혁신형 SMR 고강도 원자로용기재료 적용기술 동향

-한국원자력연구원-

SMR용 핵연료/재료 개발 및 연구동향 Workshop, 2021 원자력학회 추계 학술대회

2021. 10. 20

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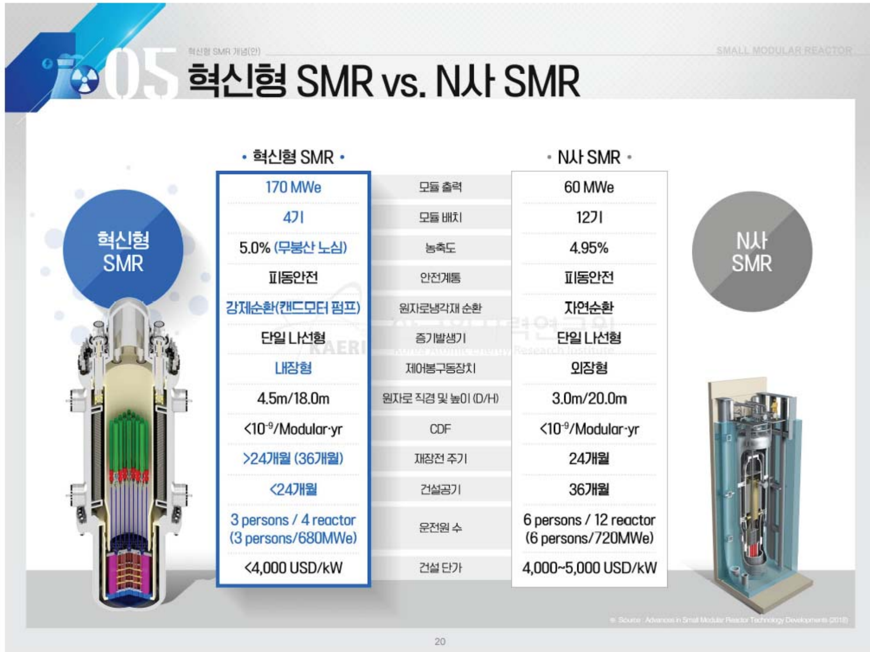
재료안전기술개발부

00 목 차

01 혁신형 SMR 개요 및 RPV 재료 Issue

◆ 원자로용기 적용재료 Issue

- 후보 재료 : SA508 Gr. 3 Cl. 1, Cl. 2
- 설계 두께(250 mm) → 제작성, 용접성(EBW : ISI 연장 or 면제, 제작기간 단축)
- 설계 무게(<600t) → 육상 운송, 무게절감
- 재료 적용성 → 중성자 조사취화, EBW 재료 특성, 코드(ASME, R.G)



• 혁신형 SMR •		• N사 SMR •
170 MWe	모듈 출력	60 MWe
4기	모듈 배치	12기
5.0% (무붕산 노심)	농축도	4.95%
피동안전	안전계통	피동안전
강제순환(캔드모터 펌프)	원자로냉각재 순환	자연순환
단일 나선형	증기발생기	단일 나선형
내장형	제어봉구동장치	외장형
4.5m/18.0m	원자로 직경 및 높이 (D/H)	3.0m/20.0m
<10⁻⁹/Modular·yr	CDF	<10⁻⁹/Modular·yr
>24개월 (36개월)	재장전 주기	24개월
<24개월	건설공기	36개월
3 persons / 4 reactor (3 persons/680MWe)	운전원 수	6 persons / 12 reactor (6 persons/720MWe)
<4,000 USD/kW	건설 단가	4,000~5,000 USD/kW

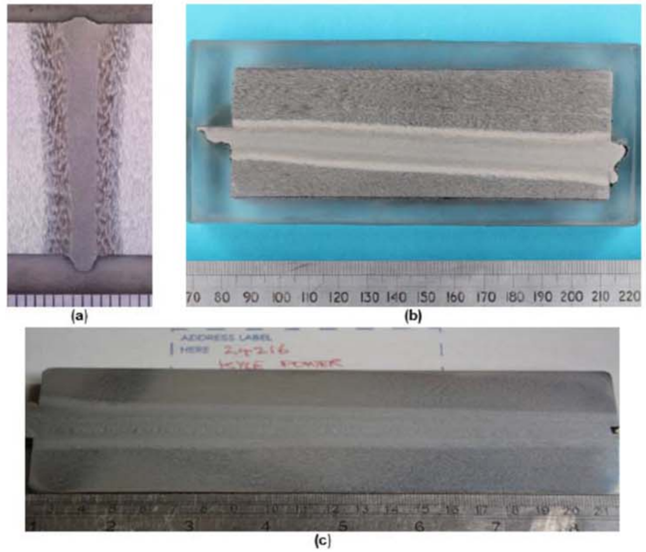
2. SMR 경쟁력 확보를 위한 혁신제작기술 LIST

구분	혁신성	Risk	비고
전자빔 (EBW) 용접	● 1패스 용접. 제작시간 단축 ● 예열/후열/패스간 온도 삭제로 제작시간 단축 ● ISI(가동중검사) 연장 또는 삭제를 통한 운영 비용 절감	● 국내 기술 및 대형장비 없음 ● ASME CODE 개정 필요 ● 규제기관 및 발전사 승인 필요	미국/영국 정부 주도로 개발 중 * 제작시간 90%단축 * ISI 검사 삭제
다이오드 레이저 클래딩	● 클래딩 두께 감소. 제작시간 단축 (10→2mm) ● 클래딩 무게 감소. 제품 무게 감소 ● 표면 후처리 불필요. 제작시간 단축 ● 자동화 용접. 제작시간 단축 가능	● 설계사양서 변경 필요 (최소 3.2→1.5mm) ● 국내 적용 사례 없음 ● 보수 방안 검토 필요	미국/영국 정부 주도로 개발 중 * 제작시간 50%단축 * 제품 무게 경량화
PM-HIP (Powder Metallurgy-Hot Isostatic Pressing)	● 원자로헤드와 같은 복잡형상 제작시간 약 90% 단축 ● 용접부 최소화로 ISI 검사 비용 절감	● 제작CODE 필요 ● 국내 적용 사례 없음 ● 보수 방안 검토 필요	미국/영국 정부 주도로 개발 중 * 제작시간 90%단축
표면처리 (피닝 및 Cold Spray)	● 응력부식균열(SCC) 방지를 통한 ISI 연장 ● SCC 원천 차단을 통한 혁신형 SMR 안전성 부각	● 제작 CODE 필요 ● 전세계 최초 적용 ● SCC 관련 기술표준을 위한 시험 필요	미국/일본 검토중 * ISI 50%이상 절감
AM (Additive Manufacturing)	● 원자로 내부구조물 제작시간 혁신단축 ● 소형내즐 및 밸브류 제작 혁신단축	● 제작 CODE 필요 ● 초대형 AM 장비 필요	미국/영국 정부 주도로 개발 중 * 제작시간 50%단축

Source: 김종욱(KAERI), i-SMR 사업추진 경과 및 향후 계획, 조성우(두산중공업), SMR 혁신 제작 기술

What Are The Critical Gaps That Must Be Addressed? (1)

- EBW must be demonstrated
  - 4.375-inch (110mm) thick (RPV)
  - currently demonstrated at 4-inches (100mm)



30mm, 130mm, and 200mm EB welds

- ATLAS HIP facility must be built
  - to increase HIP size capabilities
  - up to 3.1m diameter x 5m length
  - Can manufacture 2/3rds scale coupons today.

- EBW of SA508 RPV sections
  - Does a vessel that has been EB welded, solution annealed, and quenched and tempered require subsequent in-service inspections?
  - Is EB really a weld after solution annealing? No filler metal.
  - Need to demonstrate fracture toughness following solution anneal

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Source: David Gandy, Craig Stover, 'Advanced Manufacturing to Enable the Next Generation of Nuclear Plants', DOE AMM Meeting October 17-18, 2016

What Are The Critical Gaps That Must Be Addressed? (2)

- Diode Laser Cladding must be demonstrated
  - Vessels, nozzles, etc.
  - Robotic cladding up to 90mm wide, but <5mm thick
- Understand Irradiation Effects on PM-HIP Components
  - NEUP project for PM-HIP samples are underway
  - 304L, 316L, SA508, Grade 91, Alloys 625 and 690
- Additional development around SA508.
  - We have demonstrated good fracture toughness and other properties, but we need to develop more understanding here.
  - Utility Requirements Document modification
- ASME Code Case Development
  - PM-HIP of SA508
  - Elimination of DMWs
  - EB welding of RPV sections

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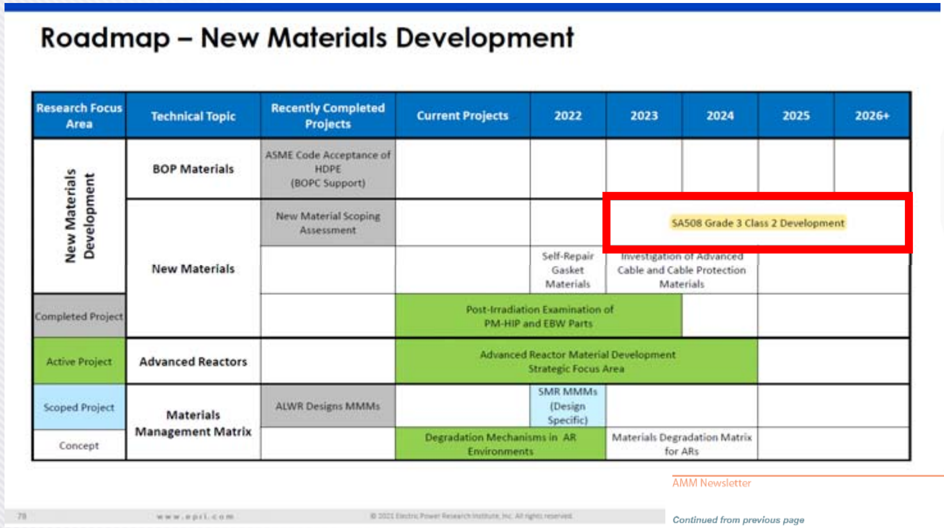
EPRI ELECTRIC POWER RESEARCH INSTITUTE

Source: David Gandy, Craig Stover, 'Advanced Manufacturing to Enable the Next Generation of Nuclear Plants', DOE AMM Meeting October 17-18, 2016

◆ SMR RPV 재료 개발

- (미국) EPRI는 SA508 Gr. 3 Cl. 2 적용기술 개발을 2023년부터 착수 예정
- (영국) SA508 Gr. 3 Cl. 2 및 SA508 Gr. 4N에 PM-HIP과 EBW 적용성 실증(2020)
- (DOE & EPRI) RPV 제작기간 단축 (30개월 이상 →12개월), 제작비용 40% 절감



Roadmap – New Materials Development

Research Focus Area	Technical Topic	Recently Completed Projects	Current Projects	2022	2023	2024	2025	2026+
New Materials Development	BOP Materials	ASME Code Acceptance of HDPE (BOPC Support)						
	New Materials	New Material Scoping Assessment			SA508 Grade 3 Class 2 Development			
				Self-Repair Gasket Materials	Investigation of Advanced Cable and Cable Protection Materials			
Completed Project			Post-Irradiation Examination of PM-HIP and EBW Parts					
Active Project	Advanced Reactors		Advanced Reactor Material Development Strategic Focus Area					
Scoped Project	Materials Management Matrix	ALWR Designs MMMs		SMR MMMs (Design Specific)				
Concept			Degradation Mechanisms in AR Environments		Materials Degradation Matrix for ARs			

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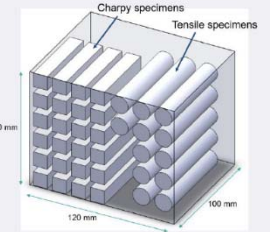
Progress

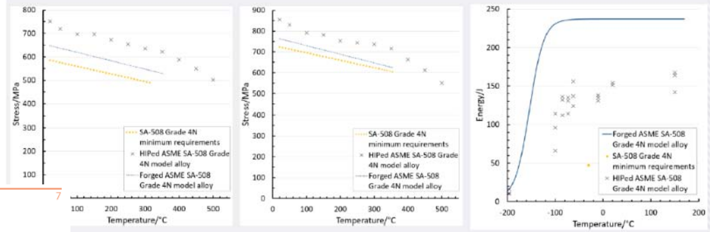
Billets & Basic Material Testing

References:

ICONE28-POWER2020-16035, 2020 [7]

ICONE27-1021, 2019 [8]





AMM Newsletter

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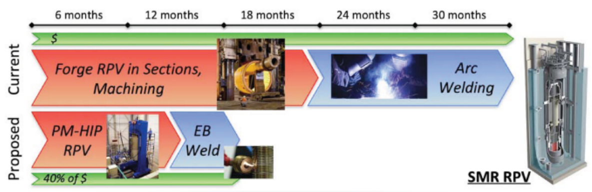
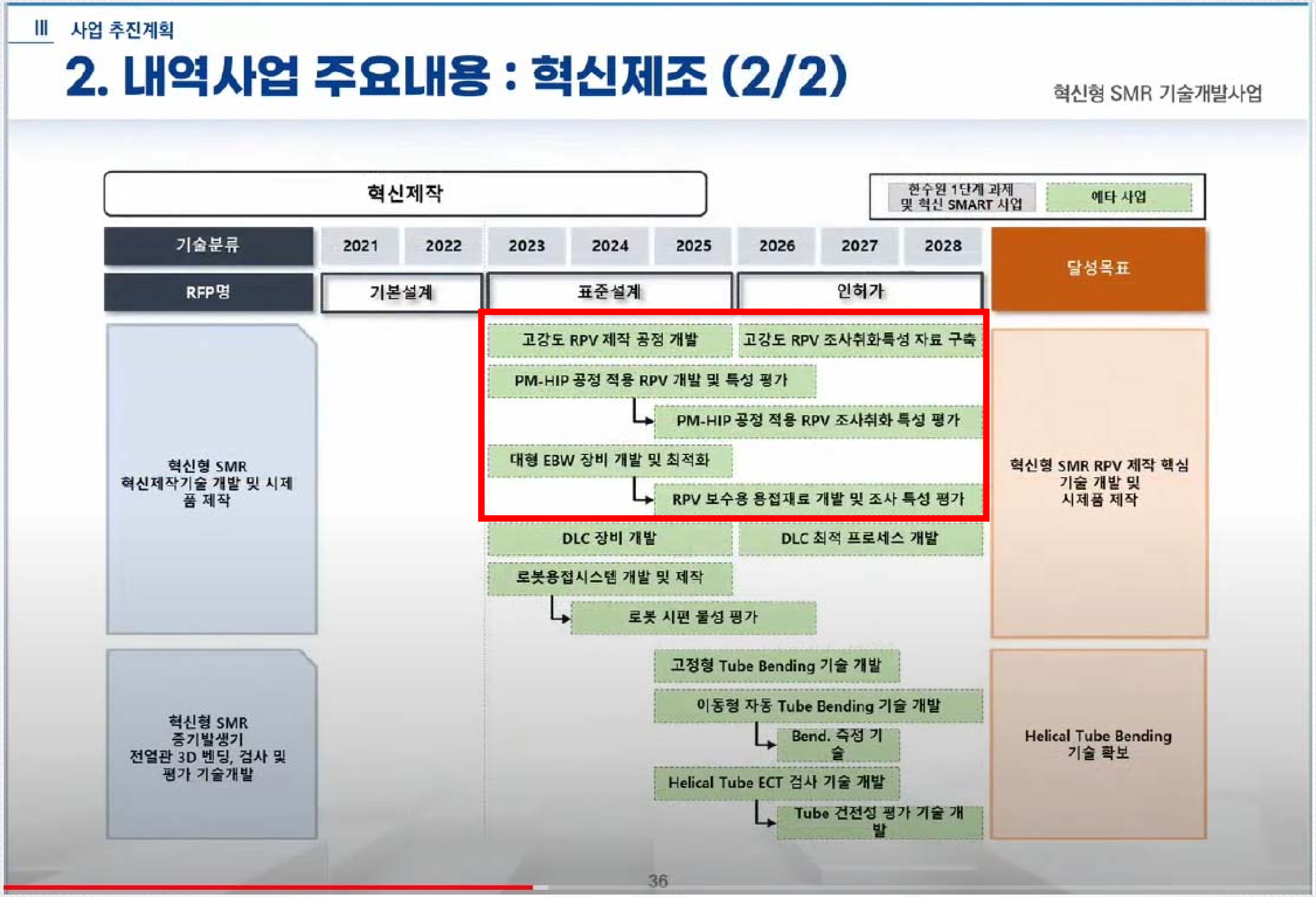


Figure 3: This project will enable the revolutionary combination of PM-HIP and EB welding to reduce pressure vessel fabrication time and cost.

Source: EPRI New Materials Development Roadmap & Rolls Royce

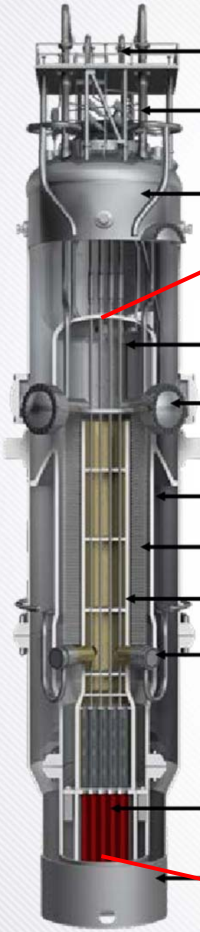
03 국내 예타사업 진행 사항



Source: 혁신형 SMR 기술개발사업 공청회(2021.08.18)

04 NuScale Reactor

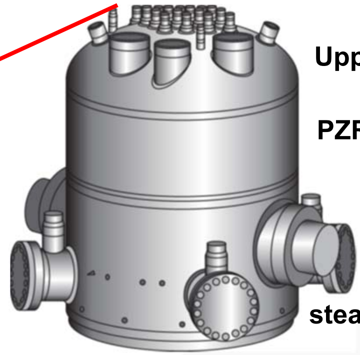
Ref. Small Modular Reactor Vessel Manufacture and Fabrication_ Phase 1_Progress _Year 2



Upper Assembly

2020

Ref. EPRI-3002019335



Upper head The SA508 Grade 3, Class 1 low alloy steel, PM-HIP, EBW

PZR shell SA508 Grade 3, Class 2 low alloy steel, forging

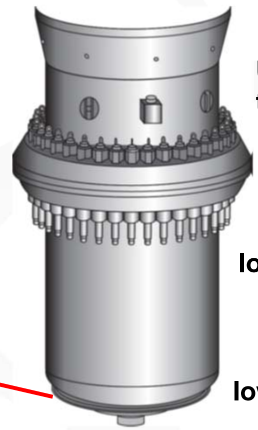
integral steam plenum The SA508 Grade 3, Class 1 low alloy steel, PM-HIP, forging, EBW

steam plenum access ports

Middle Reactor Vessel Assembly

- Upper RPV Steam Generator (SG) Shell
- Lower RPV SG Shell

복잡하지 않은 부위
→ Forging
But, 제작기간 단축을 위해 PM-HIP 적용 불가피



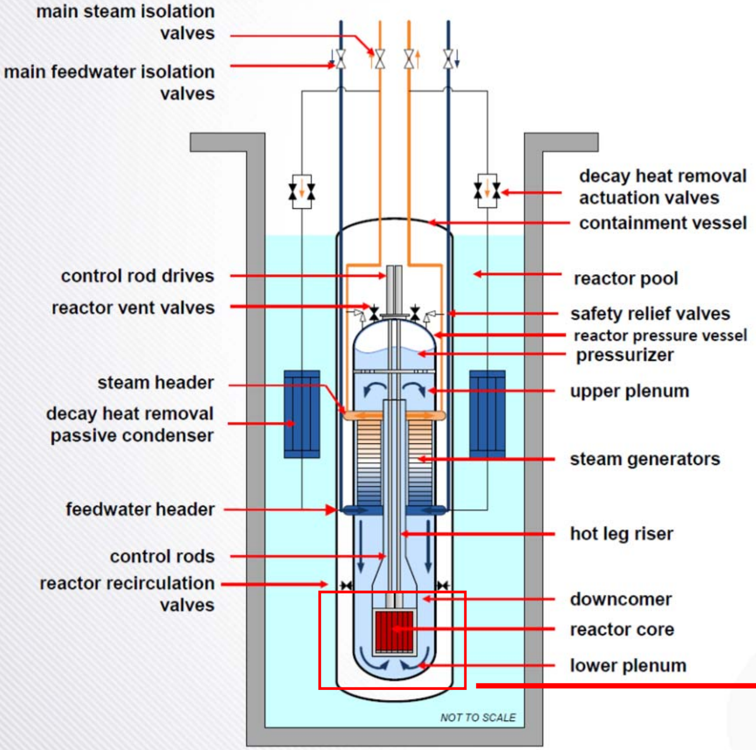
Upper RPV transition shell SA508 Grade 3, Class 1 low alloy steel
powder PM-HIP, EBW
Forged flange ring section

lower RPV flange shell SA508 Grade 3, Class 2 low alloy steel, forging, EBW

lower head SA508 Grade 3, Class 1 low alloy steel
powder PM-HIP, EBW, and BAM

Lower Assembly

04 NuScale Reactor



Upper RPV transition shell — SA508 Grade 3, Class 1 low alloy steel powder for PM-HIP

lower RPV flange shell — SA508 Grade 3, Class 2 low alloy steel , forging, EBW

lower head — SA508 Grade 3, Class 1 low alloy steel powder PM-HIP, EBW, and BAM

Lower Assembly

Ref. EPRI-3002019335
2020

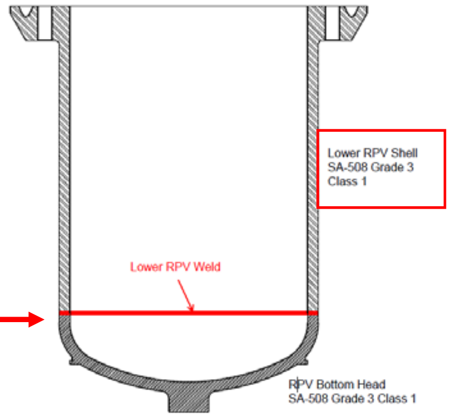


Figure 3-1 Lower reactor pressure vessel

Ref. ML18298A304
2018

Table 3-1 Lower reactor pressure vessel geometry

Parameter	Value	
RPV ID of cladding surface	96"	2.43m
RPV Base Metal Thickness	4.25"	101mm
RPV ID Cladding Thickness	0.25"	
RPV OD Cladding Thickness	0.125"	

3.2 Materials

Table 3-2 Reactor pressure vessel beltline material chemistry

	Material	Maximum Limit, wt%				
		Cu	Ni	P	S	Co
Lower RPV Shell	SA-508 Grade 3 Class 1	0.06	0.85	0.010	0.010	0.05
Lower RPV Weld	Low Alloy Steel Weld	0.06	0.85	0.012	0.015	0.05
RPV Bottom Head	SA-508 Grade 3 Class 1	0.06	0.85	0.010	0.010	0.05

Table 4-2 Reactor pressure vessel beltline material properties

Location	Material	Initial RT_{NDT}
Lower RPV Shell	SA-508 Grade 3 Class 1	-10°F max
Lower RPV Weld	Low Alloy Steel Weld	-20°F max
RPV Bottom Head	SA-508 Grade 3 Class 1	-10°F max

▪ NuScale Final Safety Analysis Report

Table 5.3-1: Reactor Vessel Parameters

Design Parameter	Value
Design pressure (psia)	2100
Design temperature (degrees F)	650
Overall height, bottom of alignment feature to top of CRDM latch housing section (inches)	778
Inside diameter of lower RPV section, cylindrical region, without clad (inches)	96.5
Outside diameter of lower RPV section, cylindrical region, without clad (inches)	105
Inside diameter of upper RPV section, cylindrical region, without clad (inches)	104.5
Outside diameter of upper RPV section, cylindrical region, without clad (inches)	112.5
Inside diameter of pressurizer, cylindrical region, without clad (inches)	106.5
Outside diameter of pressurizer, cylindrical region, without clad (inches)	115.5
Inside diameter of upper head without clad (inches)	104.5
Outside diameter of upper head without clad (inches)	112.5
Inner clad thickness (inches)	0.25
Outer clad thickness (inches)	0.125

Table 5.3-2: Chemical Composition of Reactor Pressure Vessel Beltline Materials

Material	Element	Maximum concentration (wt%)
RPV beltline forging material	Sulfur	0.010
	Phosphorus	0.010
	Copper	0.06
	Cobalt	0.05
	Nickel	0.85
As-deposited weld metal used in the RPV beltline	Sulfur	.015
	Phosphorus	.012
	Copper	.06
	Cobalt	.05
	Manganese	1.80
	Nickel	0.85

Table 5.3-3: 1/4-T Adjusted Reference Temperature Result at 57 Effective Full-Power Years Fluence

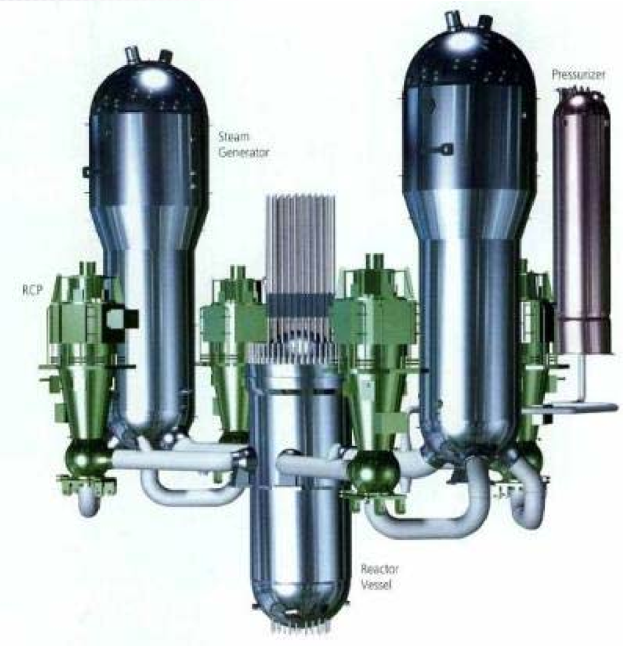
Location	Peak 1/4-T Fluence, n/cm^2, E >1 MeV	Maximum Initial RT_{NDT} (°F)	ΔRT_{NDT} (°F)	Margin (°F)	Adjusted Reference Temperature (°F)
Lower RPV shell, beltline	1.37E+19	-10	68.2	34.0	92.2
Lower RPV weld	3.21E+18	-20	84.4	56.0	120.4
RPV bottom head	3.21E+18	-10	53.4	34.0	77.4

Table 5.3-8: Pressurized Thermal Shock Screening Result

	0-T Fluence n/cm^2, E > 1 MeV	Max Initial RT_{NDT} (°F)	ΔRT_{NDT} (°F)	Margin (°F)	RT_{PTS} (°F)	Screening Criterion (°F)
(32-EFPY Fluence)						
Lower RPV shell, beltline	9.94E+18	-10	64.9	34.0	88.9	270 max
Lower RPV weld	2.32E+18	-20	77.6	56.0	113.6	300 max
RPV bottom head	2.32E+18	-10	50.4	34.0	74.4	270 max
(57-EFPY Fluence)						
Lower RPV shell, beltline	1.77E+19	-10	70.8	34.0	94.8	270 max
Lower RPV weld	4.14E+18	-20	89.9	56.0	125.9	300 max
RPV bottom head	4.14E+18	-10	55.9	34.0	79.9	270 max

SA508

ASME Code Section II, SA-508:
Specification for Quenched and Tempered Vacuum-Treated Carbon and Alloy Steel Forgings for Pressure Vessels



SA508 Low Alloy Steel:
Account for 80% in Reactor Pressure Boundary Components(RPV, SG, PRZ, Pipe…)

SA-508, Gr.3 Cl.1 (345 MPa) Mn-Mo-Ni steel

Current	Formerly
Grade 1	Class 1
Grade 1A	Class 1A
Grade 2 Class 1 & 2	Class 2 & 2A
Grade 3 Class 1 & 2	Class 3 & 3A
Grade 4N Class 1, 2 &3	Class 4, 4A & 4B

05 SA508 : ASME code Section II Materials Part A Mat. Spec.

- **Chemical requirements of SA508 low alloy steels in ASME code**

	C	Mn	Ni	Cr	Mo	Si	P	S	V	Cb
Gr.1	0.35 max	0.40-1.05	0.40 max	0.25 max	0.10 max	0.40 max	0.025 max	0.025 max	0.05 max	0.01 max
Gr.1a	0.30 max	0.70-1.35	0.40 max	0.25 max	0.10 max	0.40 max	0.025 max	0.025 max	0.05 max	0.01 max
Gr.2	0.27 max	0.50-1.00	0.50-1.00	0.25-0.45	0.55-0.70	0.40 max	0.025 max	0.025 max	0.05 max	0.01 max
Gr.3	0.25 max	1.20-1.50	0.40-1.00	0.25 max	0.45-0.60	0.15-0.40	0.025 max	0.025 max	0.05 max	0.01 max
Gr.4N	0.23 max	0.20-0.40	2.80-3.90	1.50-2.00	0.40-0.60	0.15-0.40	0.020 max	0.020 max	0.03 max	0.01 max
Gr.5	0.23 max	0.20-0.40	2.8-3.9	1.50-2.00	0.40-0.60	0.30 max	0.020 max	0.020 max	0.08 max	0.01 max
Gr.22	0.11-0.15	0.30-0.60	0.25 max	2.00-2.20	0.90-1.10	0.35 max	0.015 max	0.015 max	0.02 max	0.01 max
Gr.3V	0.10-0.15	0.30-0.60	…	2.8-3.3	0.90-1.10	0.10 max	0.020 max	0.020 max	0.20-0.30	0.01 max
Gr.3VCb	0.10-0.15	0.30-0.60	0.25 max	2.7-3.3	0.90-1.10	0.10 max	0.020 max	0.010 max	0.20-0.30	0.015-0.070
Gr.6	0.28-0.33	0.75-1.15	0.75-0.95	0.70-1.00	0.30-0.45	0.35 max	0.025 max	0.025 max	0.05 max	0.01 max

SA508 Gr.3 steel : Mn-Mo-Ni low alloy steel, SA508 Gr.4N steel : Ni-Cr-Mo low alloy steel

❖ 10CFR50, App. A, App. G to CFR 50, R.G. 1.99 rev.2
❖ ASME Sec. II, ASME Sec. III, NB-2000, 2300, App. G, Sec. XI App. G

05 SA508 : ASME Code

▪ Tensile requirements of SA508 low alloy steels in ASME code

	Tensile strength, ksi [MPa]	Yield strength, min , ksi [MPa]	El. in 2 in.or 50 mm, min, %	Reduction of area, min, %
Gr.3 Cl.1	80-105 [550-725]	50 [345]	18	38
Gr.3 Cl.2	90-115 [620-795]	65 [450]	16	35
Gr.4N Cl.1	105-130 [725-895]	85 [585]	18	45
Gr.4N Cl.2	115-140 [795-965]	100 [690]	16	45
Gr.4N Cl.3	90-115 [620-795]	70 [485]	20	48

▪ Charpy impact requirements of SA508 low alloy steels in ASME code

		Min. ave. value of set of three specimens, ft*lbf (J)	Minimum value of one specimen, ft*lbf (J)
SA508 Gr.3	Cl. 1 at +40°F[4.4°C]	30 [41]	25 [34]
	Cl. 2 at +70°F [21°C]	35 [48]	30 [41]
SA508 Gr.4N	(all classes) at -20°F [-29°C]	35 [48]	30 [41]

ASME Boiler and Pressure Vessel Code Development

Powder metallurgy-HIP of 508 low alloy steel. Currently ASME Section II is moving forward to accept over 30 alloys that can be produced by PM-HIP. These include ferritics, austenitics, and nickel-based alloys. SA508 materials are not included. Considerable research will have to be performed to understand 508 materials before these will be allowed in Section III for manufacturing of RPVs. This includes: production of multiple heats, lots of fracture toughness characterization, and irradiation testing. → Acceptance of 508 using PM-HIP as Code Case for production of vessel materials

05 SA508 : ASME code Section II Materials Part D Properties

◆ Design Stress Intensity Value, S_m

- Sec. III Div. 1, Class 1 적용 여부와 온도에 따른 설계응력값 제시
- SA-508 Gr.3 Cl.1 & 2, SA-508 Gr.4N Cl.1 & 3 사용 가능
  (최대 제한온도는 Gr.3 강 371°C, Gr.4N 강 343°C)

▪ **Table 2A Section III, Division 1, Classes 1 and MC; Section III, Division 3, Classes TC and SC; and Section VIII, Division 2, Class 1 Design Stress Intensity Values, S_m, for Ferrous Materials**

Line No.	Nominal Composition	Product Form	Spec. No.	Type/ Grade	Alloy Desig./ UNS No.	Class/ Condition/ Temper	Size/ Thickness, mm	P-No.	Group No.
38	$^3/_4$Ni–$^1/_2$Mo–$^1/_3$Cr–V	Forgings	SA–508	2	K12766	1	...	3	3
39	$^3/_4$Ni–$^1/_2$Mo–$^1/_3$Cr–V	Forgings	SA–541	2	K12765	1	...	3	3
40	$^3/_4$Ni–$^1/_2$Mo–$^1/_3$Cr–V	Forgings	SA–508	2	K12766	2	...	3	3
41	$^3/_4$Ni–$^1/_2$Mo–$^1/_3$Cr–V	Forgings	SA–541	2	K12765	2	...	3	3
42	$^3/_4$Ni–$^1/_2$Mo–Cr–V	Forgings	SA–508	3	K12042	1	...	3	3
43	$^3/_4$Ni–$^1/_2$Mo–Cr–V	Forgings	SA–508	3	K12042	2	...	3	3
39	3$^1/_2$Ni–1$^3/_4$Cr–$^1/_2$Mo–V	Forgings	SA–508	4N	K22375	3	...	3	3
40	3$^1/_2$Ni–1$^3/_4$Cr–$^1/_2$Mo–V	Forgings	SA–508	4N	K22375	1	...	11A	5
41	3$^1/_2$Ni–1$^3/_4$Cr–$^1/_2$Mo–V	Forgings	SA–508	4N	K22375	2	...	11B	10

05 SA508 : ASME code Section II Materials Part D Properties

Line No.	Min. Tensile Strength, MPa	Min. Yield Strength, MPa	Applicability and Max. Temperature Limits (NP = Not Permitted) (SPT = Supports Only) III	VIII-2	External Pressure Chart No.	Notes
38	550	345	371	371	CS–5	...
39	550	345	371	371	CS–5	...
40	620	450	371	371	CS–5	...
41	620	450	371	371	CS–5	...
42	550	345	371	371	CS–5	...
43	620	450	371	371	CS–5	...
39	620	485	343	371	CS–5	...
40	725	585	343	371	CS–5	H3, S4, W3
41	795	690	NP	343	HT–1	...

Line No.	Design Stress Intensity, MPa (Multiply by 1000 to Obtain kPa), for Metal Temperature, °C, Not Exceeding 40	65	100	125	150	200	250	300	325	350	375	400	425	450	475	500
38	184	184	184	184	184	184	184	184	184	184	184	...	...	...	...	...
39	184	184	184	184	184	184	184	184	184	184	184	...	...	...	...	...
40	207	207	207	207	207	207	207	207	207	207	207	...	...	...	...	...
41	207	207	207	207	207	207	207	207	207	207	207	...	...	...	...	...
42	184	184	184	184	184	184	184	184	184	184	184	...	...	...	...	...
43	207	207	207	207	207	207	207	207	207	207	207	...	...	...	...	...
39	207	207	207	207	207	205	204	202	200	197	194	...	...	...	...	...
40	241	241	241	241	241	239	237	236	233	230	226	...	...	...	...	...
41	264	264	264	264	264	262	260	257	255	252	...	...	...	...	...	...

06 ASME code Sec. XI App. G-2100 VESSELS

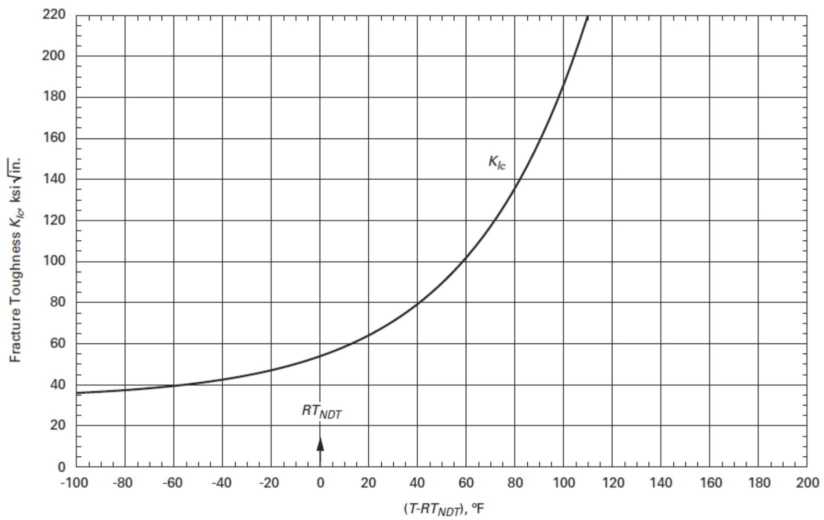
◆ G-2110 Reference Critical Stress Intensity Factor

- Fig. G-2210-1: K_{Ic} vs T 관계를 NB-2331로 결정된 RT_{NDT}와 연관지어 제시

$$K_{Ic} = 33.2 + 20.734 \exp[0.02(T-RT_{NDT})]$$

- SA-533 Grade B Class 1, and SA-508-1, SA-508-2, and SA-508-3 steel 적용 (min. YS at RT of 50 ksi (350 MPa) or less, or for materials in Table G-2110-1 that meet the requirements of NB-2331.)

Figure G-2210-1
Reference Critical Stress Intensity Factor for Material



GENERAL NOTE: 1 ksi√in. = 1.1 MPa√m

Table G-2110-1
Materials With Specified Minimum Yield Strength Greater Than 50 ksi (350 MPa) But Not Exceeding 90 ksi (620 MPa) Permitted to Use Figure G-2210-1 (Figure G-2210-1M)

SA-508 Grade 2 Class 2 (former designation SA-508 Class 2A)
SA-508 Grade 3 Class 2 (former designation SA-508 Class 3A)
SA-533 Type A Class 2 (former designation SA-533 Grade A Class 2)
SA-533 Type B Class 2 (former designation SA-533 Grade B Class 2)

06 ASME code Sec. XI App. G-2100 VESSELS

◆ G-2110 Reference Critical Stress Intensity Factor

- Min. YS at RT > 50 ksi (350 MPa) but < 90 ksi (620 MPa)
  - 모재, 용접재, 열영향부에 대해 최소한 3개 heat의 파괴인성 자료 제시(대상 온도 영역)
  - Figure G-2210-1 곡선과 동등하거나 그 이상임을 증명
  - 조사영향이 있는 곳에 사용하려면(Table G-2110-1 재료 포함) 조사취화 영향도 평가되어야 함.

- Reference Temperature T_0 (ASTM E1921) 적용도 허용

RT_{T0}를 이용한 Fig. G-2210-1은 ASTM E1921의 YS 조건을 만족하는 페라이트계 재료에 사용 가능(275~825MPa)

$$RT_{T0} = T_0 + 35^oF$$

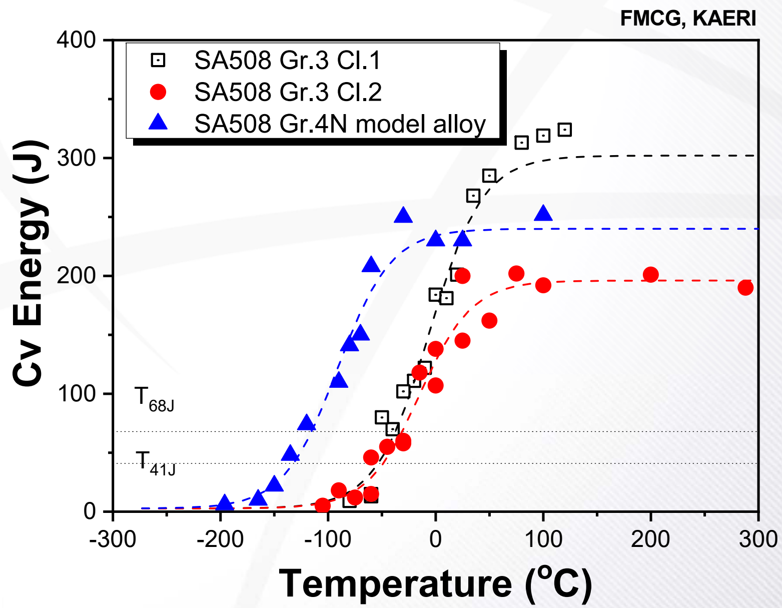
07 재료물성 비교 (SA580 Gr. 3 Cl. 1, 2 and 4N)

▪ **Materials**

		C	Mn	Ni	Cr	Mo
Spec. in ASME code	SA508 Gr.3	0.25 max	1.20-1.50	0.40-1.00	0.25 max	0.45-0.60
	SA508 Gr.4N	0.23 max	0.20-0.40	2.80-3.90	1.50-2.00	0.40-0.60
Tested materials	SA508 Gr.3 Cl.1	0.21	1.36	0.92	0.21	0.49
	SA508 Gr.3 Cl.2	0.24	1.39	0.86	0.22	0.53
	SA508 Gr.4N model alloy	0.20	0.23	3.41	1.83	0.51

▪ **Tensile Prop., USE, T_{41J}**

	YS (MPa)	TS (MPa)	USE (J)	T_{41J} (°C)
Gr.3 Cl.1	436	586	302	-53
Gr.3 Cl.2	547	695	196	-49
Gr.4N	541	669	240	-132



⇒ **인장특성 : Gr. 4N ≅ Gr.3 Cl. 2 > Gr.3 Cl. 1**

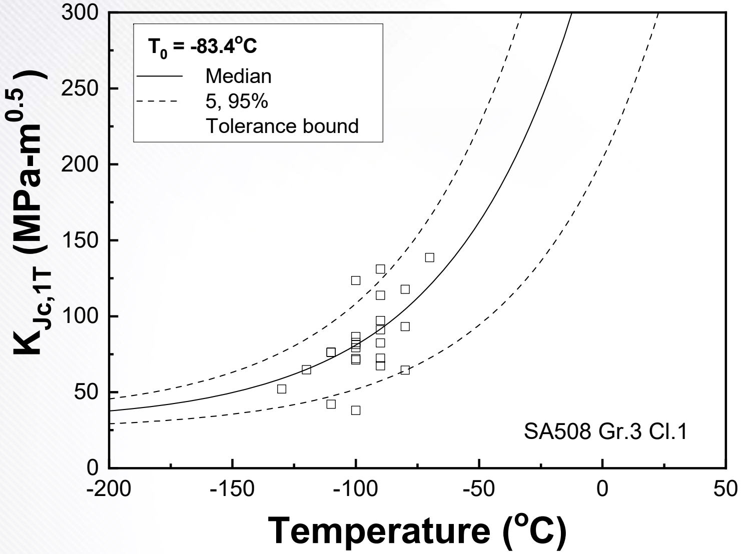
⇒ **충격천이특성 :Gr. 4N >> Gr. 3 Cl. 1 > Gr. 3 Cl. 2**

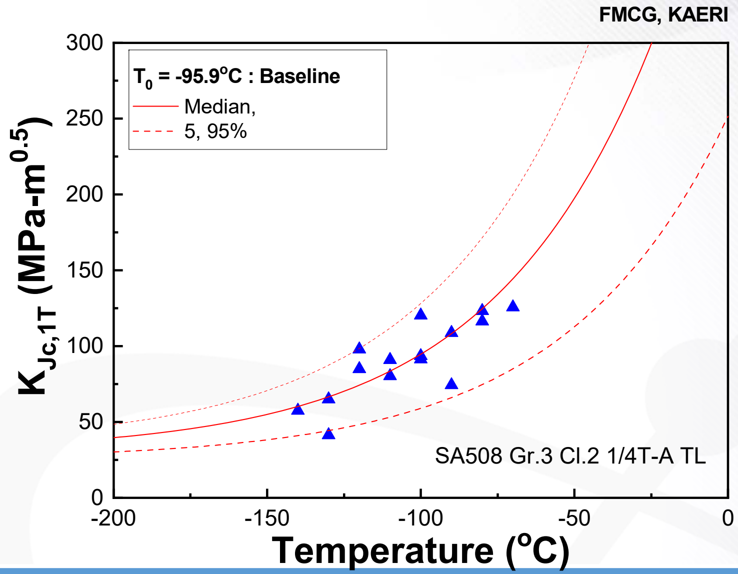
⇒ **천이온도는 Gr. 3 Cl. 1과 Gr. 3 Cl. 2가 유사**

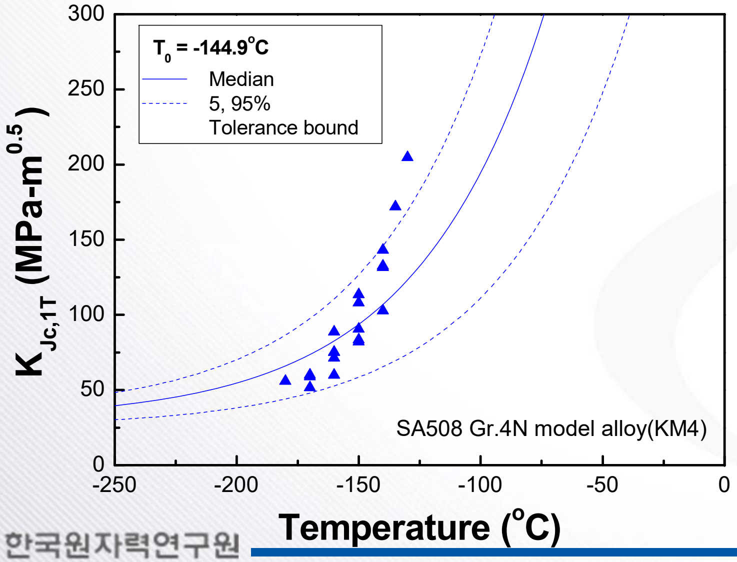
⇒ **Gr. 3 Cl.2는 상부흡수에너지가 낮음**

07 재료물성 비교 (SA580 Gr. 3 Cl. 1, 2 and 4N)

- **Fracture Toughness**







T_0 : Gr. 4N(-144.9°C)<Cl. 2(-95.9°C)<Cl. 1(-83.4°C)

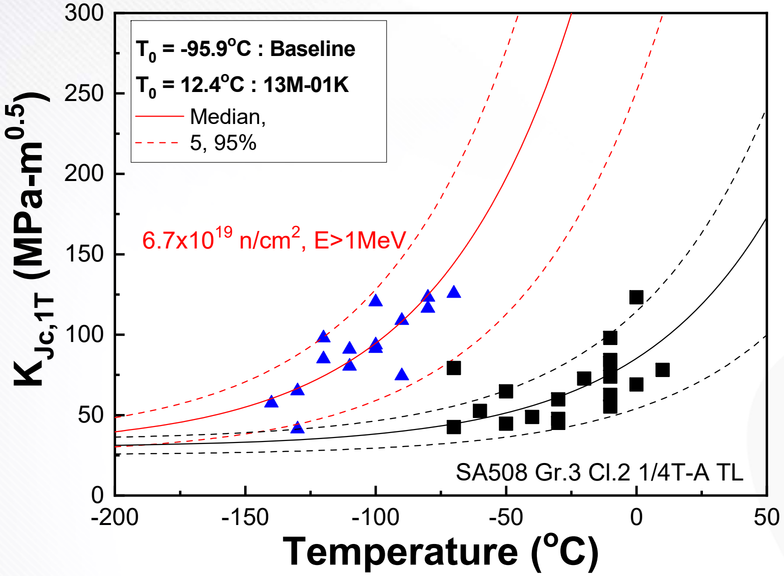
- Fracture toughness in the transition region according to ASTM E1921 mater curve method

⇒ SA508 Gr.4N model alloy shows the improved fracture toughness (T_0 = -145°C)

⇒ T_0 of SA508 Gr.3 Cl.1 steel was slightly higher than that of SA508 Gr.3 Cl.2

07 재료물성 비교 (SA580 Gr. 3 Cl. 1, 2 and 4N)

▪ 중성자 조사취화 특성 비교



- SA508 Gr. 3 Cl. 2 소재는 6.7×10^{19} n/cm^{2}의 중성자조사로 인해 T_0값이 100°C 이상 상승하는 낮은 조사취화 저항성을 보임.

⇒ SA508 Gr. 3 Cl. 2 소재를 원자로용기에 적용하려면 조사취화 저항성, 편차 등에 대한 검증이 반드시 필요함.

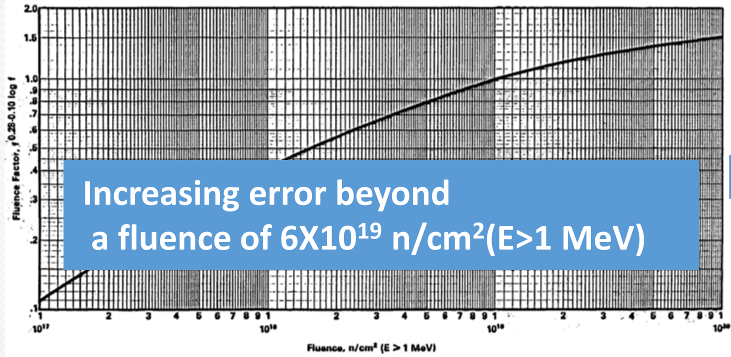
ID	Fluence (n/cm^2, E>1MeV)	Irr. temp. (°C)	$T_{0.Un-irr.}$ (°C)	$T_{0,Irr.}$ (°C)	ΔT_0 (°C)
SA508 Gr.3 Cl.1	7.08 x10^{19}	295	-83	-59	24
SA508 Gr.3 Cl.2	6.66 x10^{19}	287	-96	12	108
SA508 Gr.4N model alloy	11.1 x10^{19}	290	-151	-77	68

- SA508 Gr. 4N 모델합금은 높은 중성자 조사량에서도 상당히 우수한 파괴인성을 보임. 조사전 T_0값이 매우 낮아서, 11.1×10^{19} n/cm^2 중성자 조사 후에서도 SA508 Gr. 3소재의 조사전과 유사한 값을 나타냄.

08 RPV ETC(embrittlement trend correlation)

◆ Fluence Limit 검토

- R.G. 1.99 Rev. 1 (1977) : < $6X10^{19}$ n/cm^2(E>1 MeV)
- R.G. 1.99 Rev. 2 (1988) : < $1X10^{20}$ n/cm^2(E>1 MeV) in figure (data points: 177)
- 현재 가능한 Data points : 1900 이상



ASTM Subcommittee e10.02, R.G. 1.99 Rev. 3 개발중

- 높은 조사량에서 모재의 비보수성
- 낮은 구리 함량 RPV 재료에서의 부정확성
- 현재 database와 비교하여 표준편차를 과소평가
- Low-to-mid 조사량에서 보수적 편향
- 조사 온도에 대한 조정치 부족

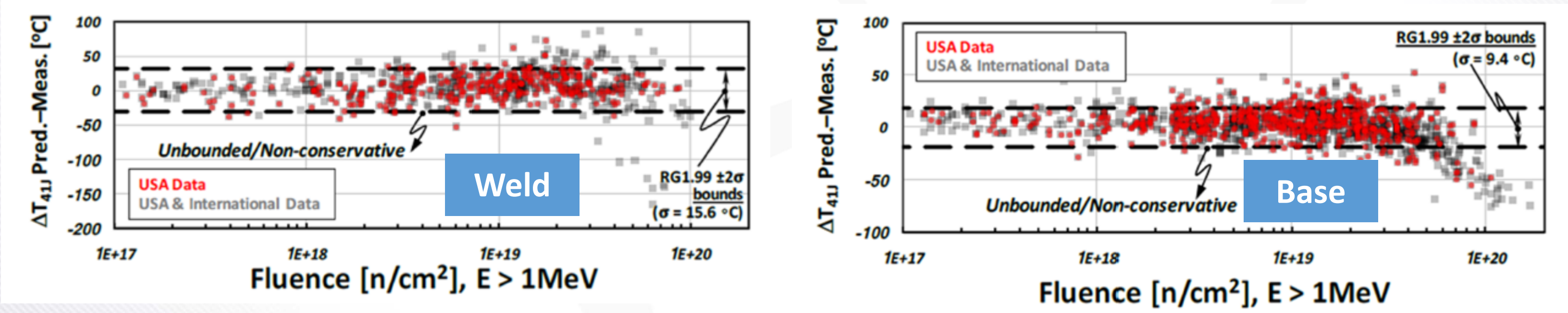


Figure 1. Estimates of the residual (RG 1.99, Revision 2 predicted minus measured values) of ΔRT_{NDT} using the current US and international database for (a) welds and (b) base metal.

08 RPV ETC(embrittlement trend correlation)

◆ Fluence Limit 검토

- ASTM E900-15 e2

  : 조사온도(T) 고려, 1×10^{17} ~ 2×10^{20} n/cm^2

1.1.1.5 Irradiation temperature within the range from 255 to 300°C (491 to 572°F).

1.1.1.6 Neutron fluence within the range from 1×10^{21} n/m^2 to 2×10^{24} n/m^2 (E> 1 MeV).

1.1.1.7 A categorical variable describing the product form (that is, weld, plate, forging).

1.1.2 *The range of material and irradiation conditions in the database for variables not included in the embrittlement correlation:*

1.1.2.1 A533 Type B Class 1 and 2, A302 Grade B, A302 Grade B (modified), and A508 Class 2 and 3. Also, European and Japanese steel grades that are equivalent to these ASTM Grades.

1.1.2.2 Submerged arc welds, shielded arc welds, and electroslag welds having compositions consistent with those of the welds used to join the base materials described in 1.1.2.1.

1.1.2.3 Neutron fluence rate within the range from 3×10^{12} n/m^2/s to 5×10^{16} n/m^2/s (E > 1 MeV).

1.1.2.4 Neutron energy spectra within the range expected at the reactor vessel region adjacent to the core of commercial PWRs and BWRs (greater than approximately 500MW electric).

1.1.2.5 Irradiation exposure times of up to 25 years in boiling water reactors and 31 years in pressurized water reactors.

$$TTS = TTS_1 + TTS_2 \quad (1)$$

where:

조사온도

$$TTS_1 = A \cdot \frac{5}{9} \cdot 1.8943 \times 10^{-12} \cdot \Phi^{0.5695} \left(\frac{1.8T + 32}{550}\right)^{-5.47} \left(0.09 + \frac{P}{0.012}\right)^{0.216} \left(1.66 + \frac{Ni^{8.54}}{0.63}\right)^{0.39} \left(\frac{Mn}{1.36}\right)^{0.3} \quad (2)$$

$$A = \begin{pmatrix} 1.011 \text{ for forgings} \\ 1.080 \text{ for plates and SRM plates} \\ 0.919 \text{ for welds} \end{pmatrix} \quad (3)$$

and:

$$TTS_2 = \frac{5}{9} \cdot \max[\min(Cu, 0.28) - 0.053, 0] \cdot M \quad (4)$$

$$M = B \cdot \max\{\min[113.87(\ln(\Phi) - \ln(4.5 \times 10^{20})), 612.6], 0\} \cdot \left(\frac{1.8 \cdot T + 32}{550}\right)^{-5.45} \left(0.1 + \frac{P}{0.012}\right)^{-0.098} \left(0.168 + \frac{Ni^{0.58}}{0.63}\right)^{0.73} \quad (5)$$

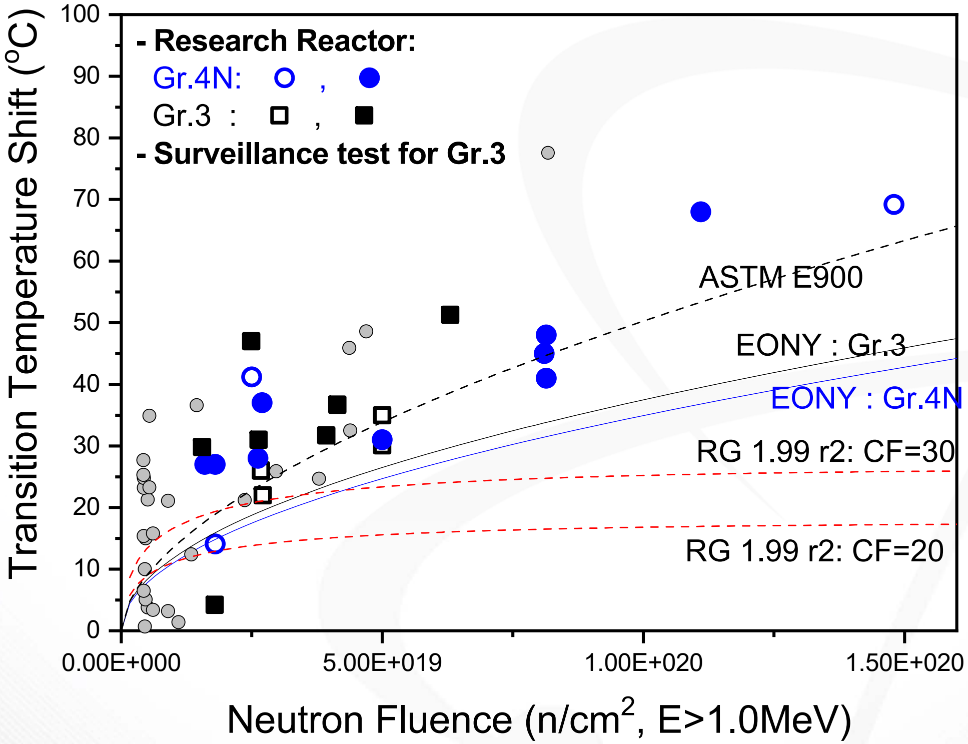
$$B = \begin{pmatrix} 0.738 \text{ for forgings} \\ 0.819 \text{ for plates and SRM plates} \\ 0.968 \text{ for welds} \end{pmatrix} \quad (6)$$

◆ Fluence Limit 검토 결과 요약

- 현재 RPV 조사취화 평가를 위해서는 R.G. 1.99 또는 10CFR50.61a를 사용해야 함
- R.G. 1.99 Rev. 2는 사용된 데이터의 양이 적고, $6X10^{19}$ n/cm^2 에서부터 계산된 trend의 문제가 있으며 $1X10^{20}$ n/cm^2(E>1 MeV) 까지만 사용 가능함.
- R.G. 1.99 Rev. 2의 여러 결점들로 인하여, ASTM Subcommittee에서 현재 가용한 데이터(1900개 이상)를 최대한 활용한 Rev. 3를 준비하고 있음.
- 10CFR50.61a에서는 Fluence limit를 지정하고 있지 않음.
- ASTM E900-15 e2에서는 **2×10^{20}** n/cm^2까지 제시하고 있음.

◆ SA508 Gr.3 Cl.1 & Gr.4N(모델합금) 조사취화 경향

- 국내 감시시험 결과 및 연구로 시험결과와 조사취화 경향 곡선 비교:
  SA508 Gr.3 Cl.1 상용소재 결과 + SA508 Gr.4N 모델합금(KAERI) 결과
- ASTM E900 모델이 가장 근접한 결과를 보이고 있음



08 RPV ETC(embrittlement trend correlation)

◆ I-SMR 관련 ETC 검토

- NuScale FSAR에서는 57 EFPY beltline 내벽 조사량이 1.77×10^{19} n/cm^2(E>1 MeV)임.
- I-SMR의 경우 NuScale에 비해 출력이 크며(170/60MWe), 내벽과 핵연료 사이 공간이 가까워 더 높은 조사량을 받을 것으로 예상함. 특히, 80년 이상의 수명으로 결정될 경우 조사량은 더 커짐.
- 현재 I-SMR 원자로 직경이 4.5m로 설계되고 있으나, 더 넓은 직경이 필요할 것으로 예상됨(설계 문제).
- 현재의 RPV 설계 두께(250mm)가 유지된 상태에서 직경이 넓어질 경우 RPV 무게는 더 증가함.
- RPV 두께를 줄이면, RPV OD와 containment vessel의 조사취화량 평가도 필요할 것으로 보임.

Table 5.3-3: 1/4-T Adjusted Reference Temperature Result at 57 Effective Full-Power Years Fluence

Location	Peak 1/4-T Fluence, n/cm^2, E >1 MeV	Maximum Initial RT_{NDT} (°F)	ΔRT_{NDT} (°F)	Margin (°F)	Adjusted Reference Temperature (°F)
Lower RPV shell, beltline	1.37E+19	-10	68.2	34.0	92.2
Lower RPV weld	3.21E+18	-20	84.4	56.0	120.4
RPV bottom head	3.21E+18	-10	53.4	34.0	77.4

Table 5.3-8: Pressurized Thermal Shock Screening Result

	0-T Fluence n/cm^2, E > 1 MeV	Max Initial RT_{NDT} (°F)	ΔRT_{NDT} (°F)	Margin (°F)	RT_{PTS} (°F)	Screening Criterion (°F)
(32-EFPY Fluence)						
Lower RPV shell, beltline	9.94E+18	-10	64.9	34.0	88.9	270 max
Lower RPV weld	2.32E+18	-20	77.6	56.0	113.6	300 max
RPV bottom head	2.32E+18	-10	50.4	34.0	74.4	270 max
(57-EFPY Fluence)						
Lower RPV shell, beltline	1.77E+19	-10	70.8	34.0	94.8	270 max
Lower RPV weld	4.14E+18	-20	89.9	56.0	125.9	300 max
RPV bottom head	4.14E+18	-10	55.9	34.0	79.9	270 max

감사합니다.