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Factors for IASCC initiation of reactor internal materials of PWRs

황성식, 최민재, 김성우, 김동진

한국원자력연구원, 재료안전기술연구부

한국원자력학회 2023춘계 학술대회

제주, ICC

2023.05.18~19

Korea Atomic Energy Research Institute

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- 내부구조물 균열개시에 미치는 영향인자

Degradation trend in NPPs

Reactor internals

IASCC in Internals
100,000 EFPH
('84)

Worldwide

316SS
195,000 EFPH
(K-1, '07)

Korean

DMW

Alloy 600
PWSCC, BAC
D. Besse('02)

Alloy 600
CRDM PWSCC
('91)

Alloy 600
SG drain pipe
PWSCC
('07, '08, '10)

SG tubings

Alloy 600
SG ODSCC
('71)

Alloy 600
SG ODSCC
('88)

Alloy 600
SG tube
rupture
('02)

Replacement with Alloy 690 ('89~)

1970 1980 1990 2000 2010 2020

Lab data

[IASCC]

- Fluence in K-1, K-2
  > $5x10^{21}$ n/cm^2

[PWSCC]

- Resistance
  Alloy 690 > 600
  (~100 times)
- Alloy 690 ≈ 600 in Cold worked, non homogeneous condition

[ODSCC]

- Cracking rate
  Alloy 690 > 600
  (2~8 times higher in Caustic and Lead contaminated)

DMW: Dissimilar metal welds, IASCC : Irradiation assisted stress corrosion cracking(조사유기 응력부식균열)

Korean R & D activities

- To utilize capabilities of current operating plants by long term operation

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Draft Korean energy policy reflects expansion of nuclear

01 September 2022

Share

South Korea's Ministry of Trade, Industry and Energy (MOTIE) has released a draft long-term energy plan looking 15 years ahead. Under the plan, the proportion of nuclear power will grow to almost one-third of the country's total energy mix by 2030 in a move aimed at boosting energy security and meeting climate goals.

The start up of Shin Hanul units 1 and 2 will help South Korea expand its use of nuclear energy (Image: KHNP)

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Construction of Shin Hanul Units 3 and 4 to Start in 2025

Nuclear Power Plant Operations to Be Extended

By Jung Suk-yee | May 12, 2022, 12:06

The government plans to apply for an extension of the service life of Kori Unit 2 next year.

Long term operation(License Renewal)

- Long Term Low Power Operation in Pressurized Water Reactors (Generic Letter No. 84-21)

UNITED STATES NUCLEAR REGULATORY COMMISSION WASHINGTON, D.C. 20555, October 16, 1984

TO ALL PRESSURIZED WATER REACTOR LICENSEES AND APPLICANTS FOR AN OPERATING LICENSE

Long term operation(License Renewal)

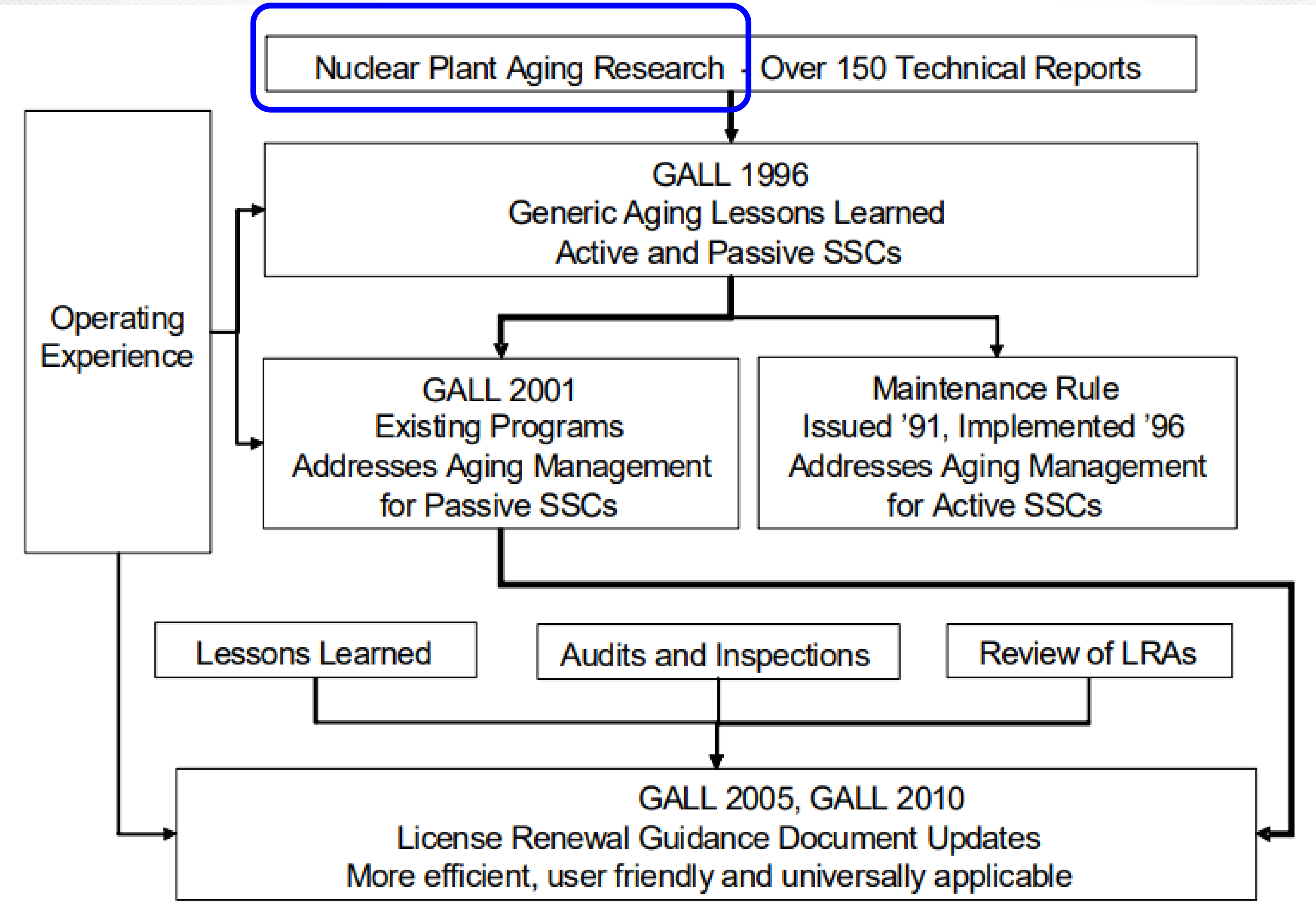
- Reactor License Renewal Overview
  - The Atomic Energy Act and NRC regulations limit commercial power reactor licenses to an initial 40 years but also permit such licenses to be renewed.
  - This original 40-year term for reactor licenses was based on economic and antitrust considerations -- not on limitations of nuclear technology. Due to this selected period, however, some structures and components may have been engineered on the basis of an expected 40-year service life.
  - The NRC has established a timely license renewal process and clear requirements, codified in 10 CFR Part 51 and 10 CFR Part 54, that are needed to assure safe plant operation for extended plant life. The timely renewal of licenses for an additional 20 years, where appropriate to renew them, may be important to ensuring an adequate energy supply for the United States during the first half of the 21st century.
  - Nuclear power comprises approximately 20 percent of all the electric power produced in the United States.

License Renewal Processes

- Introduction to License Renewal Tutorial
  - License renewal, whether initial or subsequent, rests on the determination that operating plants continue to maintain adequate levels of safety and, over the plant's life, this level has been enhanced through maintenance of the licensing bases, with appropriate adjustments to address new information from industry operating experience. Additionally, NRC activities have provided ongoing assurance that the licensing bases will continue to provide an acceptable level of safety. The license renewal review provides an independent examination, asking the following questions:
    - ✓ Does the reactor operator understand the effects of aging on critical safety components?
    - ✓ Has the operator taken appropriate actions to assure safe operation?
  - The following topics will explain the entire license renewal process:
    - ✓ Orientation
    - ✓ Safety
    - ✓ Inspections
    - ✓ Environmental Impact
    - ✓ Hearing
    - ✓ Decision
    - ✓ Review

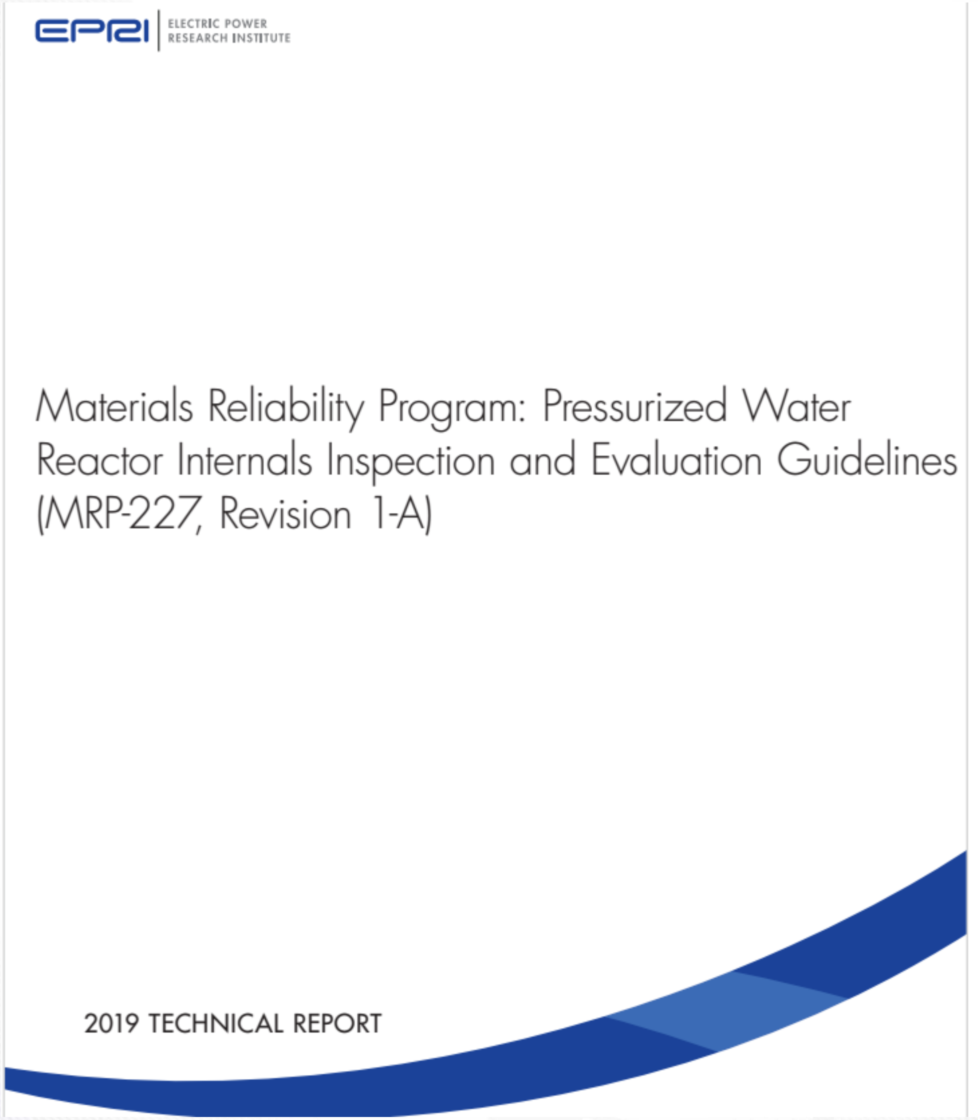
https://www.nrc.gov/reactors/operating/licensing/renewal/introduction.html

License Renewal Processes



https://inis.iaea.org/collection/NCLCollectionStore/_Public/43/130/43130440.pdf

MRP 227


ELECTRIC POWER RESEARCH INSTITUTE

Materials Reliability Program: Pressurized Water Reactor Internals Inspection and Evaluation Guidelines (MRP-227, Revision 1-A)

2019 TECHNICAL REPORT

Long term operation plan in Korea

Permanent shut down plants				
Plant	Document review	Decided	Permitted year	Cont. operation
Kori-1	'06.6~'07.12(19 mo.)	'07.12.11	'07.06.19~'17.06.18	'08.01.09~'17.06.18(9 yrs)
Wolsong-1	'09.12~'15.2(51 mo.)	'15.02.27	'12.11.20~'22.11.19	'15.06.23~'18.06.20(3 yrs)

Design life of 10 units (to be considered for continued operation)										
Plants	Kori-2	Kori-3	Kori-4	HB-1	HB-2	WS-2	WS-3	HU-1	HU-2	WS-4
Design life	'23.04	'24.09	'25.08	'25.12	'26.09	'26.11	'27.12	'27.12	'28.12	'29.02

KHNP, 'Status of continued operation for Korean NPPs', Long life operation symposium, June 15, 2022, Seoul

Long term operation plan in Korea

4. 향후 계속운전 추진에 대한 제언

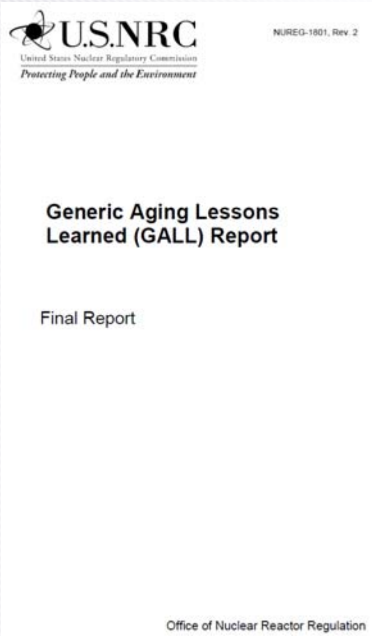
- ❖ (탄소중립) 기후변화 대응을 위한 탄소중립약속 이행과 에너지 안보 확보를 위해서 원전 계속운전확대는 필수
- ❖ (안전강화) 계속운전동안 안전 유지·강화를위해서는 글로벌 영구정지·가동중 원전의 경년열화재료에 대한 자료 확보와 분석에 투자확대가 시급
  - ✓ 고리 1호기, 교체 설비 등 경년열화설비들의 연구용 재료 채취를 허용
- ❖ (최신기술) 원전 전주기 안전강화를 위해 계속운전 단계에는 4차 산업기술 선도적 도입과 지속적으로 투자하고,이에 대한 전문역량 강화가 필요
  - ✓ 디지털트윈, 블록체인, 인공지능 등 안전운영에도움이 되는 R&D 지원을 확대
- ❖ (규제개선) 글로벌 에너지 시장변화·인허가현황을 분석하여 우리나라에 적합한 계속운전 심사기간·절차개선이 바람직함
  - ✓ 예) 가동중 원전 PSR은10년마다 지속 추진, 계속운전은 최소한 20년이상 승인

KPVP 제1회 가동원전의 장기운영 안전성 심포지움

18

염학기, 해외 계속운전 원전의 주요 현황과 이슈KPVP 제1회 가동원전의 장기운영 안전성 심포지움 2022. 6

계속운전 관련 중요문서

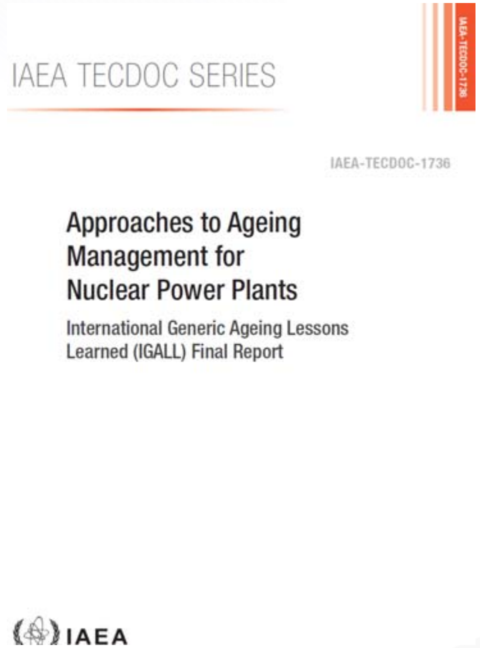

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment
NUREG-1801, Rev. 2

Generic Aging Lessons Learned (GALL) Report

Final Report

Office of Nuclear Reactor Regulation

2010

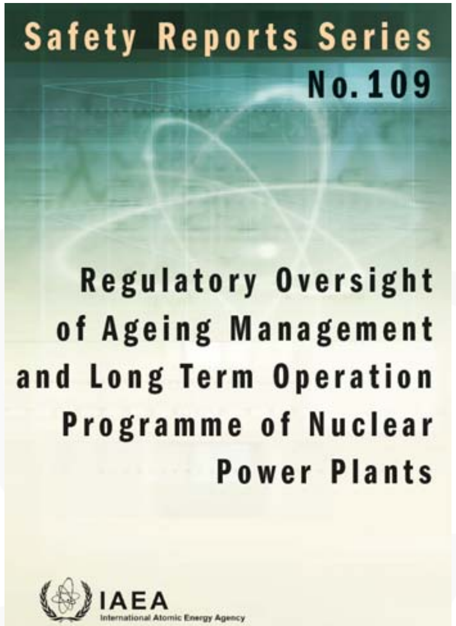

IAEA TECDOC SERIES
IAEA-TECDOC-1736

Approaches to Ageing Management for Nuclear Power Plants

International Generic Ageing Lessons Learned (IGALL) Final Report

IAEA

2014


Safety Reports Series
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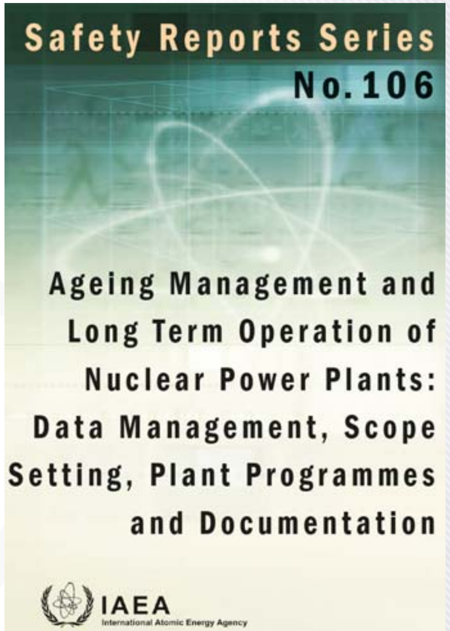
Regulatory Oversight of Ageing Management and Long Term Operation Programme of Nuclear Power Plants

IAEA
International Atomic Energy Agency

2022

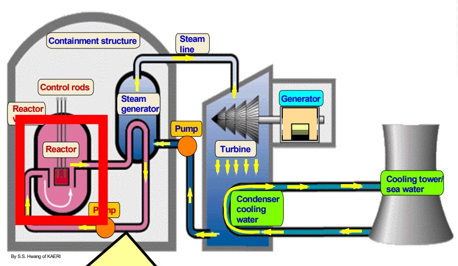

Safety Reports Series
No.106

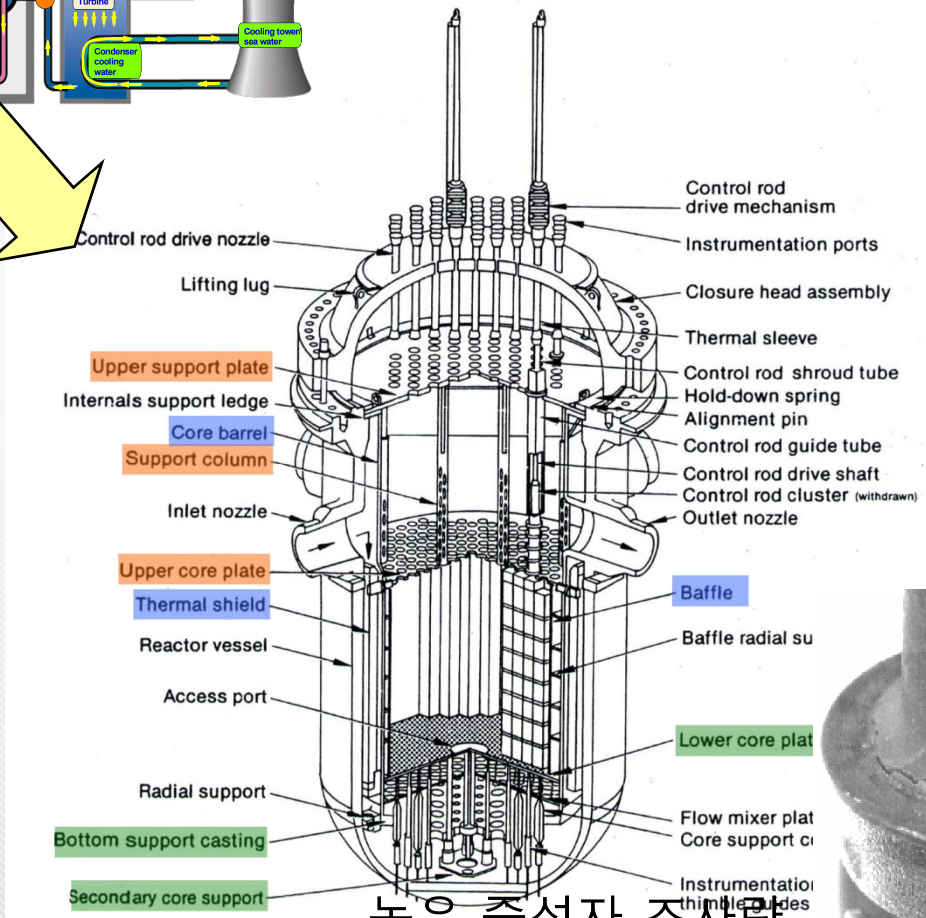
Ageing Management and Long Term Operation of Nuclear Power Plants: Data Management, Scope Setting, Plant Programmes and Documentation

IAEA
International Atomic Energy Agency

2022

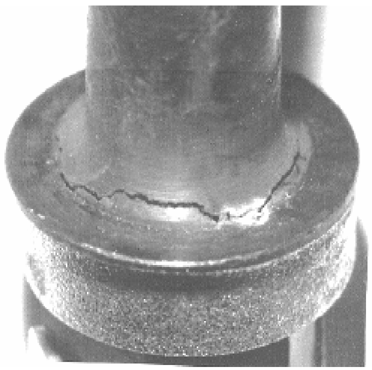
원자로 내부구조물

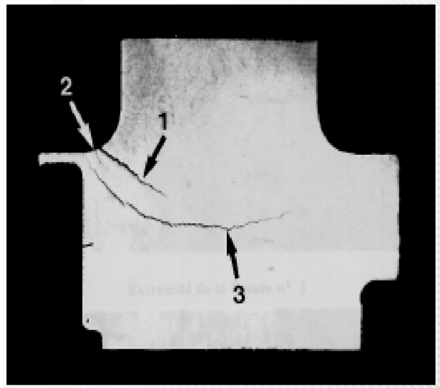




높은 중성자 조사량
(30~50 dpa max.)

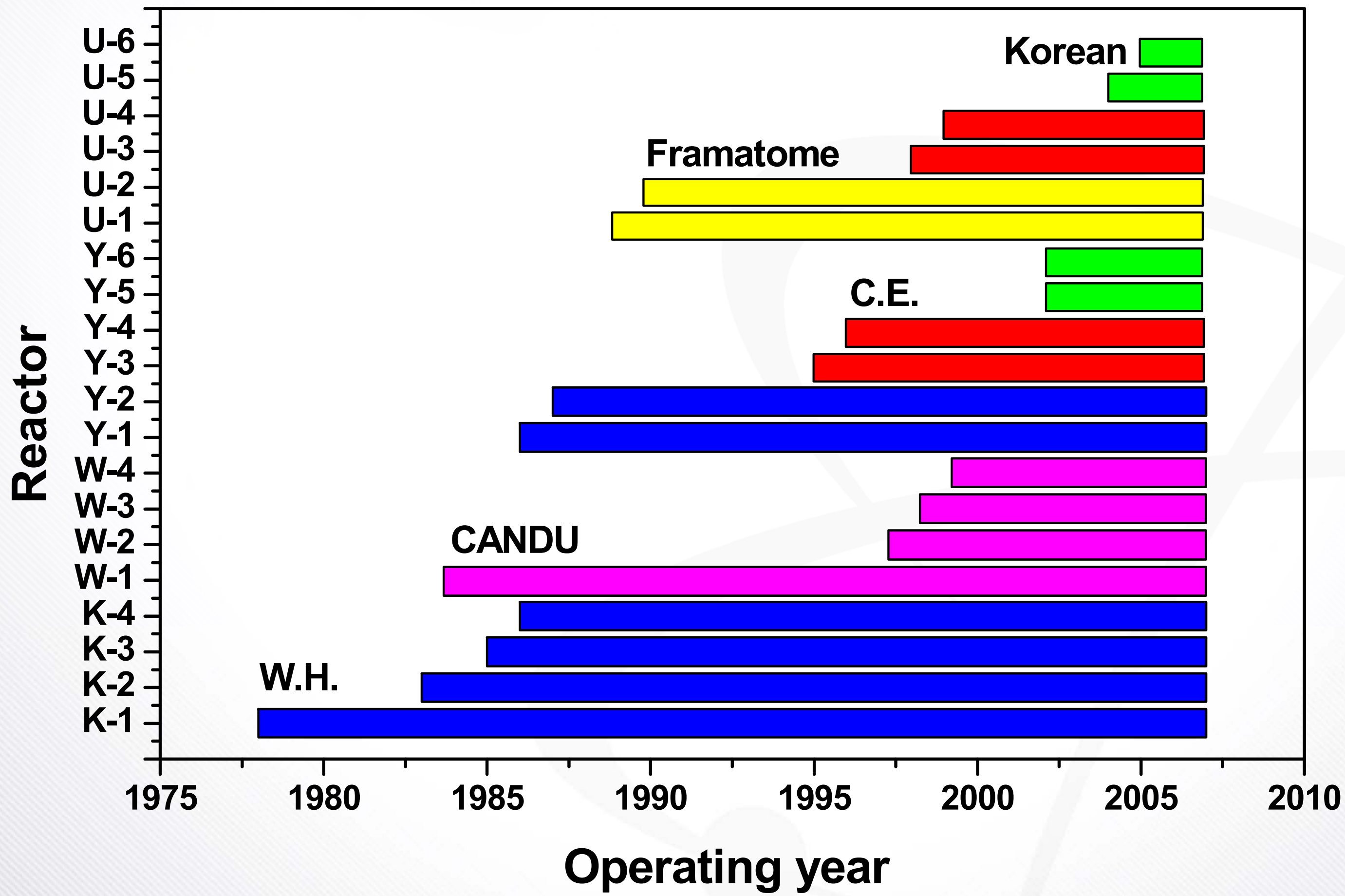
- ◆ 내부구조물의 역할
  - 노심의 기하학적 건전성 유지
- ◆ 구성
  - Upper core structure
  - Core baffle/former/barrel
  - Thermal shield
  - Lower core support structure
- ◆ 열화 환경
  - 방사선, 고온, 응력, 냉각재
- ◆ 잠재적 주요 열화 기구
  - Irradiation embrittlement
  - Void swelling
  - **Irradiation-assisted SCC***





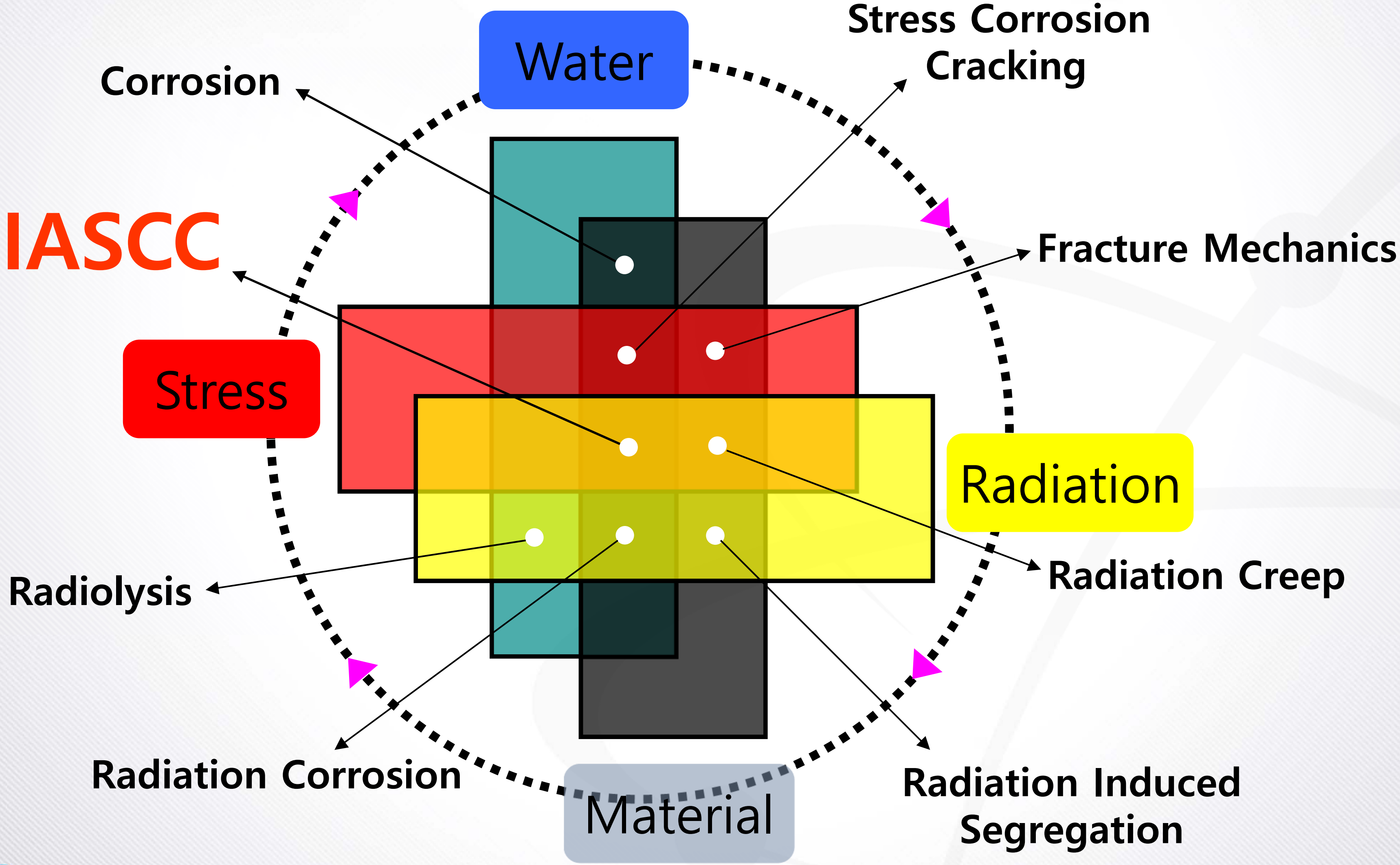
Reactor internals in Korean NPPs

- Korean baffle/former(Westinghouse type): Cod worked type 316 stainless steels
- Number of bolts : ~ 700 ~ 1000

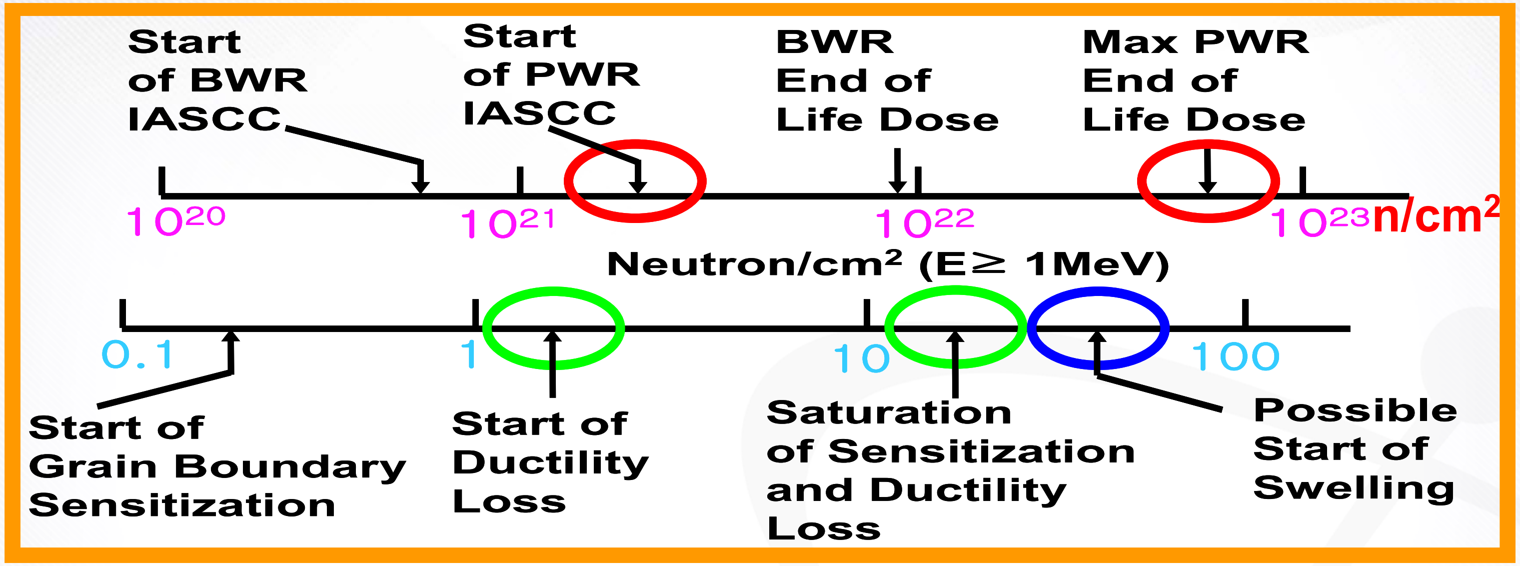


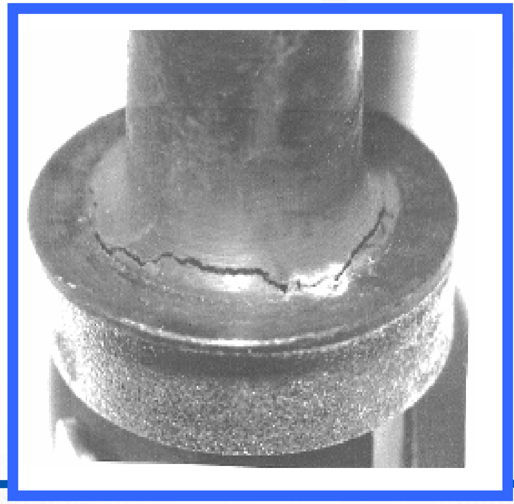
IASCC

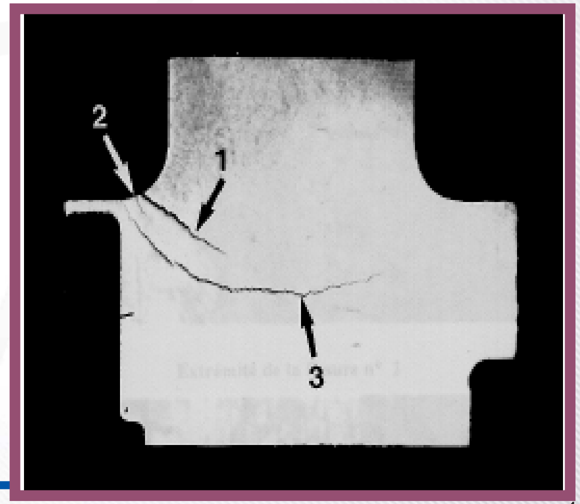
- IASCC : Irradiation Assisted Stress Corrosion Cracking (Mostly IGSCC mode)



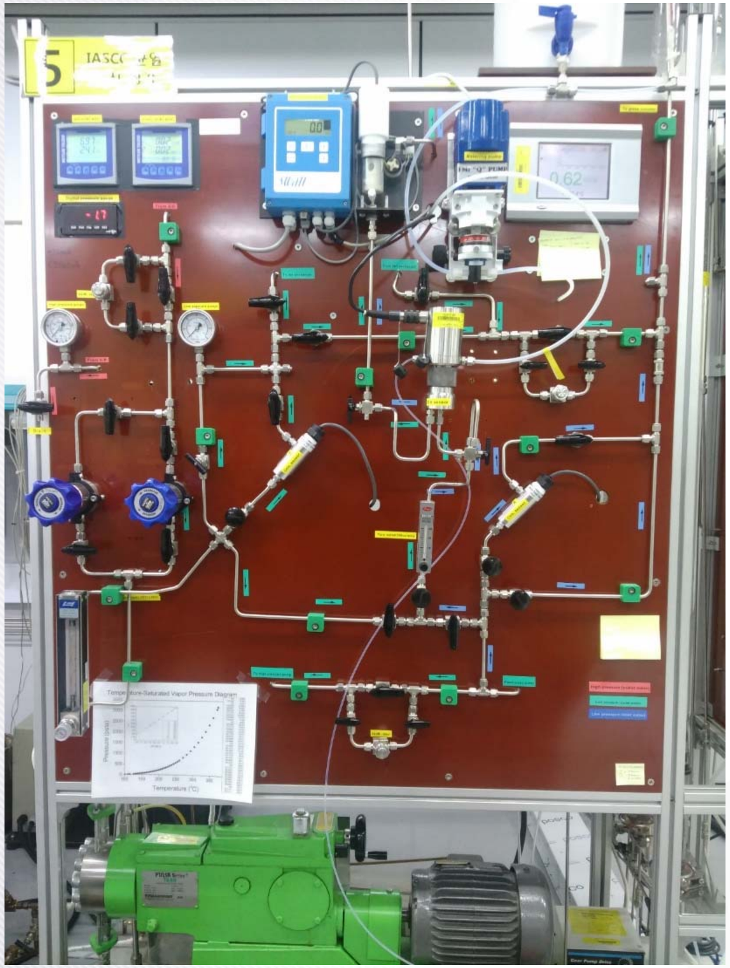
IASCC - Fluence







IASCC initiation test facility at KAERI



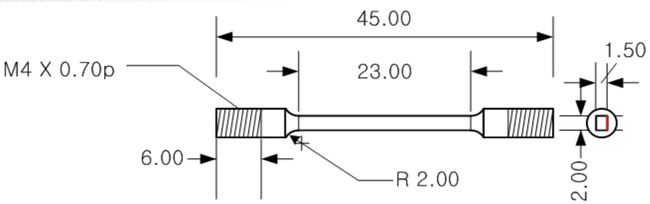
- Li 2 ppm, B 1200 ppm
- 온도 : 325^{o}C
- DO < 5 ppb
- DH : 25 cc/kg, 50 cc/kg
- DPA : 1, 3, 5, 10
- Strain : 10%
- Strain rate : 3.4 x 10^{-7}

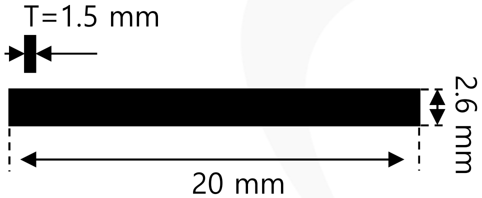
Specimens

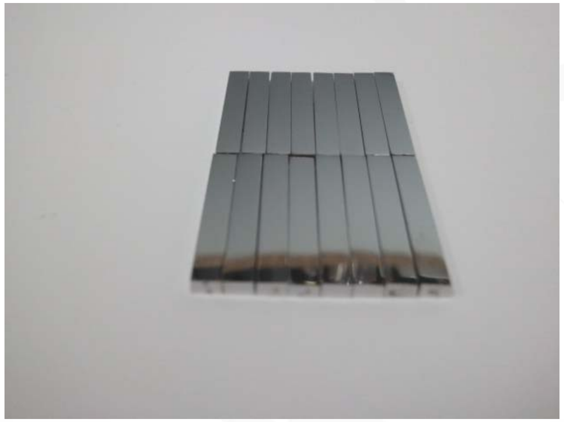
Table 1. Chemical compositions of the test alloy (wt%) and proton dose levels

Material	Cr	Ni	P	Mo	Mn	Si	S	C	Fe	Proton Doses(dpa)
316 SS	16.7	10.8	0.1	2.0	1.3	0.59	0.001	0.047	Bal.	1,3,5,10

- Ground (#400 ~ #2400), then electro polished (50-H_3PO_4 + 25-H_2SO_4 + 25-$C_3H_5(OH)_3$)





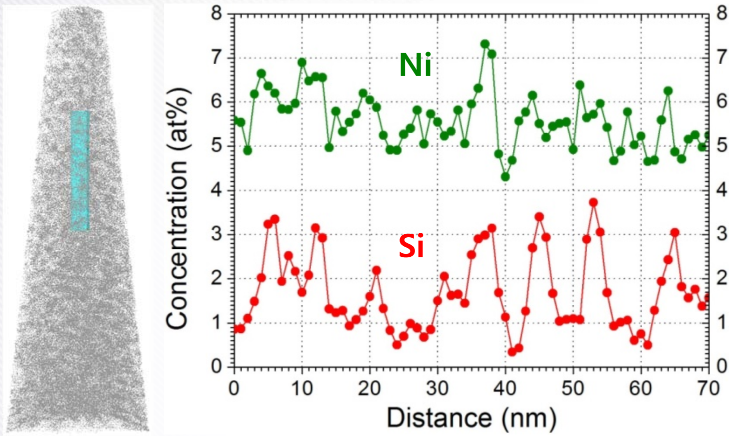


TEM bars

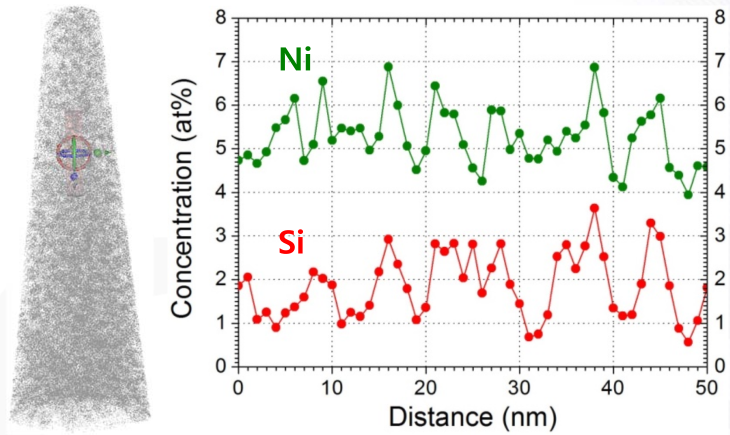
Electropolished before proton irradiation

SSRT Tensile specimen

Ni/Si-rich Clusters in 5 dpa irradiated 316 SS



(a) (b)



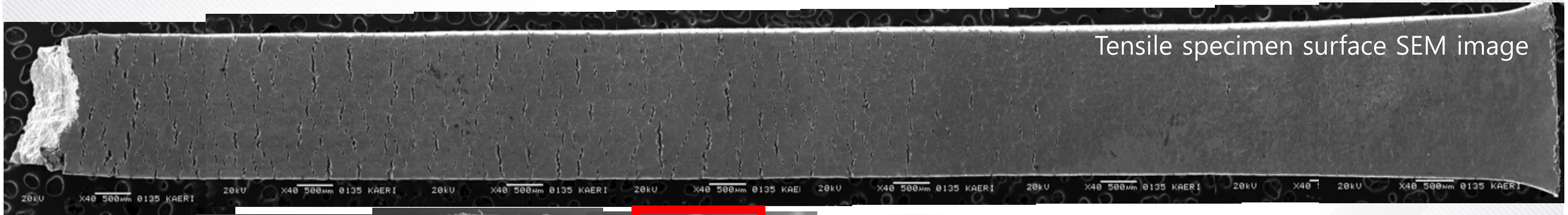
(a) (b)

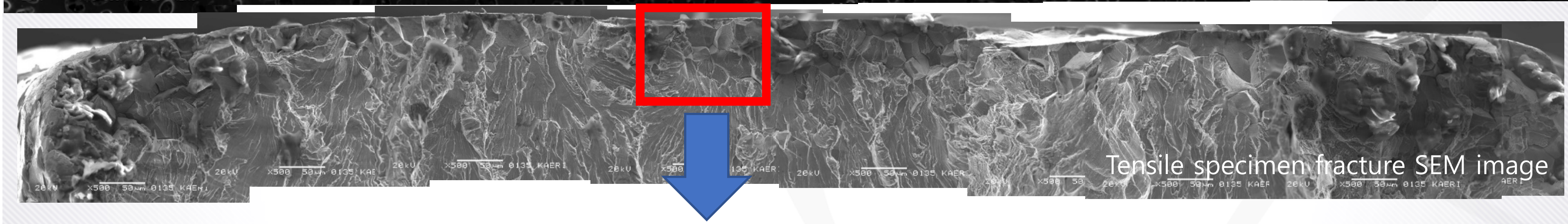
APT results showing Ni/Si-rich clusters in proton irradiated (360°C:5dpa) in 316 SS.
(a) Si atom map, and (b) variations of concentration profile of Ni and Si across clusters

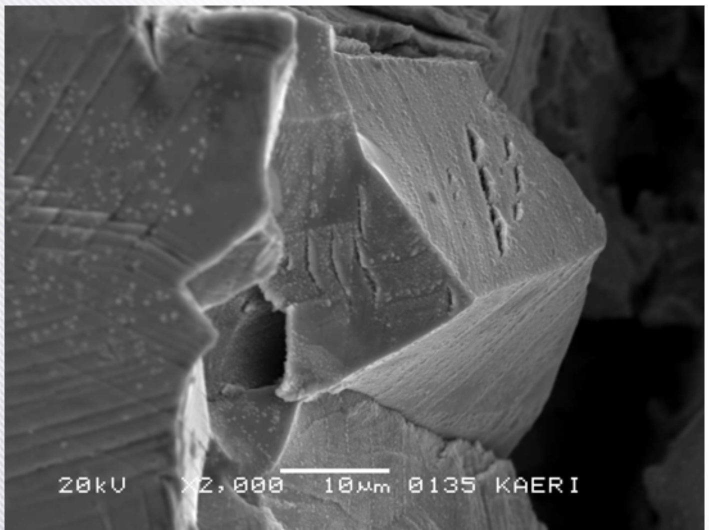
- ❖ Ni/Si-rich clusters were observed inside grains.
- ❖ Si clusters are clearly seen
- ❖ The heights of Ni and Si concentrations are periodically well matched across the clusters → **Ni/Si-rich clusters**

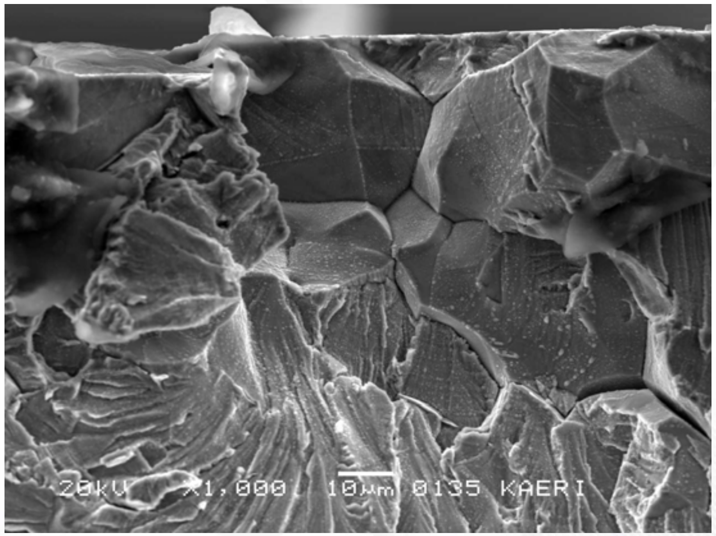
IASCC initiation evaluation

- 5 dpa





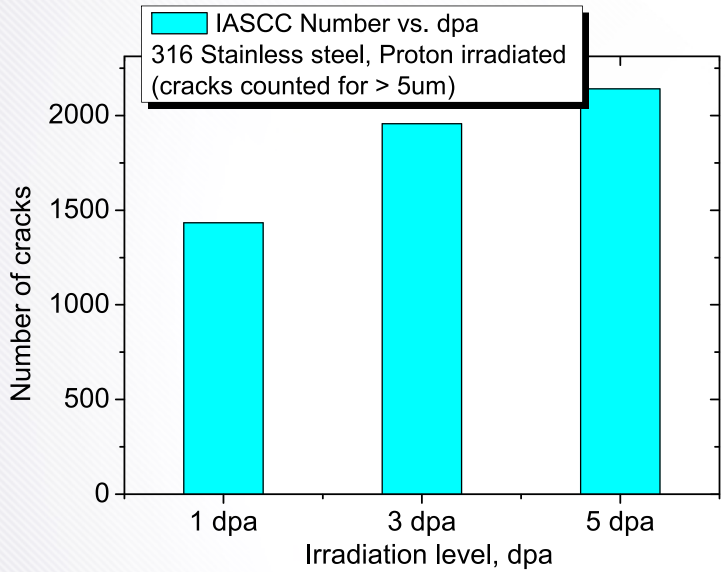




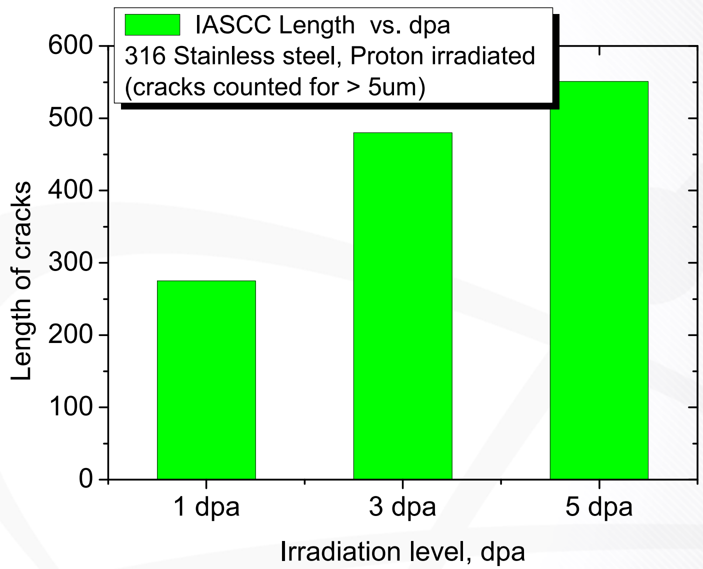
IGSCC in 20 µm deep

Effect of Dose on IASCC initiation

- Number of cracks vs. dpa (counted over 5 μm long)
- Total crack length on side surface (counted over 5 μm long)



(a) Number of cracks vs. Dose



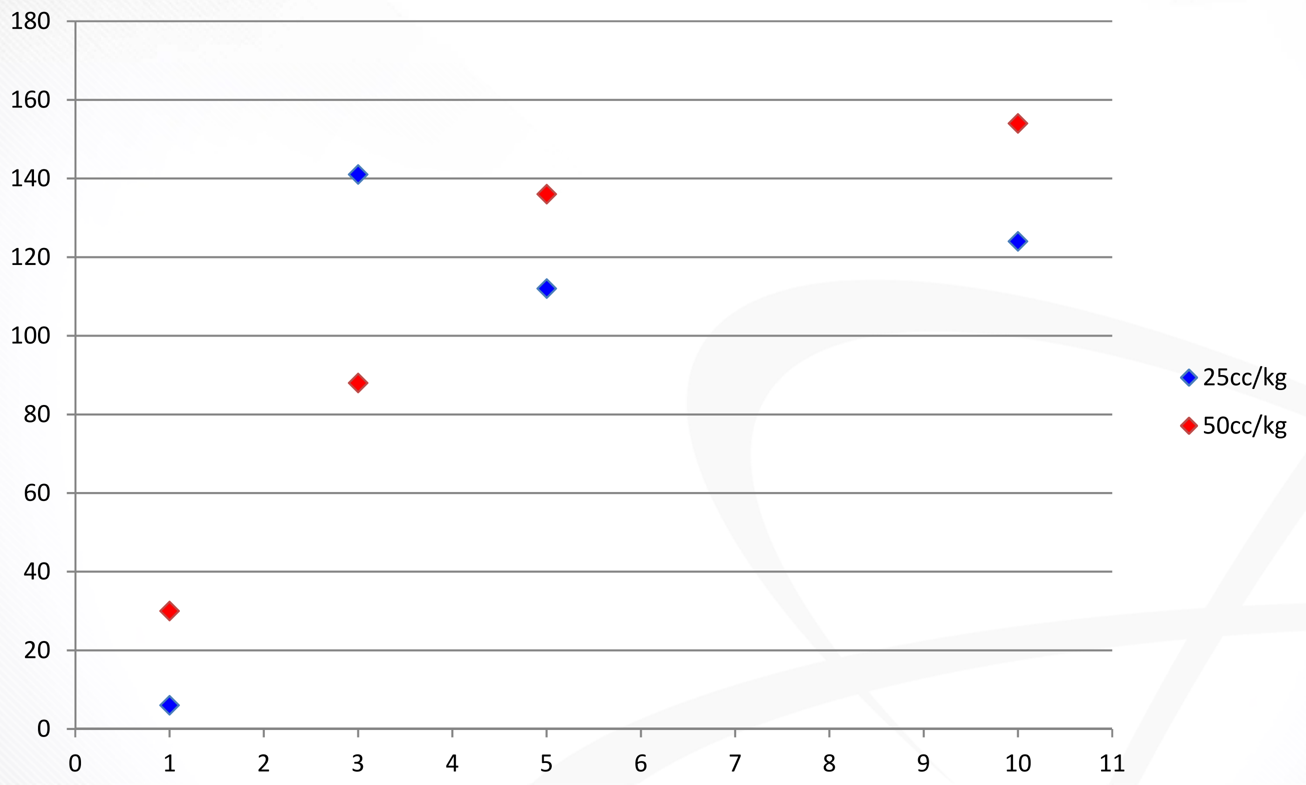
(b) Length of cracks vs. Dose

DPA	1	3	5
Crack numbers	**1433**	**1957**	**2141**

DPA	1	3	5
Crack length(um)	**275**	**480**	**551**

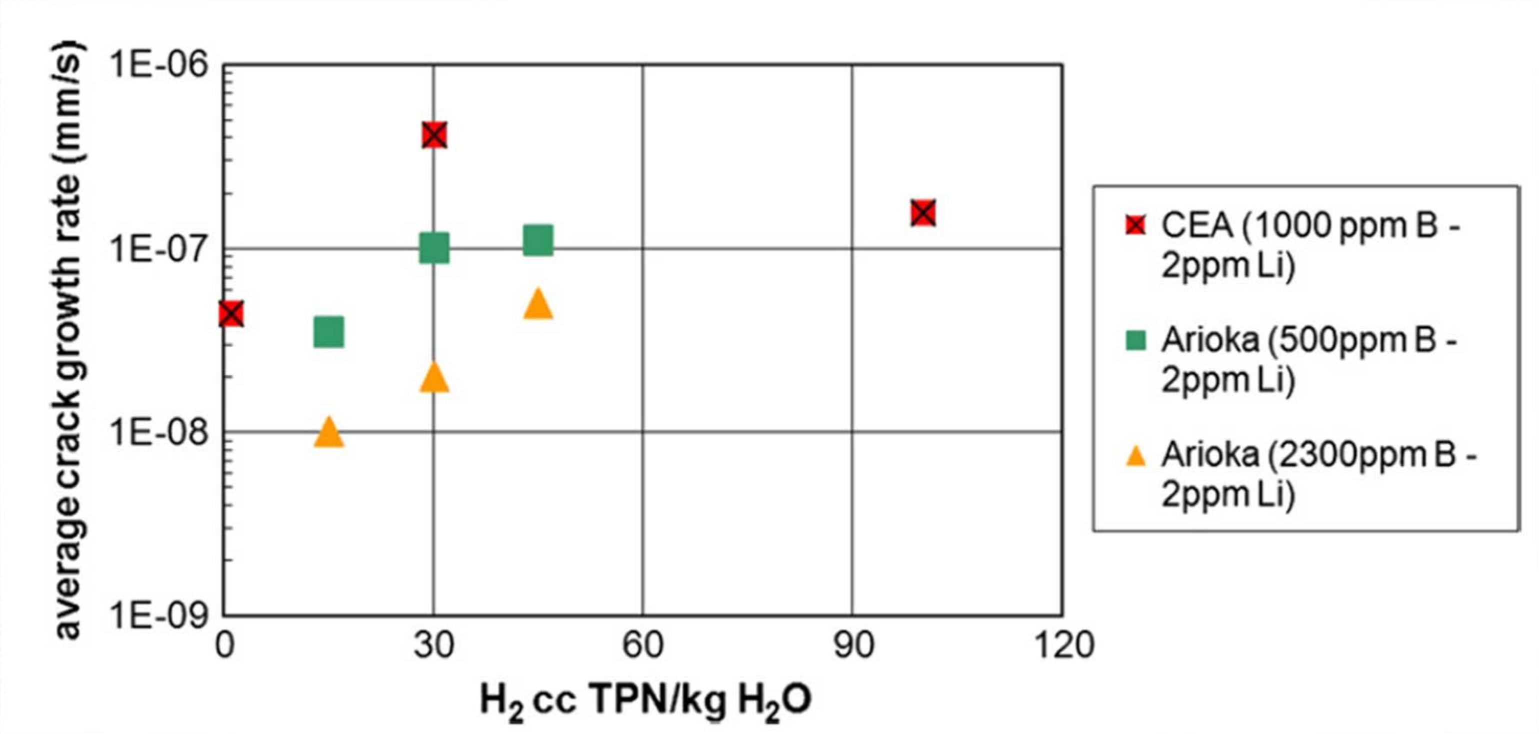
The total crack length at the side surface is a good measure in evaluating IASCC initiation susceptibility for proton-irradiated samples

Effect of DH on IASCC initiation



Susceptible IASCC initiation at high DH (KAERI)

Effect of DH on IASCC growth



Susceptible IASCC growth at high DH (KAERI)

D. Feron, E. Herms, B. Tanguy, 'Behavior of stainless steels in pressurized water reactor primary circuits', Journal of Nuclear Materials 427 (2012) 364–377.

Effect of chemical elements on IASCC

- Effect of C, S on IASCC

wt %	Ni	Cr	Mo	Mn	Si	P	C	S
STS316	10.8	16.7	2.0	1.3	0.59	0.05	**0.0470**	**0.0010**

KAERI specimen

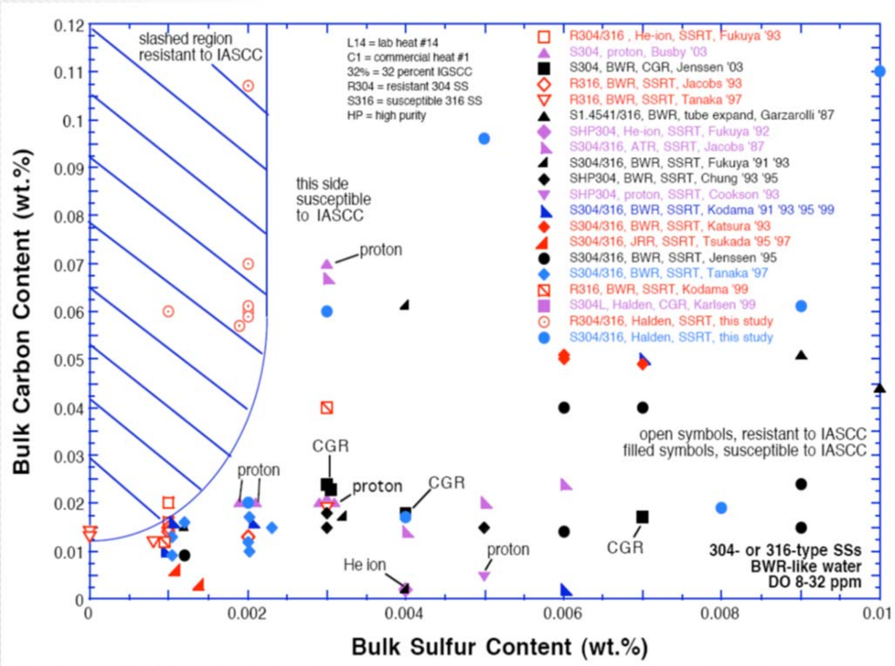


Fig. Effect of C, S on IASCC of BWR water

Source : H.M. Chung, NUREG-CR-6892 (2005)

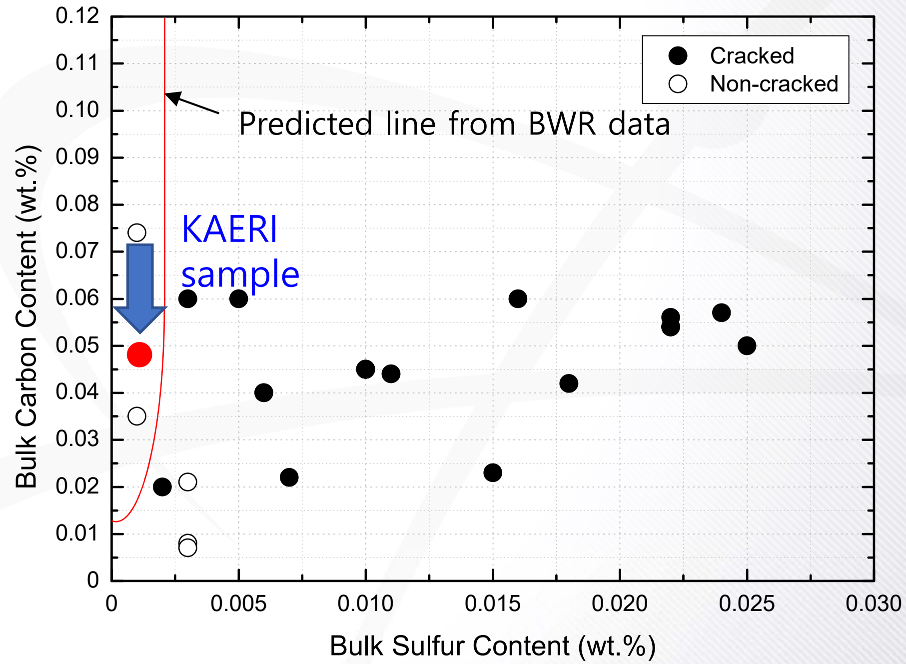
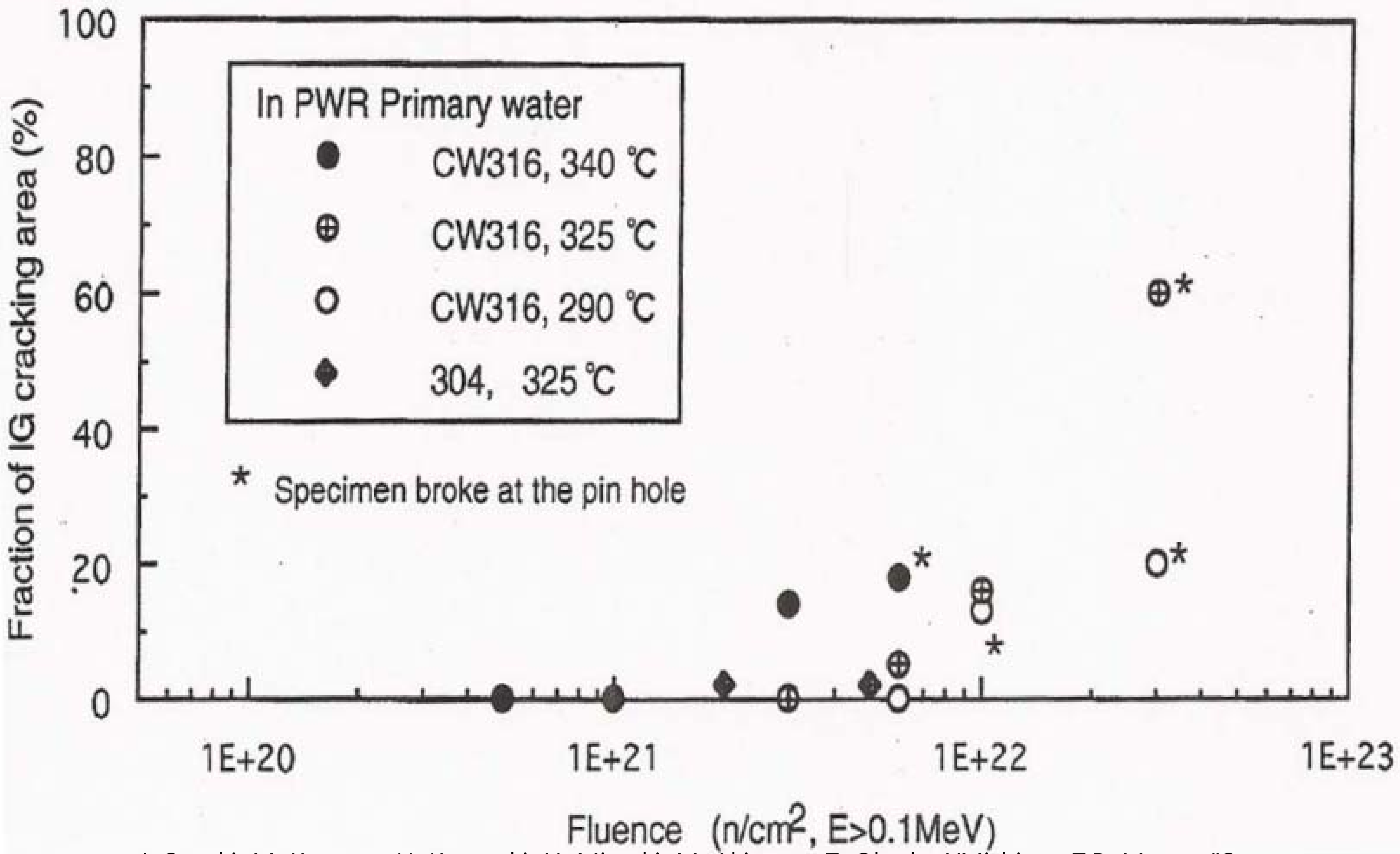


Fig. Effect of C, S on IASCC of PWR water

Effect of fluence on IASCC



I. Suzuki, M. Koyama, H. Kanasaki, H. Mimaki, M. Akiyama, T. Okudo, YMishima, T.R. Mager, "Stress corrosion cracking of irradiated stainless steels in simulated PWR primary water", Int. Conf. on Nuclear Eng., vol. 5, p. 205, ASME, 1996.

요약

- 국내외 계속 운전 준비
- 계속운전을 위한 재료 열화연구 방안
- 균열개시에 미치는 영향인자: 용존수소(DH), 화학조성의 영향, 응력, 임계조사량
  - 수소를 첨가한 HWC PW 용액에서는 전반적인 균열민감도는 감소하나 작은 표면 균열의 발생은 증가하여 균열개시민감도는 증가.
  - Hf와 Si의 첨가는 해로움. Mo와 Ti는 거의 효과가 없었으며, Ni 또는 Ni + Cr은 IASCC 민감성 낮춤.
  - IASCC 개시 응력: 조사된 항복 강도의 약 50 ~ 55 %의 응력이 필요. 조사된 항복 강도의 62 % 미만의 응력에서는 수명 종료까지 IASCC 균열이 발생하지 않을 것으로 예상.
  - 임계조사량: 2~5 dpa (1 x 10^{21} n/cm^2)

Thank You for Your Attention!