of Reactor Vessels and Internals
23-24 May 2019, NRC, USA

Current Status of Aging Management on Reactor Vessels in Korea (focusing on surveillance test)

Tae-Kwang Song, Yong-Beum Kim
KINS

Table of Contents

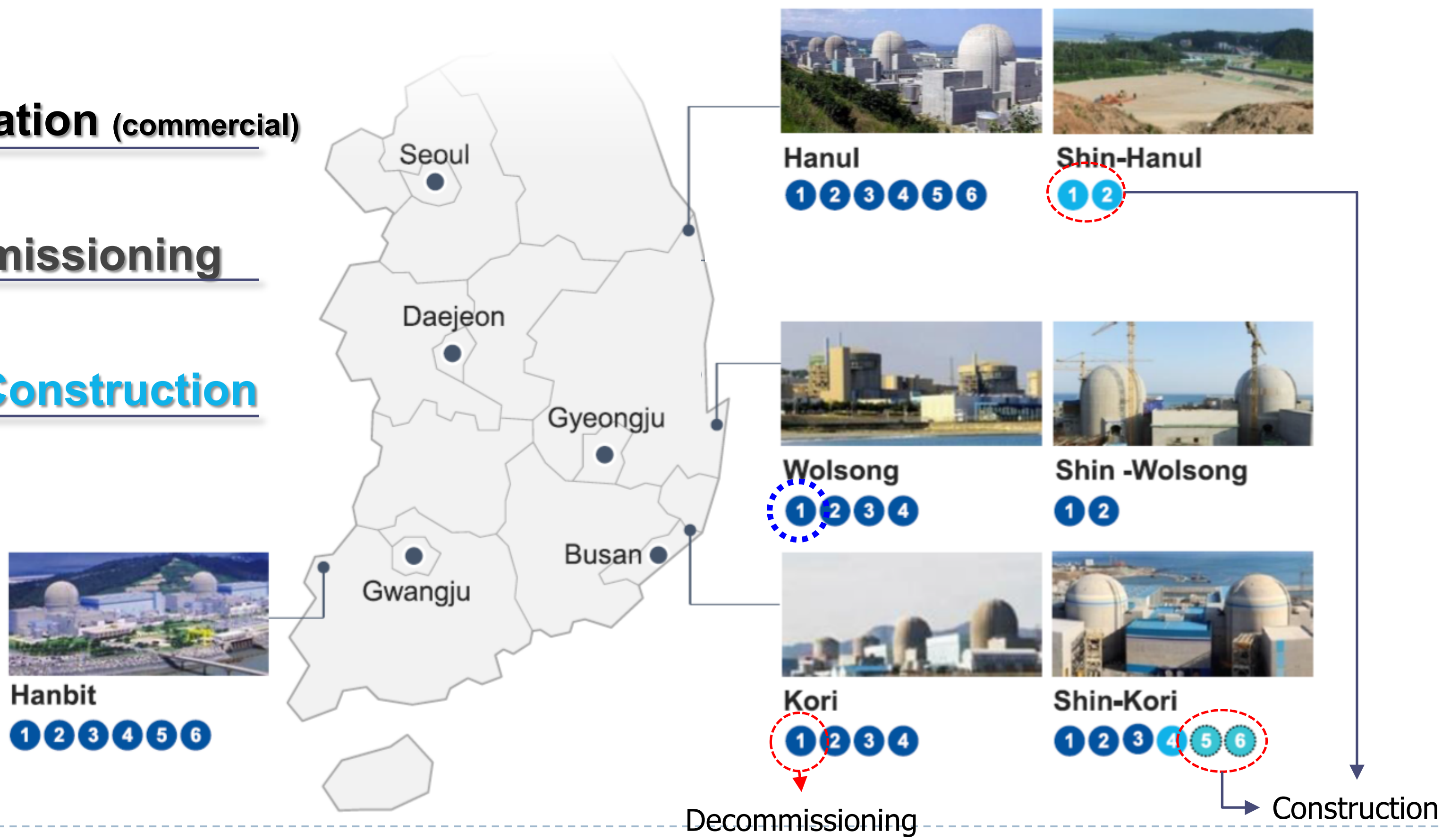
Overview of NPPs in Korea (1)

- Status of Nuclear Power Plants in Korea
  - As of May 2019

In Operation (commercial)
24 Units

Decommissioning
1 Unit

Under Construction
5 Units



Overview of NPPs in Korea (2)

Current Status of Operating NPPs

Site	Unit	MW	Reactor Type	Commercial Operation
Kori	2 3 4	650 950 950	Westinghouse Westinghouse Westinghouse	July 1983 Sep. 1985 April 1986
Shin-Kori	1 2 3	1000 1000 1400	OPR-1000 OPR-1000 APR-1400	April 2011 July 2012 Dec. 2016
Wolsong	1 2 3 4	679 700 700 700	PHWR PHWR PHWR PHWR	April 1983 July 1997 July 1998 Oct. 1999
Shin-Wol song	1 2	1000 1000	OPR-1000 OPR-1000	July 2012 July 2015
Hanbit	1 2 3 4 5 6	950 950 1000 1000 1000 1000	Westinghouse Westinghouse OPR-1000 OPR-1000 OPR-1000 OPR-1000	Aug. 1986 June 1987 Mar. 1995 Jan. 1996 May 2002 Dec. 2002
Hanul	1 2 3 4 5 6	950 950 1000 1000 1000 1000	Framatome Framatome OPR-1000 OPR-1000 OPR-1000 OPR-1000	Sep. 1988 Sep. 1989 Aug 1998 Dec 1999 July 2004 April 2005

Overview of NPPs in Korea (3)

Reactor Types

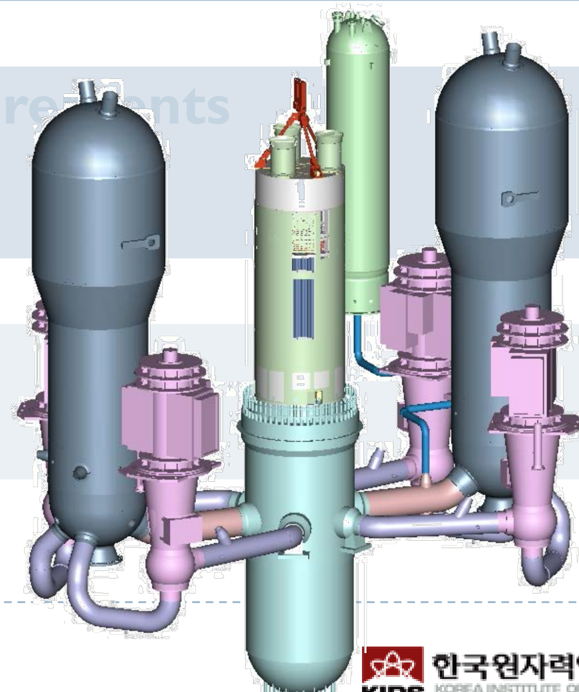
"different reactor type(WH vs KSNP)"

"different design life(40 yrs vs 60 yrs)"

Westinghouse Type	• Kori Units 1~4, Hanbit* Units 1&2
Framatome Type	• Hanul** Units 1&2
KSNP**** Type (OPR-1000)	• Hanbit Units 3~6, Hanul Units 3~6 • Shin***-Kori Units 1&2, Shin-Wolsong Units 1&2
KSNP Type (APR-1400)	• Shin-Kori Units 3~6, Shin-Hanul Units 1&2
PHWR Type	• Wolsong Units 1~4

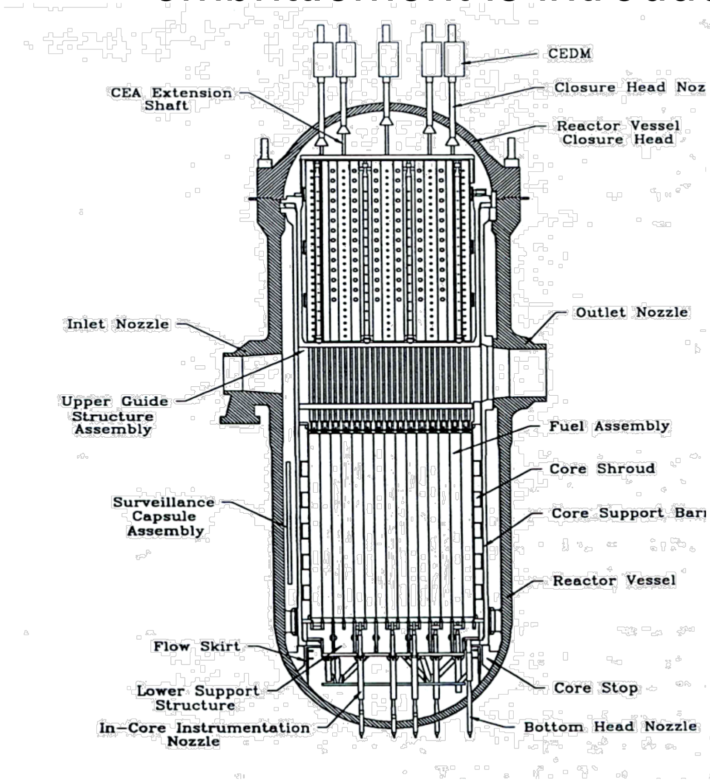
* Former name is Younggwang
** Former name is Uljin
*** The term of 'Shin-, 新' means 'new'
**** KSNP(Korea Standard Nuclear Plant) has been developed based on CE type reactor

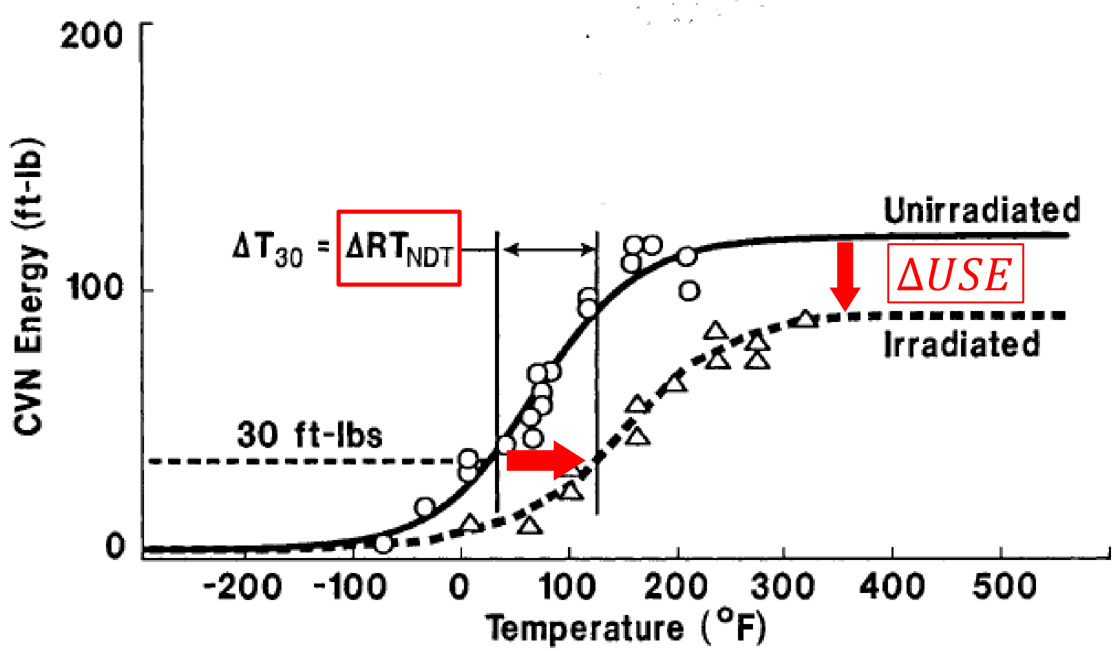
Contents



Irradiation Embrittlement

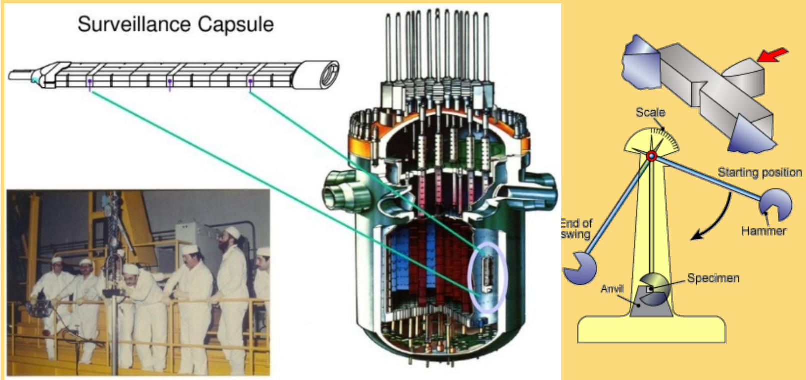
- Irradiation Embrittlement
  - If fast neutron fluence(E≥1.0MeV) exceeds 10^{17} n/cm^2, irradiation embrittlement is introduced in typical low alloy ferritic RPV material



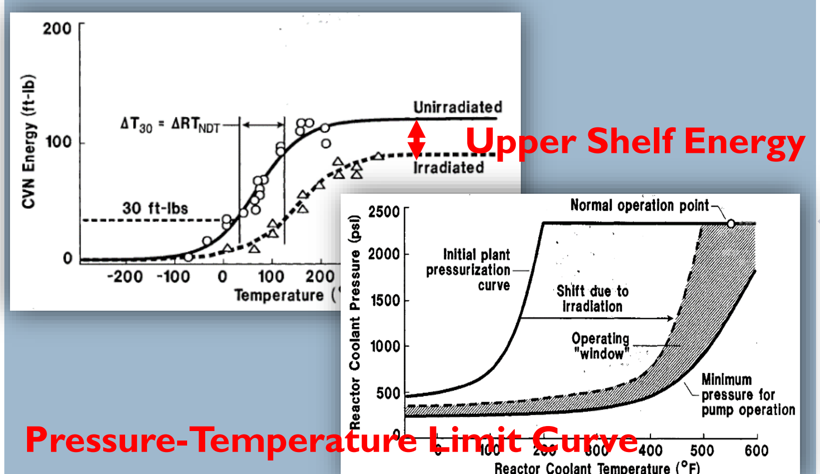


$$Adjusted\ RT_{NDT} = Initial\ RT_{NDT} + \Delta RT_{NDT} + Margin$$

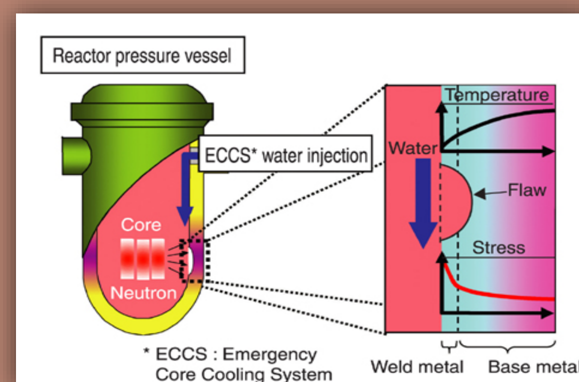
Requirements on Surveillance Test



Requirements on Fracture Toughness



Requirements on Pressurized Thermal Shock



NSSC : Nuclear Safety and Security Committee

Requirements on Surveillance Test

Korea
- NSSC Notice 2017-20
- KINS/RG N6.02

USA
- 10 CFR 50 App. H
- Reg. Guide 1.99
- ASTM E185-82

Requirements on Fracture Toughness

Korea
- NSSC Notice 2017-20
- KINS/RS 6.4.1.5
  KINS/RS 6.4.2.1
- KEPIC MI, Appendix E, G, K

USA
- 10 CFR 50 App. G
- Reg. Guide 1.99
  Reg. Guide 1.161
- ASME Section XI, Appendix E, G, K

Requirements on Pressurized Thermal Shock

Korea
- NSSC Notice 2017-29
- KINS/RS 6.4.2.2

USA
- 10 CFR 50.61
- 10 CFR 50.61a

Surveillance Test Requirements

- Surveillance Test
  - to monitor changes in the fracture toughness properties of ferritic materials in the reactor vessel beltline region which result from exposure of these materials to neutron irradiation and the thermal environment
- NSSC Notice 2017-20 and 10 CFR 50, App. H
  - require to perform surveillance program
  - based on ASTM E185-82
- ASTM E185-82 provide surveillance program including
  - surveillance materials
  - type of specimens
  - number of specimens
  - location of capsules
  - number of capsules
  - withdrawal schedule

Withdrawal Schedule in ASTM E185-82

		Predicted Transition Temperature Shift at Vessel Inside Surface		
		≤ 56℃ (≤100 ℉)	>56 ℃(≤100 ℉) ≤ 111 ℃ (≤200 ℉)	〉 111℃ (>200 ℉)
Minimum Number of Capsules		3	4	5
Withdrawal Sequence	First	6[A]	3[A]	1.5[A]
	Second	15[B]	6[C]	3[D]
	Third	EOL[E]	15[B]	6[C]
	Fourth	-	EOL[E]	15[B]
	Fifth	-	-	EOL[E]

[A] Or at the time when the accumulated neutron fluence of the capsule exceeds 5X10^{22} n/m^2 (5X10^{18} n/cm^2), or at the time when the highest predicted ΔRT_{NDT} of all encapsuled materials is approximately 28℃(50℉), whichever comes first.

[B] Or at the time when the accumulated neutron fluence of the capsule corresponds to the approximately EOL fluence at the reactor vessel inner wall location, whichever comes first.

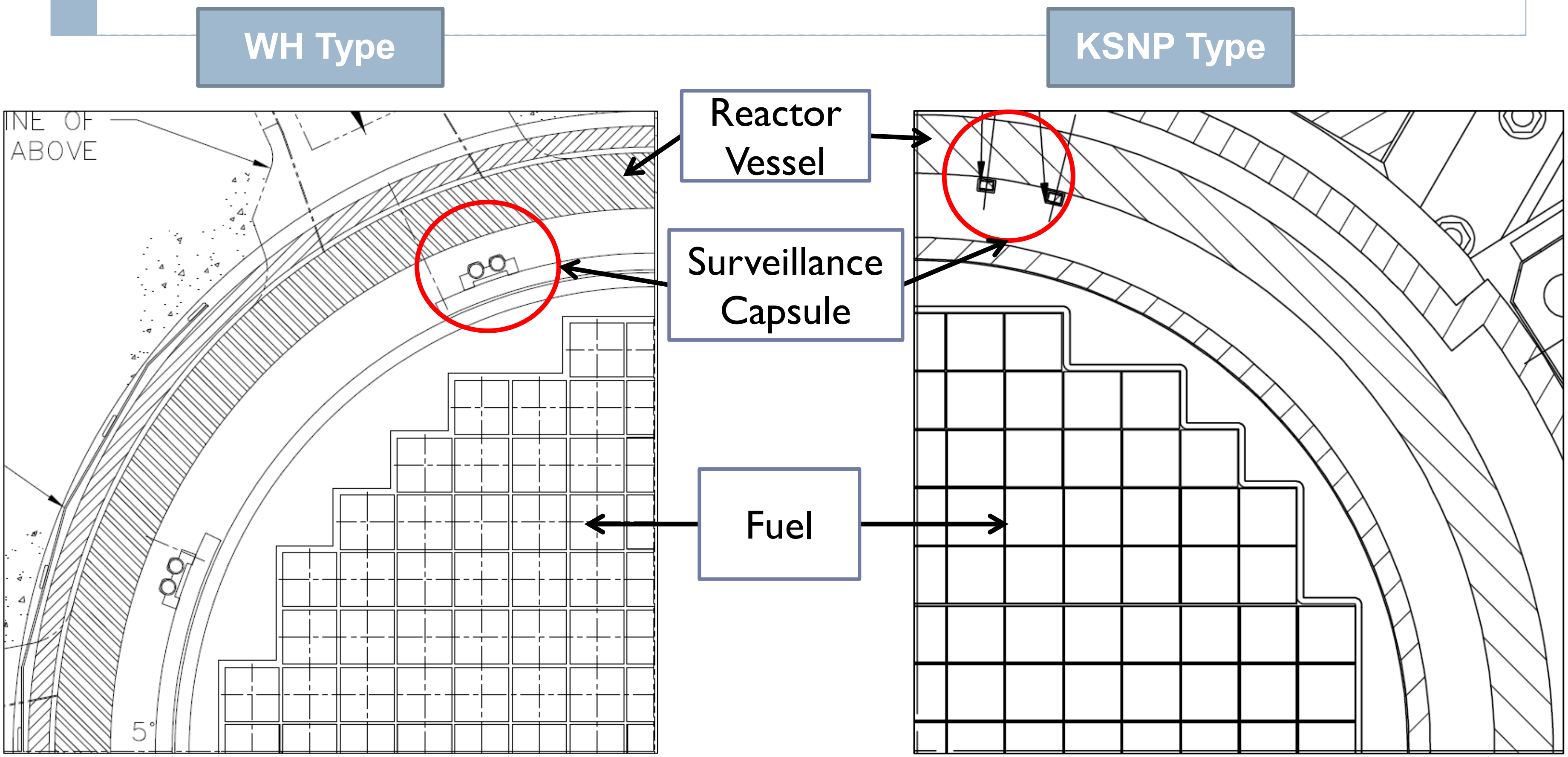
[C] Or at the time when the accumulated neutron fluence of the capsule corresponds to the approximately EOL fluence at the reactor vessel ¼ T location, whichever comes first.

[D] Or at the time when the accumulated neutron fluence of the capsule corresponds to a value midway between that of the first and third capsules.

[E] Not less than once or greater than twice the peak EOL vessel fluence. This may be modified on the basis of previous tests. This capsule may be held without testing following withdrawal.

EFPY, Effective Full Power Year

Issue 1: Lead Factor



❑ Lead Factor

- WH Type : 2.9 ~ 3.5
- KSNP Type : ~1.3

$$\text{Lead Factor} = \frac{\text{Fluence of Surveillance Capsule}}{\text{Fluence of Vessel Wall}}$$

Withdrawal Schedule of WH Type Reactor

❑ Assumption
- 40 years design life
- predicted transition shift at vessel inside surface < 56℃

Sequence	Schedule	Remarks
First	< 6 EFPY	- Earlier one of [6EFPY, the time when the accumulated neutron fluence of the capsule exceeds 5X10^{22} n/m^{2}]
Second	9 EFPY	- 15 EFPY or at the time when the accumulated neutron fluence of the capsule corresponds to the approximately EOL fluence at the reactor vessel inner wall location, whichever comes first - Earlier one of [15EFPY, 9.4 EFPY] = 32 EFPY/ 3.4 (lead factor)
Third	14 EFPY	- Not less than once or greater than twice the peak EOL vessel fluence - Between [1.0 EOL, 2.0 EOL] - If third surveillance is performed at 14 EFPY, 48 EFPY data would be obtained = 48 EFPY / 3.4 (lead factor)

Possible to obtain EOL(40 years) data

Possible to obtain CO(60 years) data

CO : Continued Operation (extended life to 60 yrs)

Withdrawal Schedule of KSNP Type Reactor

❑ Assumption
- 40 years design life
- predicted transition shift at vessel inside surface < 56°C

Sequence	Schedule	Remarks
First	< 6 EFPY	- Earlier one of [6EFPY, the time when the accumulated neutron fluence of the capsule exceeds $5X10^{22}$ n/m^2]
Second	15 EFPY	- 15 EFPY or at the time when the accumulated neutron fluence of the capsule corresponds to the approximately EOL fluence at the reactor vessel inner wall location, whichever comes first - Earlier one of [15EFPY, 24.6 EFPY] = 32 EFPY/ 1.3 (lead factor)
Third	32 EFPY	- Not less than once or greater than twice the peak EOL vessel fluence - Between [1.0 EOL, 2.0 EOL] - If third surveillance is performed at 32 EFPY, 42 EFPY data would be obtained = 42 EFPY / 1.3 (lead factor)

Impossible to obtain EOL(40 years) data

Impossible to obtain CO(60 years) data

CO : Continued Operation (extended life to 60 yrs)

Obtaining EOL(40 years) Data

- Adjusted withdrawal schedule was submitted for Operation License Review

Sequence	Withdrawal Schedule (EFPY)											
	Hanbit				Hanul				Shin-Kori		Shin-Wolsong	
	3	4	5	6	3	4	5	6	1	2	1	2
First	6.20	6.02	6.49	6.54	6.61	6.57	6.93	7.16	6 *	6 *	6 *	6 *
Second	14.60	14.88	15*	15*	15.7	15*	15*	15*	15*	15*	15*	15*
Third	26*	26*	26*	26*	23*	23*	23*	23*	26*	26*	26*	26*
4th~6th	Standby	Standby	Standby	Standby	Standby	Standby	Standby	Standby	Standby	Standby	Standby	Standby

Source: FSAR of each plant. As of April 2018

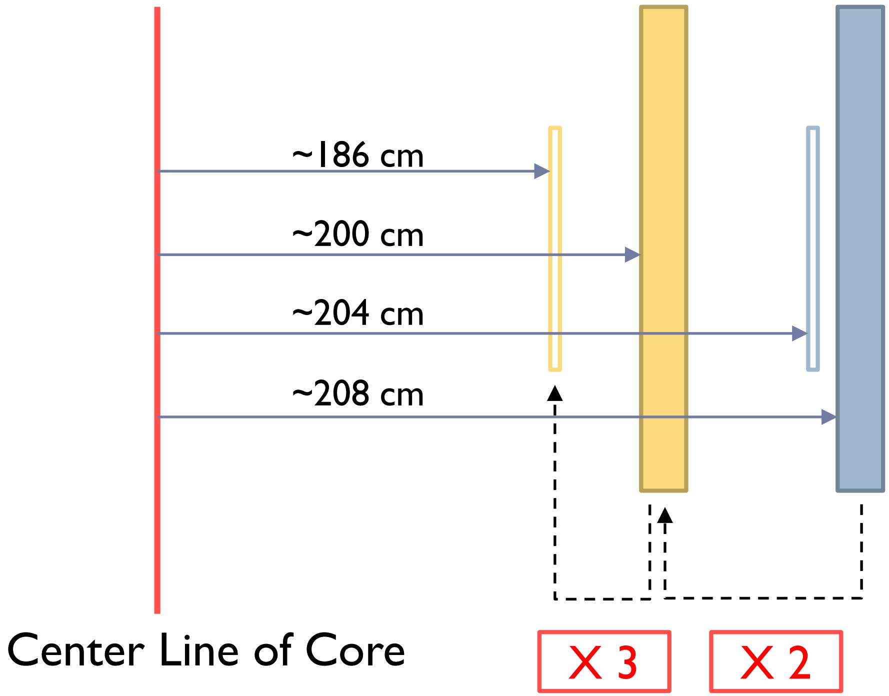
* : planned schedule (not performed)

Obtaining CO(60 years) Data (1)

- Accelerated Surveillance Test using WH reactors
  - New surveillance capsules were fabricated using archive materials of KSNP reactors, then inserted into WH reactors during 2014~2016

KSNP Reactors	WH Reactors	Remarks
Hanbit 3	Hanbit 1	two additional surveillance capsules per each KSNP reactor (one for 60 years, another for 80 years)
Hanbit 4		
Hanbit 5	Hanbit 2	
Hanbit 6		
Hanul 3	Kori 3	
Hanul 4		
Hanul 5	Kori 4	
Hanul 6		

Obtaining CO(60 years) Data (2)

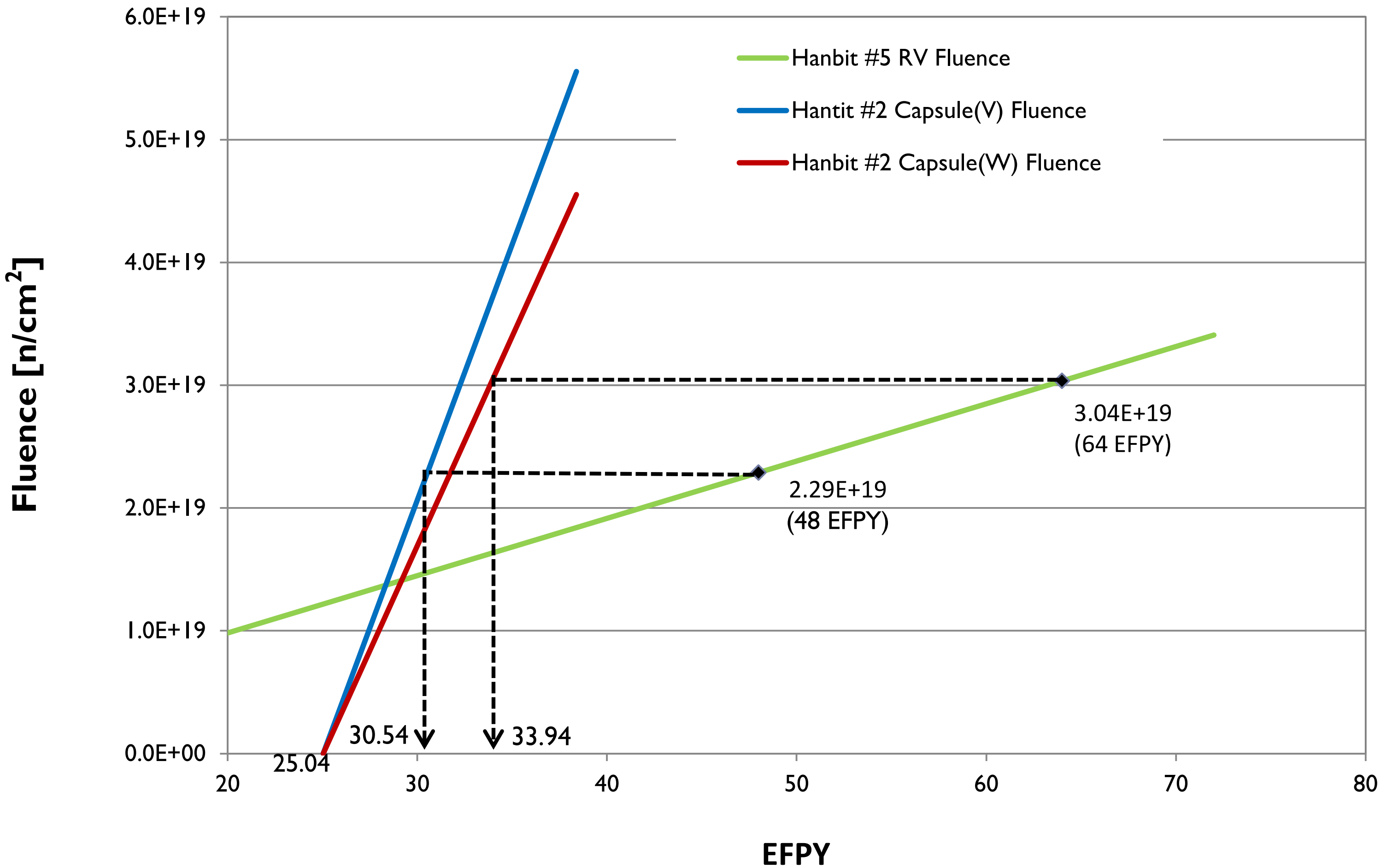


- WH Surveillance Capsule
- WH Vessel
- KSNP Surveillance Capsule
- KSNP Vessel

$$\text{Relative Lead Factor} = \frac{\text{Fluence of WH SC}}{\text{Fluence of KSNP Vessel Wall}}$$

Plant	Location		Flux	Relative Lead Factor*
Hanbit 2	Surveillance Capsule	V(107°)	1.32E+11	8.73
		W(110°)	1.08E+11	7.19
	RV Inner wall		3.59E+10	-
Hanbit 5	RV inner wall		1.50E+10	-

Obtaining CO(60 years) Data (3)



Issue 2: 60 years Design Life

- Current withdrawal schedule
  - Based on 40 years design life
    - ASTM E185-82 7.6.2 "The withdrawal schedule is in terms of effective full-power years of the vessel with a design life of 32 EFPY"
  - Difficult to apply directly to 60 years design life reactors
  - Design life of APR 1400 reactor is 60 years

New criteria for withdrawal schedule is needed

- Design Life, Operating License Period, Continued Operation
  - Operating license period varies from country to country
    - (Korea) operating license period is determined by the design life of reactors
    - (USA) In AEA sec.103, "license shall be issued for a specified period,•••, but not exceeding 40 years
  - Design Life, LR(License Renewal), SLR(Subsequent License Renewal)…

Issue 2: 60 years Design Life

- Revision of Withdrawal Schedule in ASTM E185
  - Based on combination of Reactor Year and Fluence (E185-82)
  - Based on Fluence (since E185-02)

E185-82

TABLE 1 Minimum Recommended Number of Surveillance Capsules and Their Withdrawal Schedule (Schedule in Terms of Effective Full-Power Years of the Reactor Vessel)

	Predicted Transition Temperature Shift at Vessel Inside Surface: ≤56°C (≤100°F)	>56°C (>100°F) ≤111°C (≤200°F)	>111°C (>200°F)
Minimum Number of Capsules	3	4	5
Withdrawal Sequence:			
First	6^A	3^A	1.5^A
Second	15^B	6^C	3^D
Third	EOL^E	15^B	6^C
Fourth		EOL^E	15^B
Fifth			EOL^E

^A Or at the time when the accumulated neutron fluence of the capsule exceeds 5 × 10²² n/m²(5 × 10¹⁸ n/cm²), or at the time when the highest predicted ΔRT_{NDT} of all encapsulated materials is approximately 28°C (50°F), whichever comes first.
^B Or at the time when the accumulated neutron fluence of the capsule corresponds to the approximate EOL fluence at the reactor vessel inner wall location, whichever comes first.
^C Or at the time when the accumulated neutron fluence of the capsule corresponds to the approximate EOL fluence at the reactor vessel ¼ T location, whichever comes first.
^D Or at the time when the ac... apsule corresponds to a value midway be...
^E Not less than once or greater... This may be modified on the basis of pr... ithout testing following withdrawal.

- End Of Life & Fluence

E185-02

LE 1 Suggested Withdrawal Schedule

Sequence	Target Fluence	Priority
First	5×10^{18} n/cm²(5×10^{22} n/m²) for PWRs; $E > 1$ MeV	2 (Required if $\Delta RT_{NDT} > 56°C$ [100°F])
Second	EOL ¼-T	1 (Required for all materials)
Third	EOL ID	1 (Required for all materials)
Fourth	(EOL ¼-T - 1st Capsule)/2	3 (Required if $\Delta RT_{NDT} > 111°C$ [200°F])
Subsequent	Supplemental Evaluations	Not Required

E185-16

TABLE 1 Recommended Withdrawal Schedule

Sequence	Target Fluence	Notes
First	¼ MDF	Testing Required
Second	½ MDF	Testing Required
Third		Testing Required
Fourth		Testing Required
Standby		Testing Not Required

- End of License Fluence
- Maximum Design Fluence

Proposed Withdrawal Schedule in Korea

		Predicted Transition Temperature Shift at Vessel Inside Surface		
		≤ 56℃ (≤100 ℉)	>56 ℃(≤100 ℉) ≤ 111 ℃ (≤200 ℉)	〉 111℃ (>200 ℉)
Minimum Number of Capsules		4 ~~3~~	4	5
Withdrawal Sequence	First	A ~~6~~[A]	A ~~3~~[A]	A ~~1.5~~[A]
	Second	C ~~15~~[B]	C ~~6~~[C]	D ~~3~~[D]
	Third	B ~~EOL~~[E]	B ~~15~~[B]	C ~~6~~[C]
	Fourth	E -	E ~~EOL~~[E]	B ~~15~~[B]
	Fifth	-	-	E ~~EOL~~[E]

A ~~Or~~ at the time when the accumulated neutron fluence of the capsule exceeds $5X10^{22}$ n/m^2 ($5X10^{18}$ n/cm^2), or at the time when the highest predicted ΔRT_{NDT} of all encapsuled materials is approximately 28℃(50℉), whichever comes first.

B ~~Or~~ at the time when the accumulated neutron fluence of the capsule corresponds to the approximately EOL fluence at the reactor vessel inner wall location~~, whichever comes first.~~

C ~~Or~~ at the time when the accumulated neutron fluence of the capsule corresponds to the approximately EOL fluence at the reactor vessel ¼ T location~~, whichever comes first~~.

D ~~Or~~ at the time when the accumulated neutron fluence of the capsule corresponds to a value midway between that of the first and third capsules.

E Not less than once or greater than twice the peak EOL vessel fluence. This may be modified on the basis of previous tests. This capsule may be held without testing following withdrawal.

Proposed Withdrawal Schedules in Korea

Application to APR-1400 model

- Assume
  - Lead Factor : 1.4(APR-1400)
  - Calculation of Fluence at ¼ T location: RG-1.99 method $f = f_{surf}(e^{-0.24x})$

Sequence	Schedule	Remarks
First	< 6 EFPY	- At the time when the accumulated neutron fluence of the capsule exceeds $5X10^{22}$ n/m^2]
Second	17 EFPY	- At the time when the accumulated neutron fluence of the capsule corresponds to the approximately EOL fluence at the reactor vessel ¼ T location $= 48 \times \frac{1}{\cong 2} \times \frac{1}{1.4}$ $f = f_{surf}(e^{-0.24x})$ → f @ ¼T= ~$0.5f_{surf}$
Third	34 EFPY	- At the time when the accumulated neutron fluence of the capsule corresponds to the approximately EOL fluence at the reactor vessel inner wall location $= 48 \times \frac{1}{1.4}$ (design life/lead factor)
4th~6th	Standby	

Concluding Remarks

- Surveillance test requirement in Korea is presented
  - current surveillance test is based on ASTM E185-82
- Low value of Lead Factor issue was resolved by
  - adjusting withdrawal schedule of KSNP type reactor (40 yrs data)
  - using WH reactor for acceleration surveillance test (60 yrs data)
- Revised withdrawal schedule is proposed to cover all the plant regardless of design life (in processing)