Integrity of Mechanical Components and Safety Classification

Sep. 22, 2022
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Purposes of this lecture

There are lots of mechanical components (MC) in NPPs such as pressure vessels, heat exchangers, piping & supports, pumps & valves, and its parts.

- The integrity of MCs shall be maintained to ensure the nuclear safety.
- However, it is not easy to maintain the integrity of MCs for its design life (40~60 years) because of severe loading condition and harsh environmental condition.
- Lots of failure in MCs have been world widely reported in NPPs.

=> How to maintain the integrity of Mechanical Components in NPPs?

Contents

I Integrity of Mechanical Component

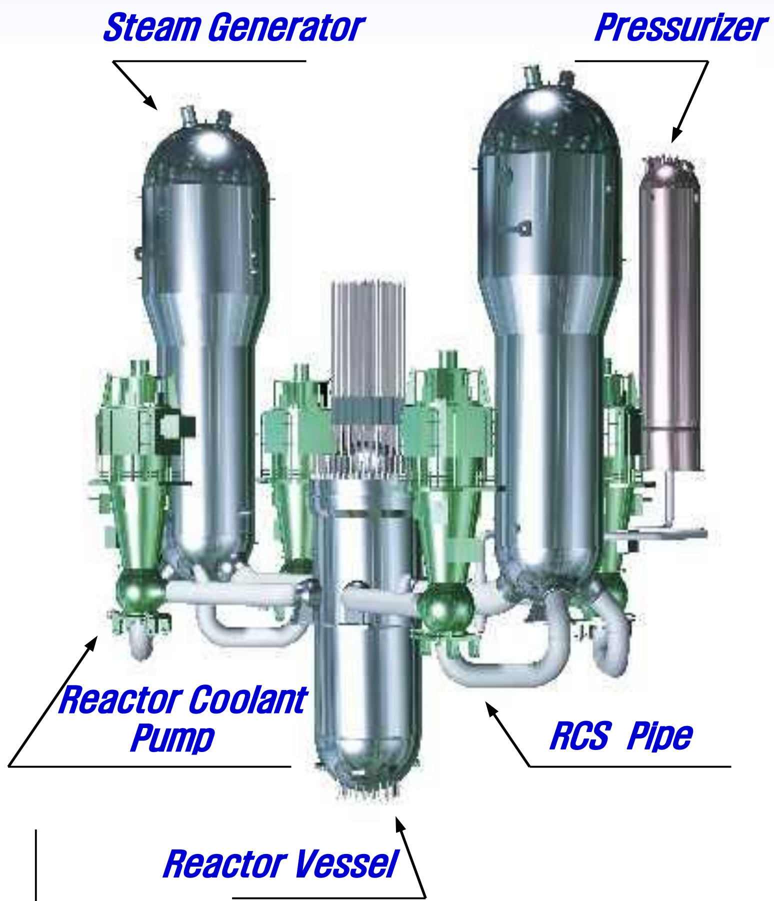
II Safety Classification

III Concluding Remark

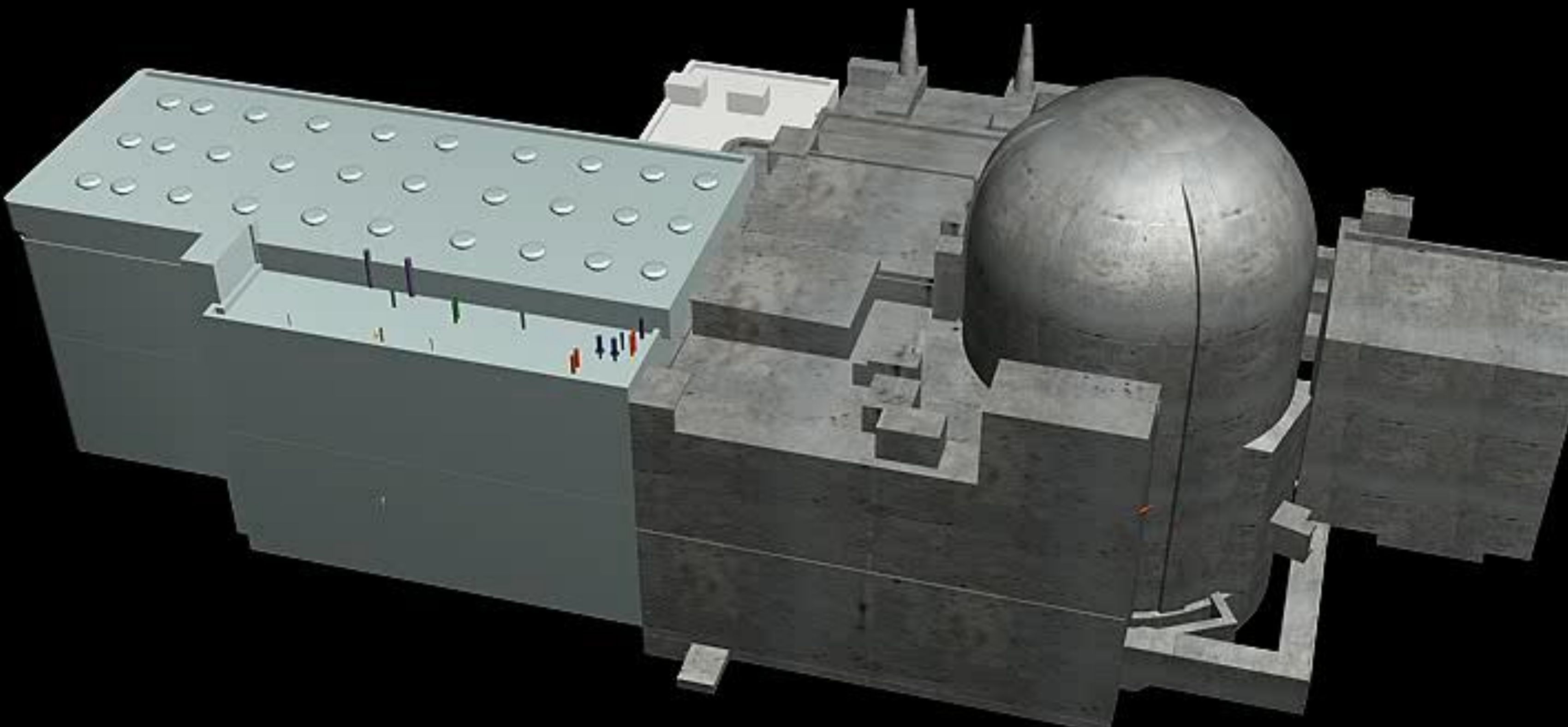
Ⅰ. Integrity of Mechanical Component

Nuclear Systems

- **NSSS**
  - Nuclear Steam Supply System
  - Reactor Coolant System
  - Primary System
- **ESF**
  - Engineered Safety Feature
  - Safety System
  - SIS, SDS, Spray Sys.
- **BOP**
  - Balance of Plant
  - Secondary System
  - MSS, FWS, TBN, CC, ESW, etc.



[Reactor Coolant System]



1. Mechanical Components in NPP

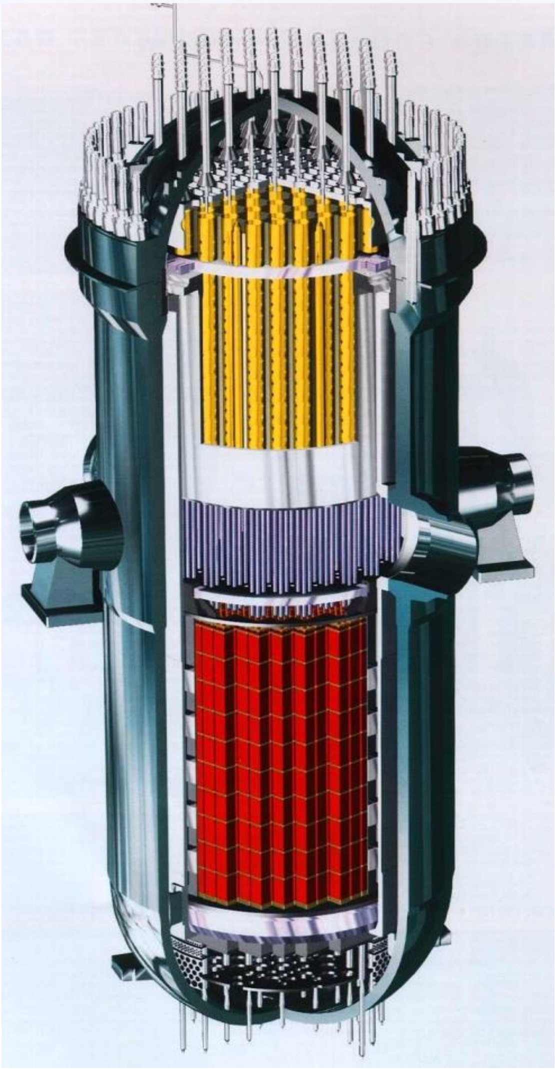
- **Pressure retaining Components**
  - Pressure Vessel : Reactor Vessel (Rx), Pressurizer
  - Heat Exchanger : Steam Generator (SG), SI/SC Heat Exchanger
  - Piping and Support
  - Pump and Valve

- **Non-pressure retaining Components**
  - Rx/SG internals, Diesel Generator, and Turbine, etc.

Mechanical Components (1)

❑ Pressure Vessel

- Reactor : Vessel, Rx Internals, Control Rod Driving Mechanism, Reactor Support
- Pressurizer : PRZ Vessel, Heater, Safety/Relief Valve, PRZ Support
- High Pressure, Thermal Transient
- Carbon Steel (CS) with internal Stainless Steel (SS) Cladding.
- Design Life of Reactor Vessel : 40~60 yrs

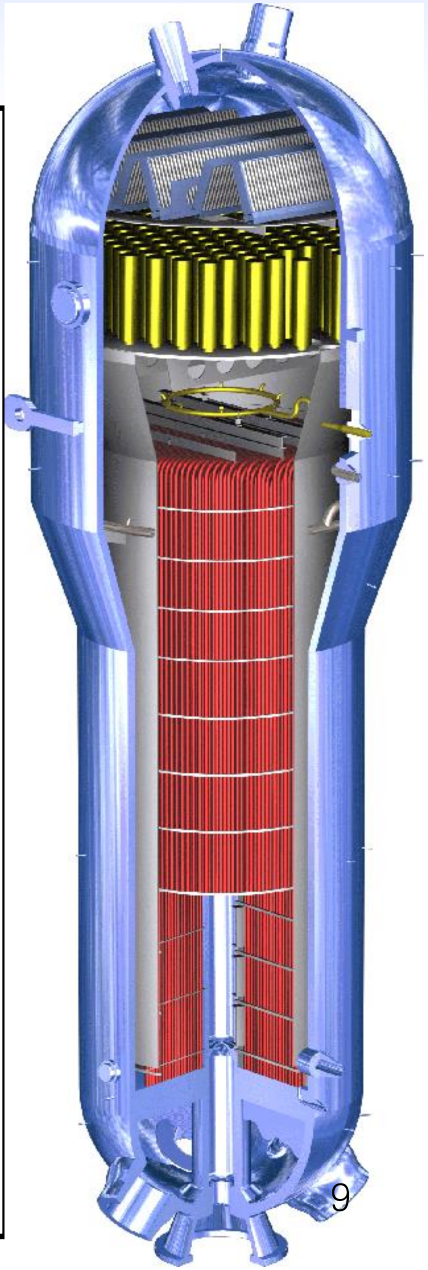


Mechanical Components (2)

❑ Heat Exchanger

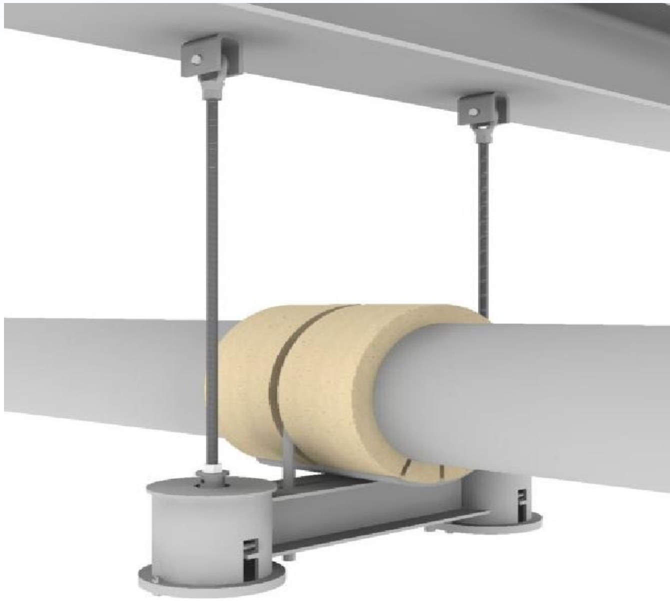
- Steam Generator in NSSS
  - SG Vessel, SG Internals, Support, SG Tube
  - SG Tube : Boundary of NSSS and BOP
  - Vessel (Carbon Steel), Tube(Inconel 600/690)

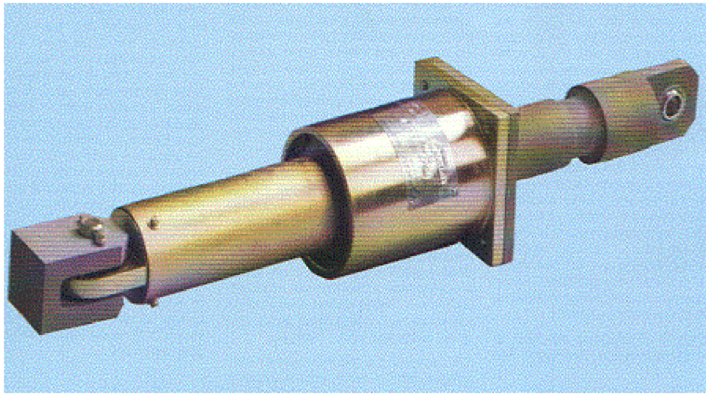
- Heat Exchanger in ESF & BOP
  - Lots of Heat Exchanger in ESF & BOP
  - SI Hx, SD Hx, SP Hx
  - Hx Vessel, Hx Internals, Support, HX tube
  - Vessel (Carbon Steel), Tube(Ni alloy)



Mechanical Components (3)

- Piping & Support
  - total 160km Piping in one APR-1400 plant
    - Lots of Weld (about 3,000 welds in safety class piping)
  - Carbon Steel piping or Stainless Steel piping
    - RCS Piping : CS(CE), SS(WH)
    - ESF Piping : SS
    - BOP Piping : CS
  - Piping Support
  - Snubber against Earthquake

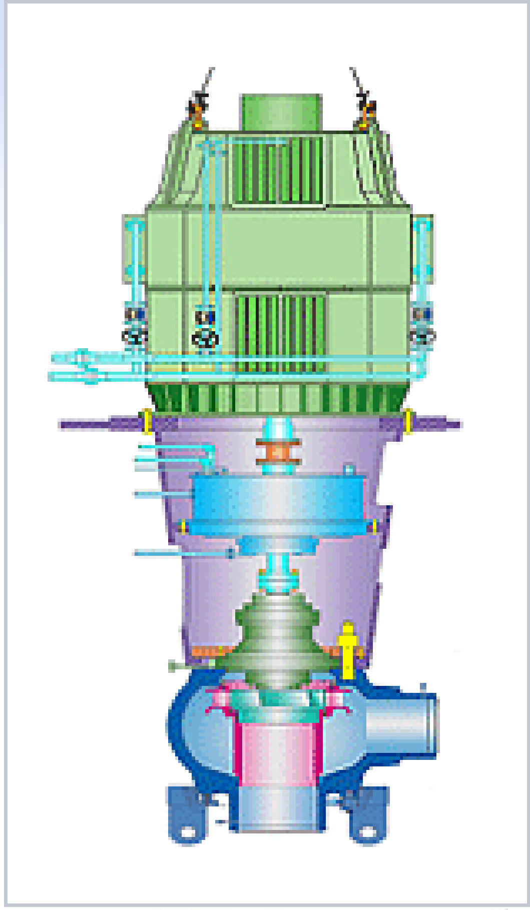




Mechanical Components (4)

- Pump
  - 300 pumps in one APR-1400 plant
  - Reactor Coolant Pump in NSSS
  - Pressure retaining portion

- Valve
  - About 20,000 valves in one APR-1400 plant
  - Motor Operated Valve for control
  - Pressure retaining portion

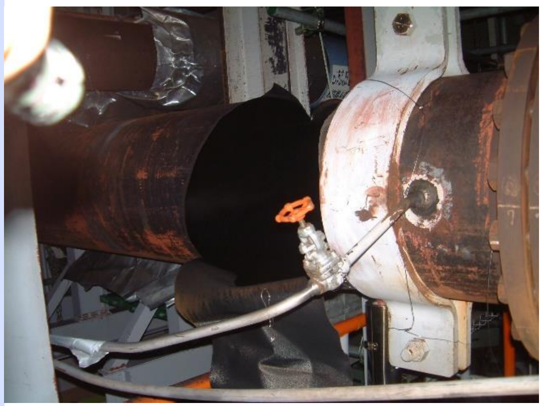


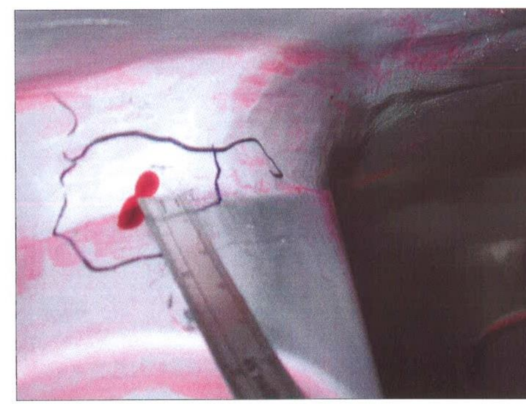
Regulation & Guides, and Codes & Standards

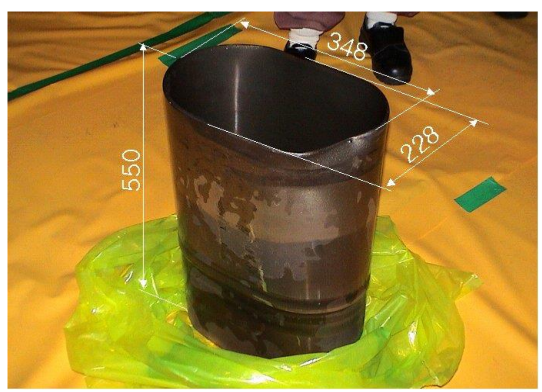
- In order to maintain the integrity of nuclear components in NPPs, various regulation & guides, and codes & standards are used in design, material, manufacture, inspections, and test.
  - Those are developed considering failure experiences of nuclear components in NPPs in the world since early 60's.

2. Failure of Mechanical Components

- In Spite of comprehensive efforts to maintain the integrity of mechanical component, lots of failures in mechanical components of NPPs have being world-widely reported.







Failure Cases of Mechanical Components

- Piping Failure
  - OPDE Piping Failure Database
  - FAC (Flow Accelerated Corrosion)
  - HDPE (High Density Poly Ethylene)

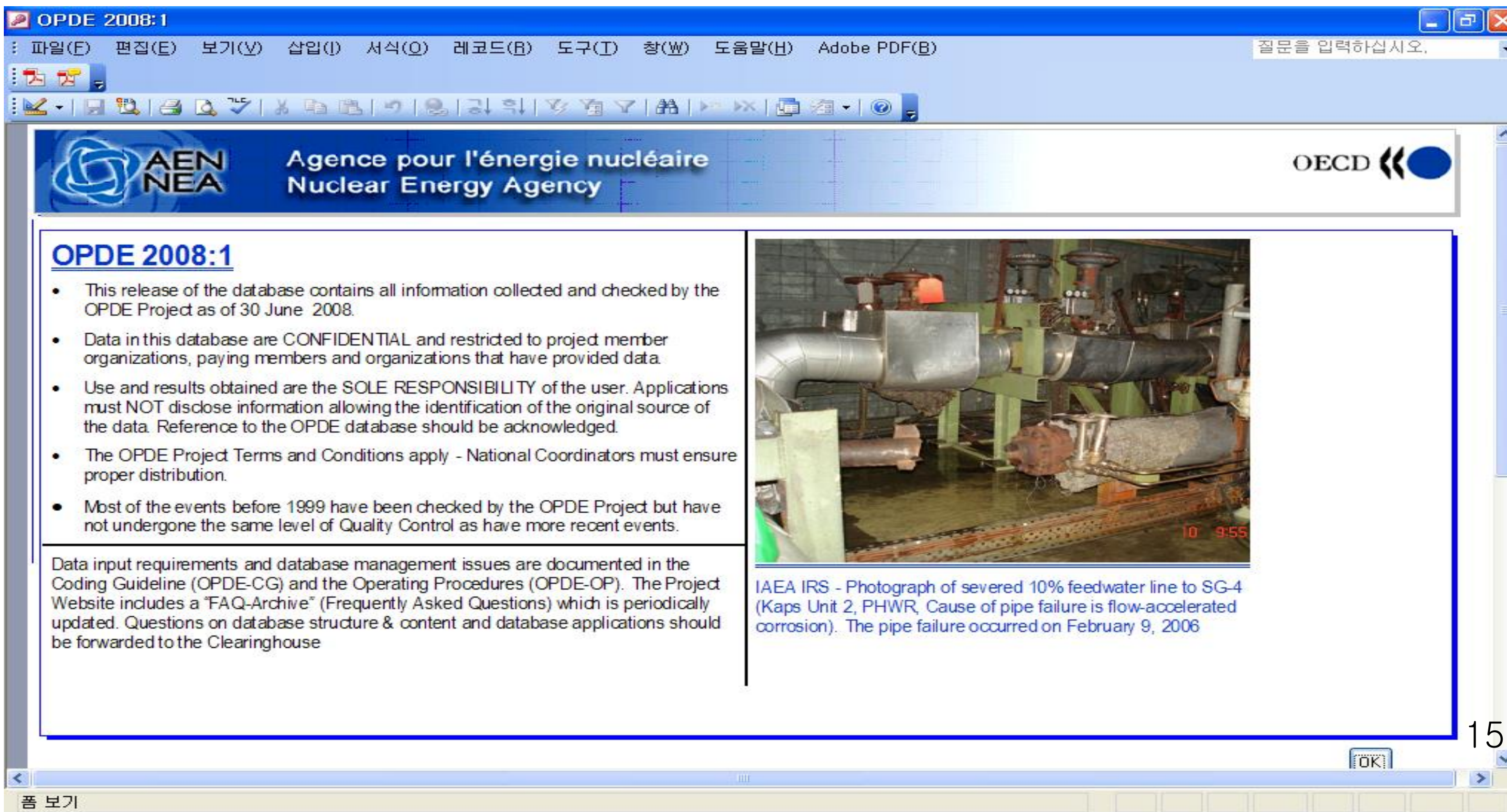
- Reactor Failure
  - PWSCC (Primary Water Stress Corrosion Cracking) : CRDM Cracking
  - BAC (Boric Acid Corrosion) : Reactor Head Damage

- Steam Generator Tube Rupture
  - PWSCC (Primary Water Stress Corrosion Cracking) : SG Tube Rupture

(1) OECD Research Program on Piping Failures in NPP

❑ OECD Piping Failure Exchange (OPDE) Database

- Sponsored by IAGE Group in OECD/NEA
- 3,600 Piping Failure Data from 12 countries including Korea
- Web based Database



Root Cause Analysis of Piping Failure using OPDE

- Analysis of 2400 Piping Failure in OPDE
  - about 80% failures due to Corrosion and Fatigue
  - About 70% Failures occurred in small piping less than Dia=4 inches

- Enhanced Inspection focused on corrosion/fatigue and small piping.

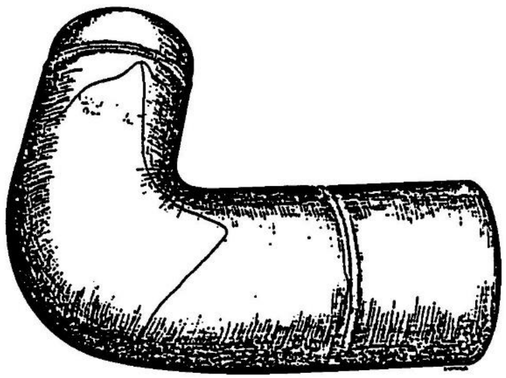
Root Cause		#	Sum	ratio
Corrosion	SCC	430	1029	43%
	FAC	390		
	Gen, Cor	209		
Fatigue	Vibration	684	843	35%
	Thermal	103		
	Mech.	56		
Human Error		234	233	10%
Over Load		139	139	6%
etc		15	15	1%
unclear		141	141	5%

Diameter	#	rate	Root Cause
Less then 1 in	1121	47%	Vib, FAC, H.E
1~4 in	540	23%	Vib, FAC, SCC
4~10 in	429	18%	FAC, SCC, Vib, O.L
10~30 in	299	12%	SCC, FAC, Fatigue
Larger than 30 in	11	0.5%	O.L, Fatigue, SCC, FAC

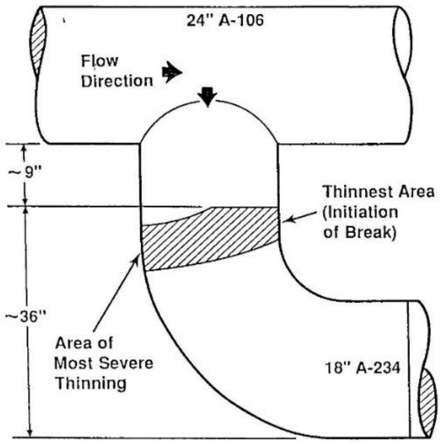
(2) Piping Rupture in USA

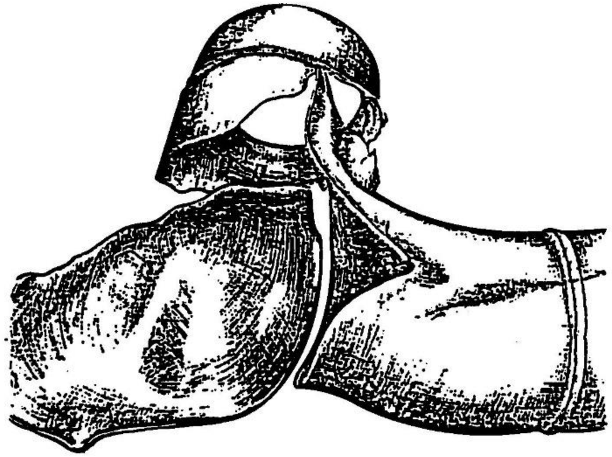
- Surry unit 2 in 1986 in USA.
- 4 workers died, 2 workers injured
- Root Cause : Flow Accelerated Corrosion (FAC)

- US NRC enforced the enhanced UT inspection of secondary carbon steel piping from this accident.



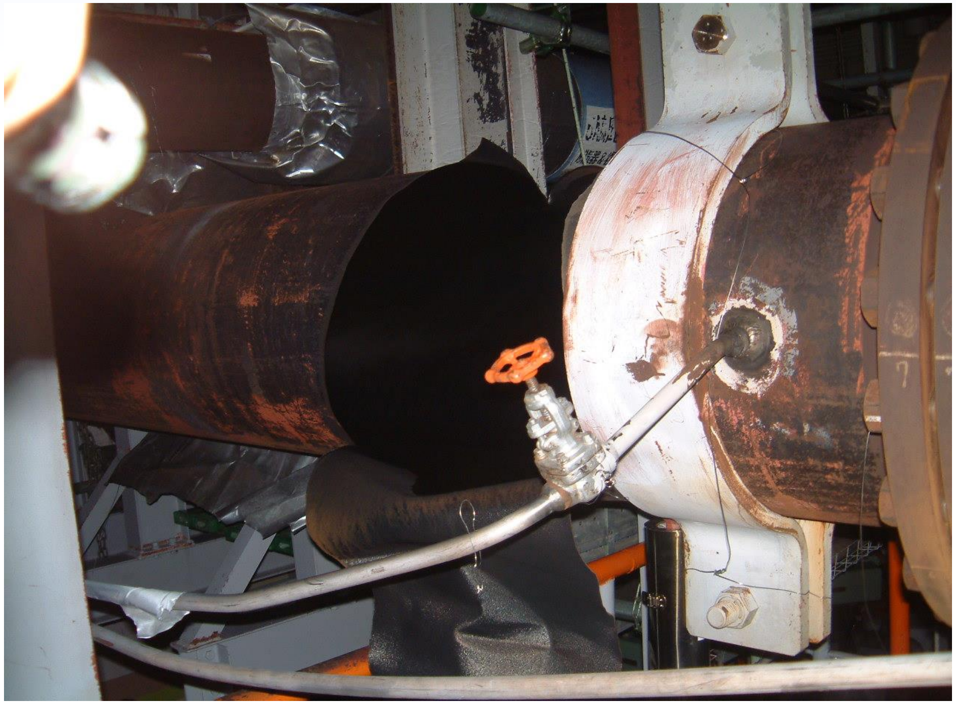
(a) Rupture lines in intact pipe

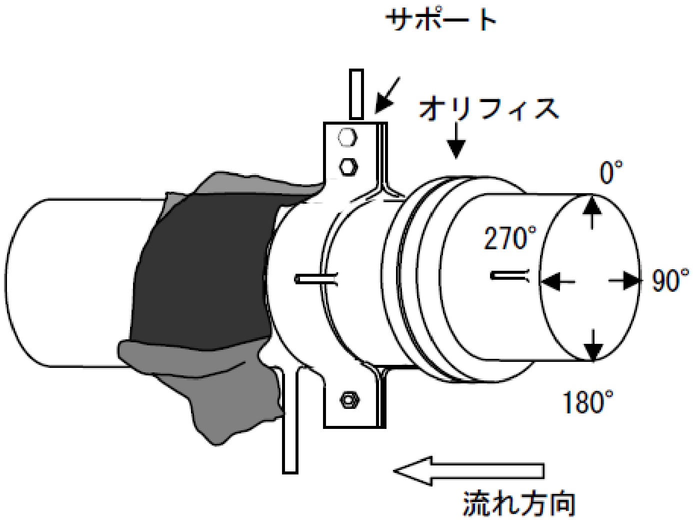




(b) Pipe after rupture

(3) Piping Rupture in Japan





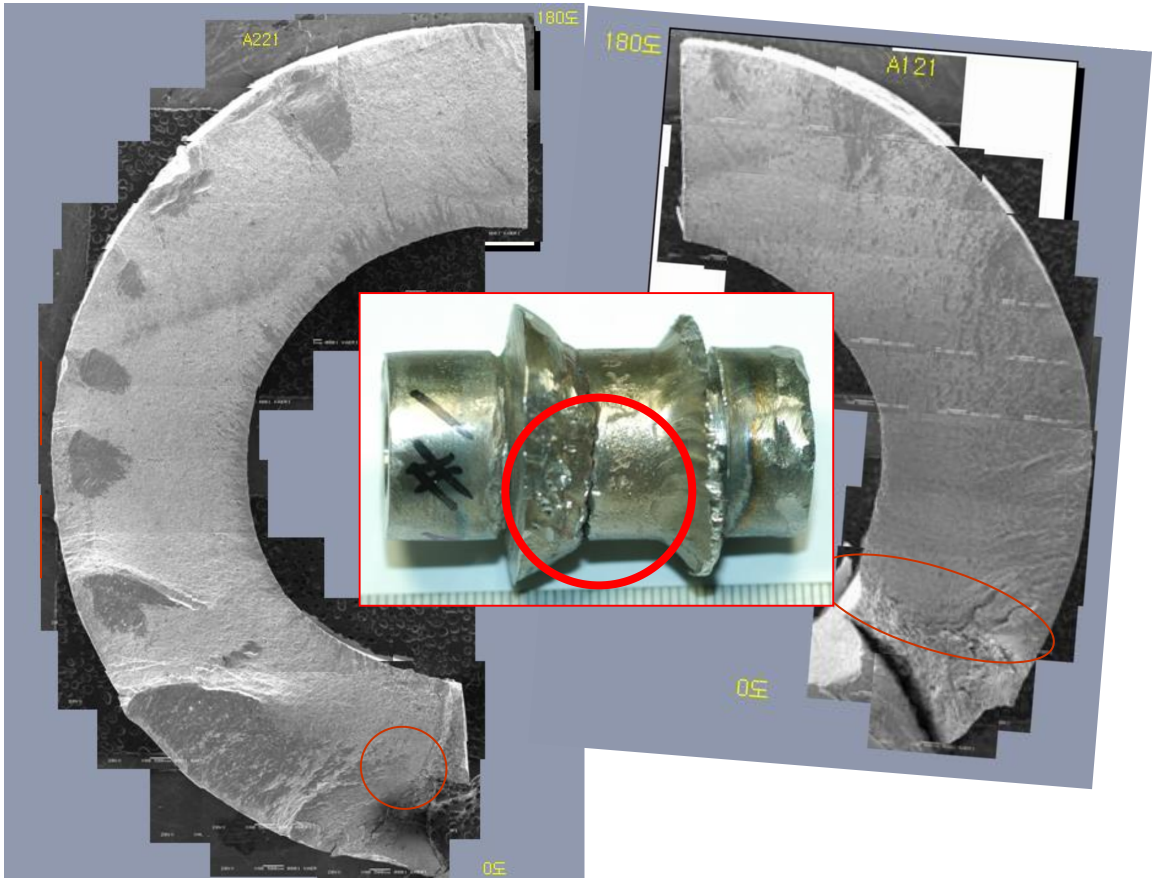
- Mihama Unit #3 in Japan
- Event Date : Aug. 2004
- Piping was totally ruptured and 5 workers died,
- Piping Outer Diameter = 560 mm, Design Wall Thickness = 10 mm
- Root Cause : Flow Accelerated Corrosion (FAC)

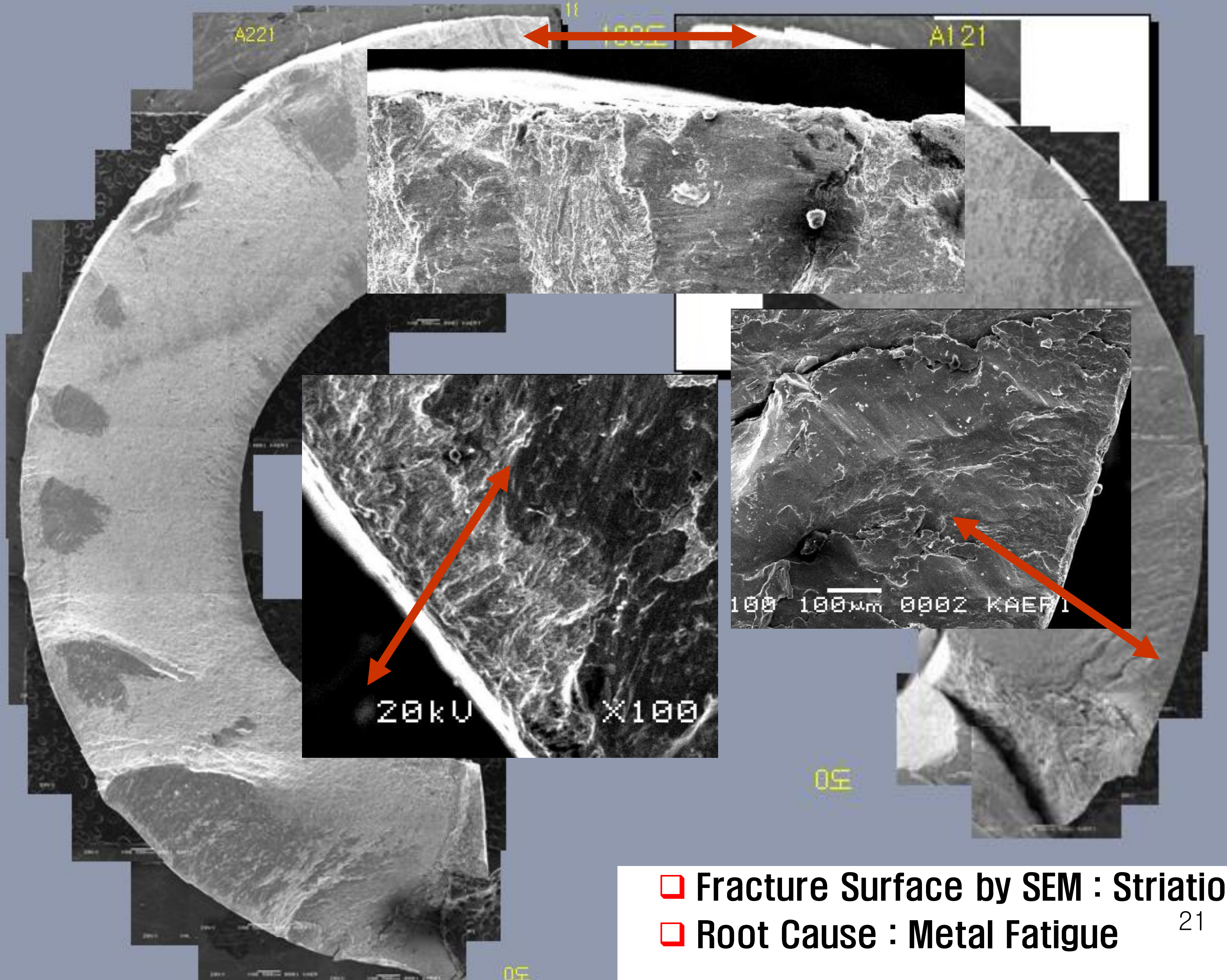
(4) HDPE Piping Failure in Korea

- HDPE(High Density Poly Ethylene) Piping in Fire Protection System buried in yard in Korean APR-1400 Plant
- Event Date : 2012.12~2014.09 (10 times piping failures)
- Root Cause : Water Hammer during Operation and Test & HDPE Piping Material problems

(5) Failure in Drain Line connected to Charging Pump

- ❑ CVCS Charging Line piping failure in Korean NPP
- ❑ Root Cause : Metal Fatigue

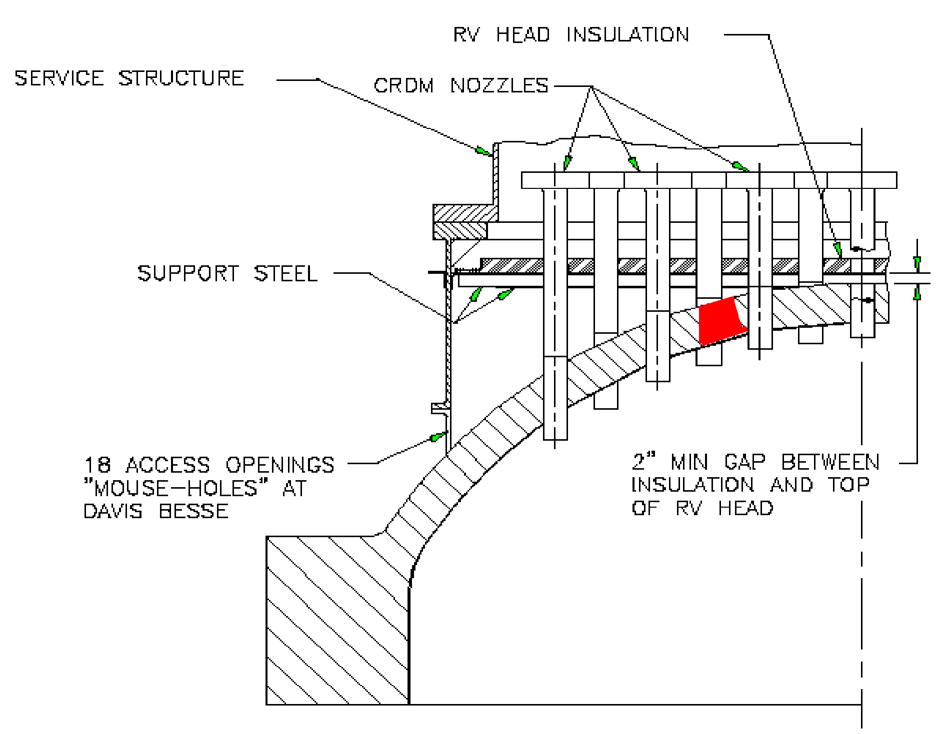




- Fracture Surface by SEM : Striation
- Root Cause : Metal Fatigue

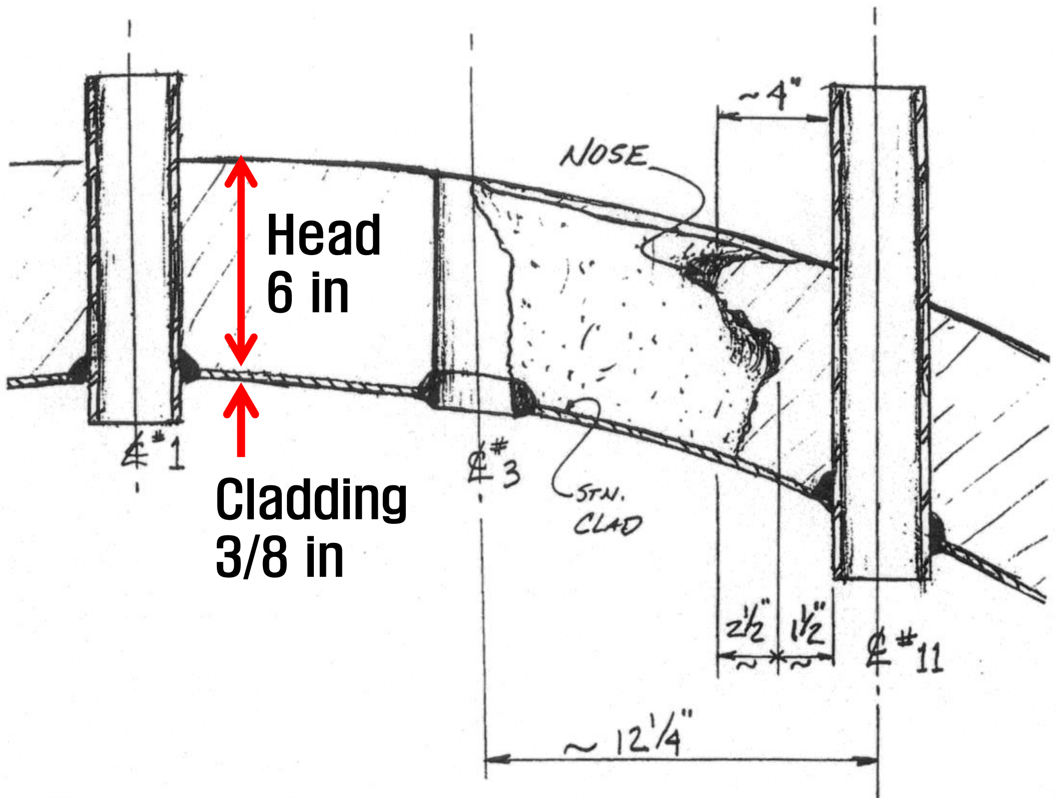
(6) Reactor Vessel Failure in USA

- Severe damage near CRDM nozzle in Reactor Head were found in Davis-Besse NPP during O/H in March, 2002 in Davis-Besse NPP.
- Failure Size : 4~5 in (wide). 6 in (depth) / 1.75 in (depth)
- Root Cause : PWSCC (Primary Water Stress Corrosion Cracking) and BAC (Boric Acid Corrosion)



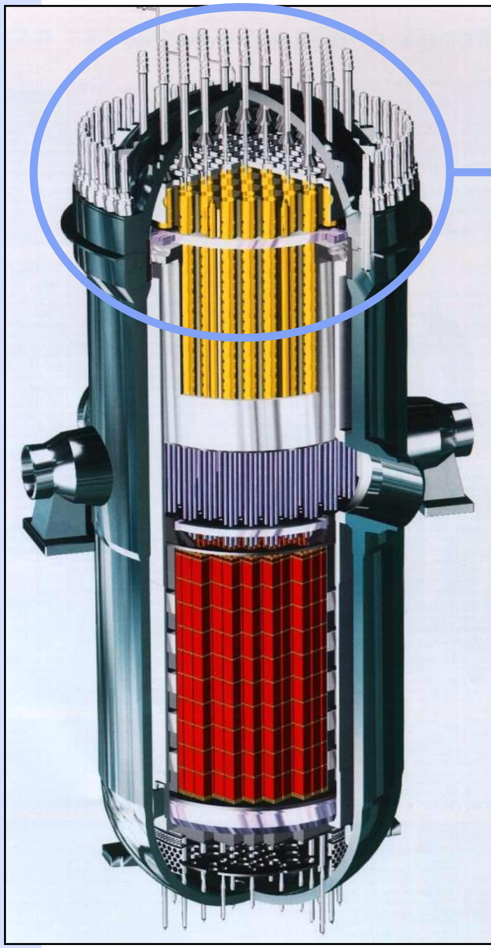
Photograph of Failure Near CRDM #3

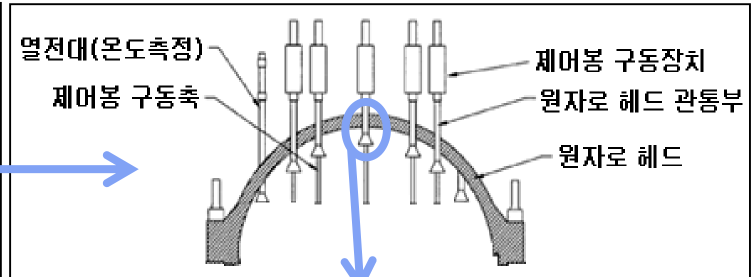
Schematic Diagram of Failure Near CRDM #3

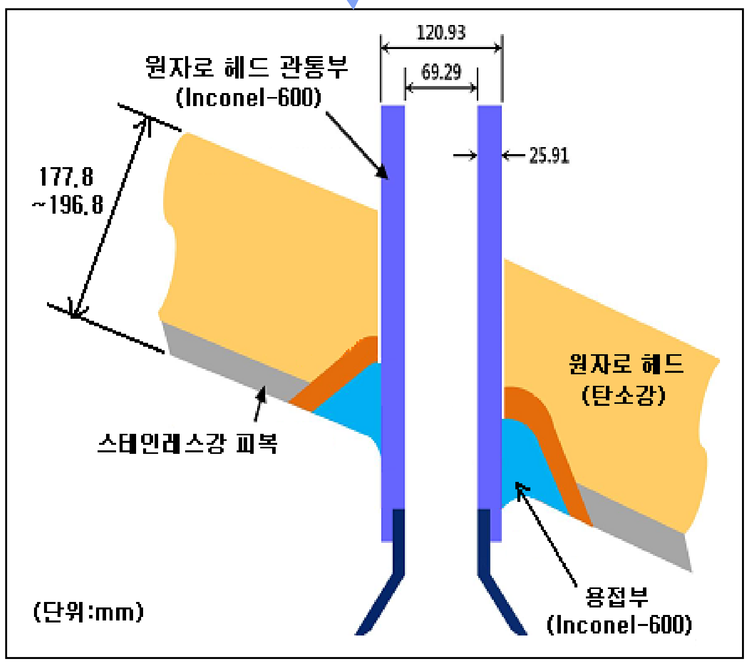


- The mechanical integrity of the failed reactor head was maintained during operation by the remaining stainless steel cladding parts (thickness=3/8 inch)

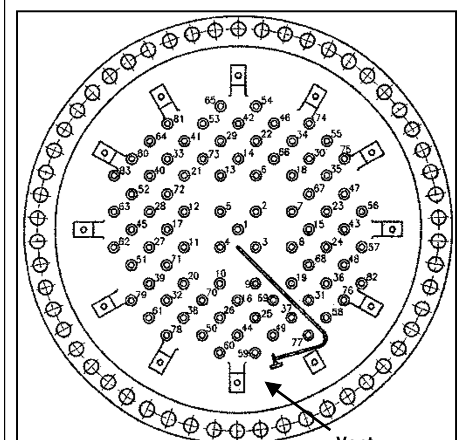
(7) Cracking in Reactor Head CRDM Penetration in Korea







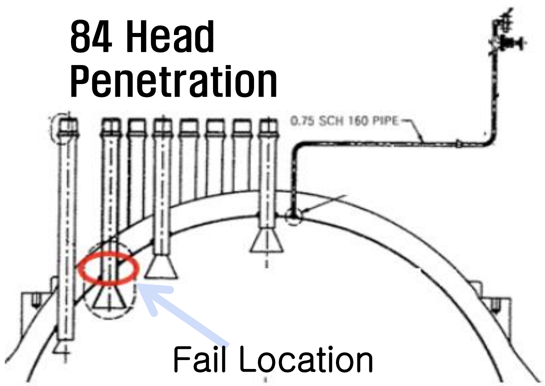
◎ 84 penetration
- CRDM : 81
- Thermo Couple : 2
- Vent line : 1



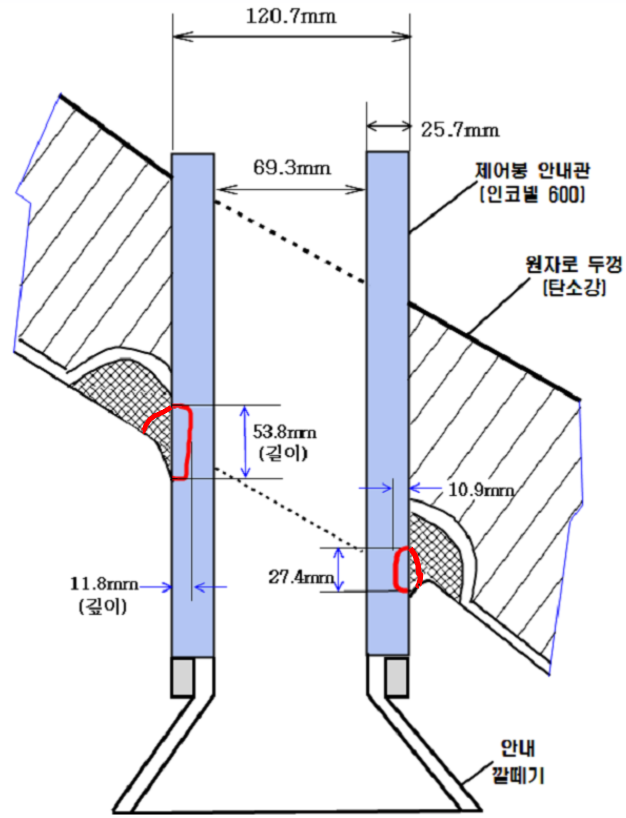
Reactor

Reactor Head and Penetration

Cracking in Reactor Head CRDM Penetration in Korea



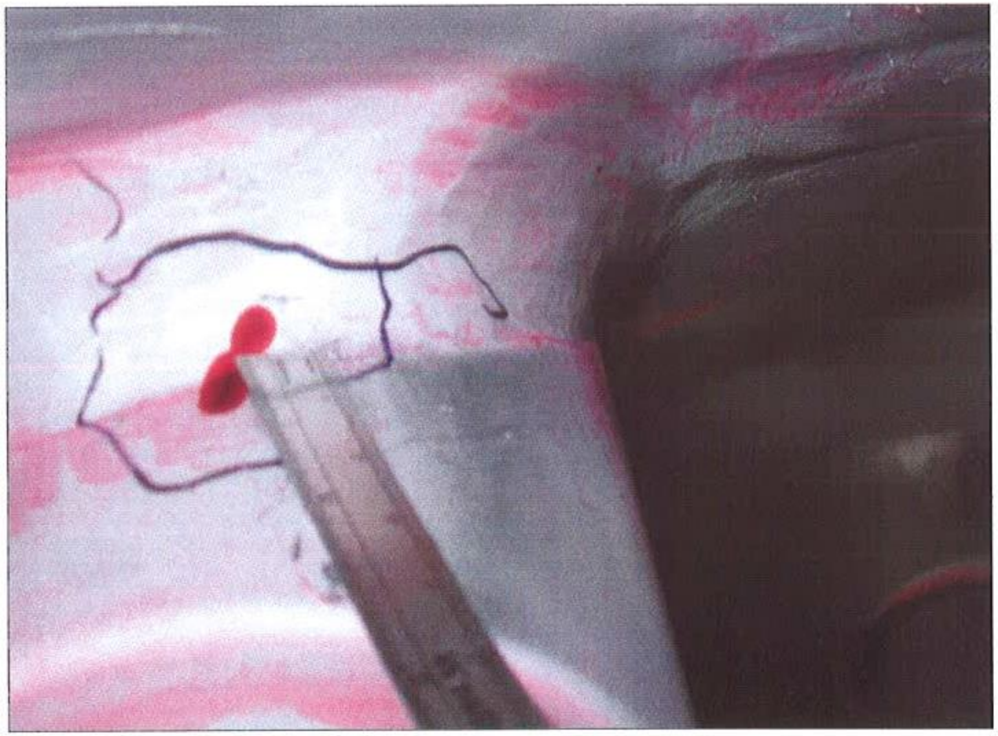
Rx Head Penetration

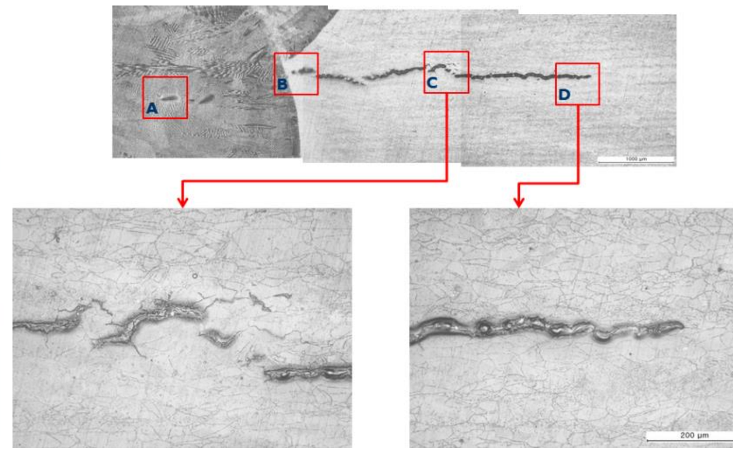


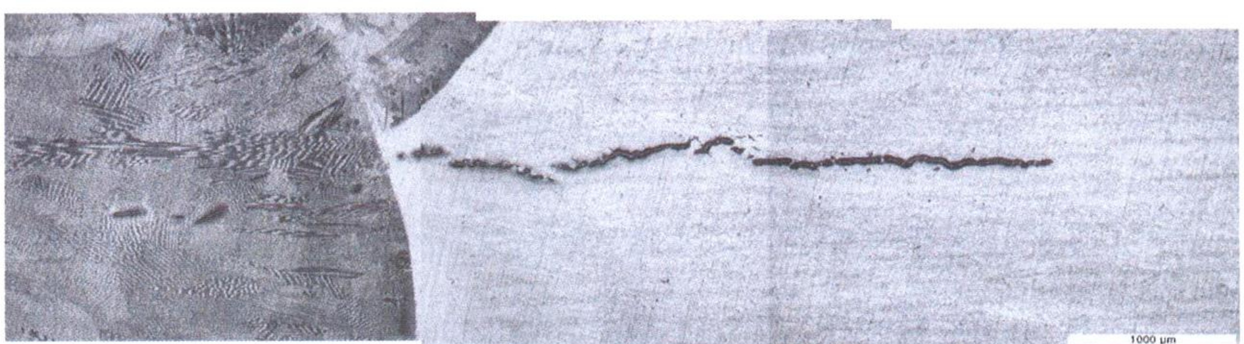
Location of Cracks

- ❑ Some cracks in 6 penetrations were identified in penetration and weld metal.
- ❑ Root Cause : PWSCC (Primary Water Stress Corrosion Cracking)

Cracking in Reactor CRDM Penetration

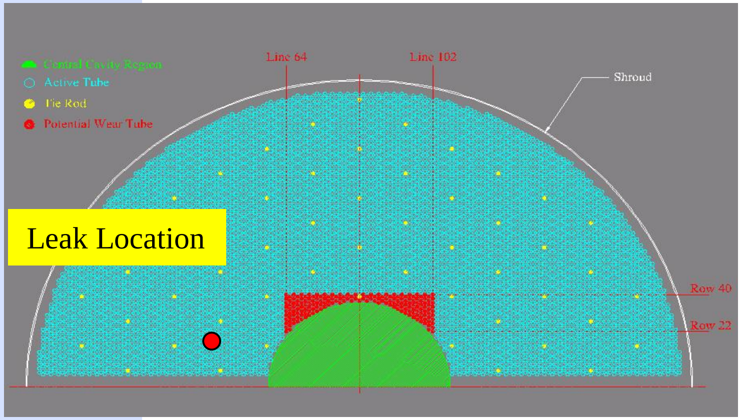


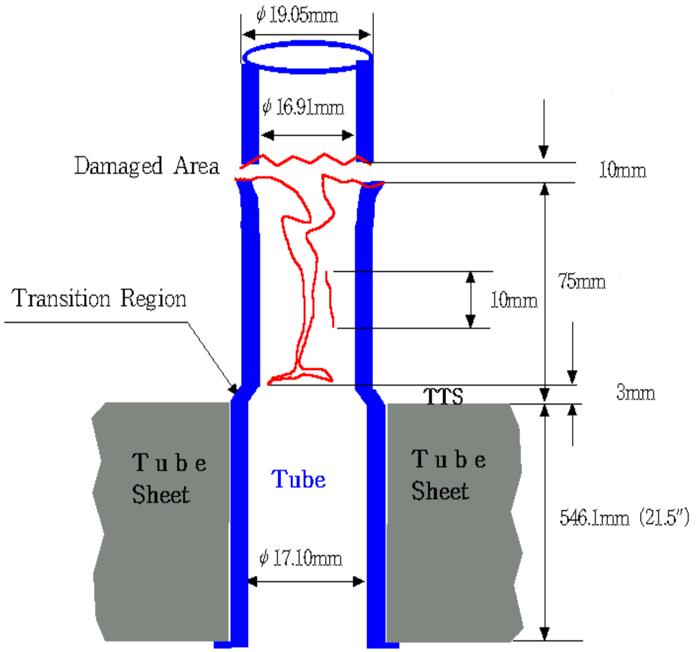


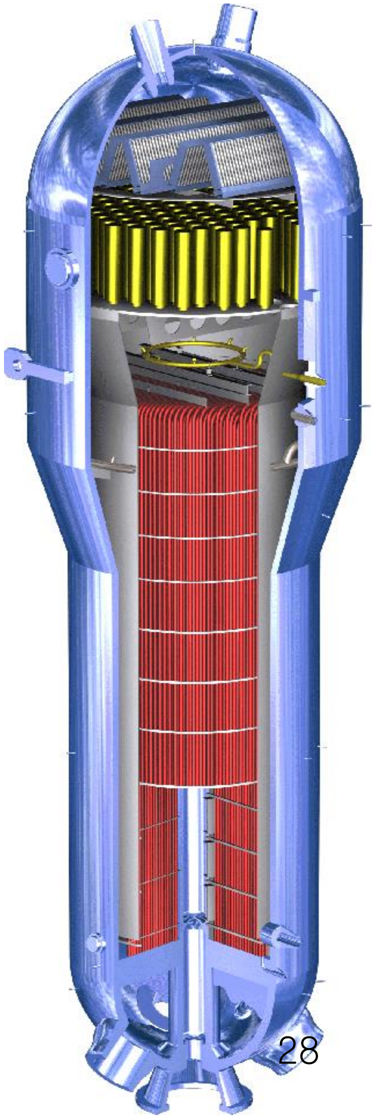


(8) Steam Generator Tube Rupture in Korea

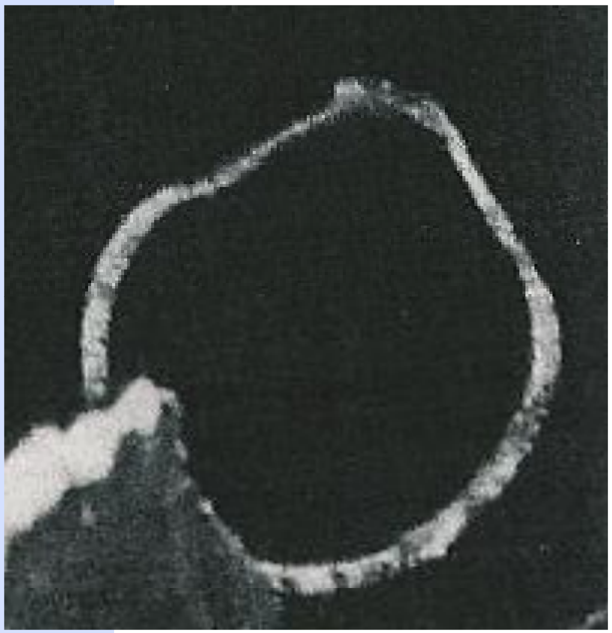
- ❑ Steam Generator Tube rupture event in Korean NPP in 2002 (the most severe NPP accident in Korea)
- ❑ One(1) SG tube (total 8214 tubes) was totally ruptured and primary coolant water was leaked to secondary side. (Leak 45 ton)
- ❑ Root Cause : PWSCC (Primary Water Stress Corrosion Cracking)



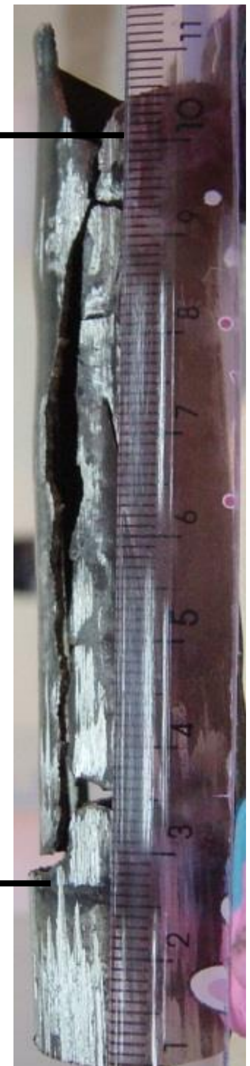




Shape of Ruptured SG Tube



TTS+78mm



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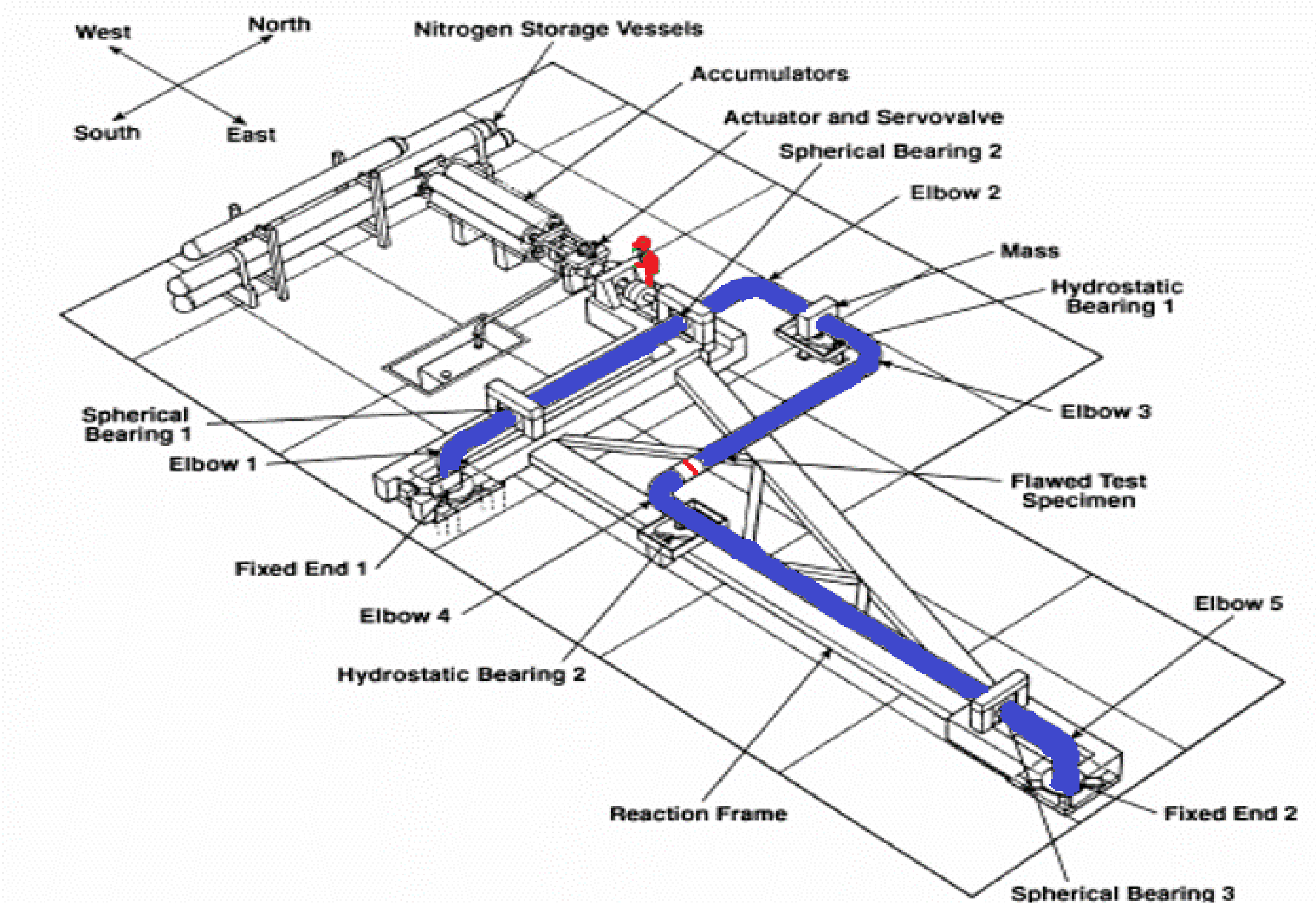
(9) Piping Rupture Experiment

- To improve the integrity of nuclear components, research activities are very important.
- International Research Project (IPIRG-BINP-MERIT-PATRIDGE project)
  - 6 countries including Korea, 30 years research program
- Experiments were performed by Battelle Memorial Institute in USA

- Piping: 12 in diameter Stainless Steel piping with a crack (total 20m)
- Test Load: Normal Operation Condition with Simulated SSE loading
- Test Results
  - Piping system was totally ruptured with explosive behavior.
  - Test facility was totally collapsed.
- The test verified the risk of nuclear piping rupture under the normal operation condition with seismic event.

Piping Rupture Experiment Facility



Why are mechanical components failed? (1)

- Design Problem
  - No consideration in Design
    - Thermal Stratification in Pressurizer Surge Line designed in 1970s.
    - Pressurized Thermal Shock (PTS) in Reactor Vessel
- Material Problem * Primary Water Stress Corrosion Cracking
  - PWSCC* in Inconel 600 : Cracking in Rx head CRDM and SG tube
  - High Density Poly Ethylene Piping Failure
- Poor Workmanship during Manufacturing and Construction
  - Installation and welding process

Why are mechanical components failed? (2)

- **Operational Problem**
  - Human Error by Operator may cause various problems including severe accident in Chernovyl and TMI.
  - Overload due to Water/Stream Hammer
- **Aging Problem**
  - Lots of aging mechanisms have being reported in mechanical components as follows;
    - FAC (Flow Accelerated Corrosion)
    - BAC (Boric Acid Corrosion)
    - PWSCC (Primary Water Stress Corrosion Cracking)
    - Radiation Embrittlement
    - Fatigue & Vibration etc.

3. Integrity of Mechanical Components

➔ How to maintain the integrity of Mechanical Components in NPP?

❖ **During Design & Construction Stage**

1) Design
2) Material
3) Manufacturing & Installation
4) Inspection & Test

❖ **During Operation Stage**

5) In-Service Inspection (ISI)
6) Repair & Replacement
7) Aging Management (AM)

(1) Design of Mechanical Components

- [Step 1] Classification of Safety Class
  - ✓ Safety Class 1, 2, 3 and Non-Safety Class

- [Step 2] Determination of Loading Condition
  - ✓ Pressure/Thermal Load, Seismic Load, Accident Load etc.
  - ✓ Service Level A, B, C, D and test condition

- [Step 3] Design Analysis according to ASME Code Sec. III (KEPIC Code MN)
  - ✓ Stress Analysis for all components
  - ✓ Fatigue Analysis for Class 1 Components
  - ✓ Fracture Analysis for Reactor

(2) Material of Mechanical Components

- Carbon steel, Stainless steel, and Inconel are widely used in mechanical components.
- The materials of base metal and weld metal listed in ASME Code sec. III and Sec. II for safety class components should be used.
- The material should be manufactured by certified material manufacturer that is certified by ASME.
- The certified material test report (CMTR) should be issued by certified material manufacturer.

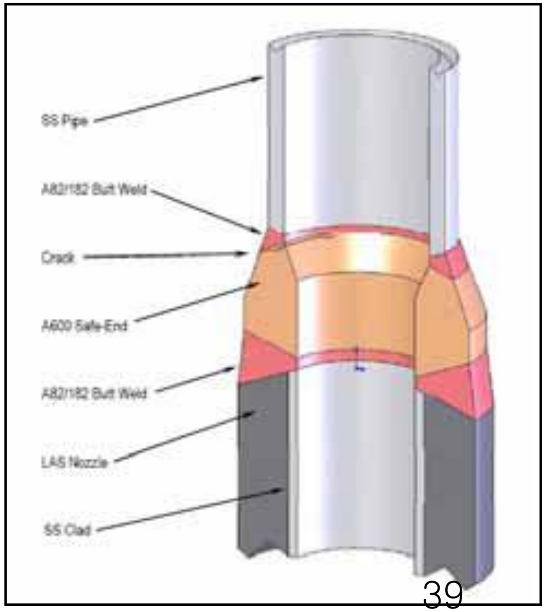
(3) Manufacturing & Installation

- Weld points are the weakest point against the integrity of mechanical components
  - ✓ Lots of failures at weld point have been widely reported.

- Any shop/field weld should be performed by ASEM Code Sec. III and Sec. IX.
  - ✓ Welding method and welder should be qualified.

Characteristics of Welding

- ❑ Complex Metallurgy in Weld Area
  - ❖ Weld metal, Heat Affected Zone (HAZ), Base metal
  - ❖ Different Material Properties
- ❑ Complex Mechanical Characteristic
  - ❖ Configuration, Stress concentration, Residual Stress etc.
- ❑ Difficulties in Welding Process
  - ❖ Alignment, Counter Bore/Root/Crown, Grinding
  - ❖ Heat Treatment and Inspection
- ❑ Poor Field Conditions for Weld working
  - ❖ Lots of micro-crack in weld area
  - ❖ Not easy to maintain Weld Quality



(4) Inspection & Test

- All welding area should be inspected by NDE (Non-Destructive Examination such as RT, PT, MT, VT, and UT according to ASEM Code Sec. III and Sec. V.

- All pressure retaining system should be hydrostatically test (Hydro-test) according to ASEM Code Sec. III.

(6) In-Service Inspection

- Selected safety component should be periodically inspected by NDE such as UT, PT, MT and VT for every 10-year.
  - ✓ Safety Class 1 : 100% vessel, 25% piping weld
  - ✓ Safety Class 2 : 7.5% piping weld
- Pressure retaining system should be periodically hydro-tested.

(7) Repair & Replacement

- Failed component should be repaired or replaced according to codes and standards used in construction.
  - ✓ Any flaw such as crack and wall thinning not to satisfy ASME code Sec. XI acceptance criteria should be removed and repaired.

- Some components having lots of flaw have been replaced with new components.
  - ✓ Steam Generator : In 600 cracking
  - ✓ Reactor vessel head : in 600 cracking
  - ✓ Heat Exchanger : Corrosion

(8) Aging Management

- Aging management of mechanical components are very important to maintain the integrity during operation.
  - ✓ All mechanical components would be degraded and failed in nature.
  - ✓ It is important to maintain the safety margin in spite of aging.

- Lots of aging mechanism have been world-widely reported
  - ✓ Corrosion : PWSCC, BAC, FAC, etc.
  - ✓ Fatigue : thermal fatigue, vibration
  - ✓ Radiation : embrittlement, swelling, void
  - ✓ Thermal Embrittlement

Ⅱ. Safety Classification

Why is the safety classification required?

- There are lots of mechanical components (MC) in NPP.
  - Some MCs are more important to nuclear safety including reactor vessel, pressurizer, steam generator, and containment in NPP.
  - However, some MCs do not affect significantly to nuclear safety including secondary systems.
- The safety classification based on graded approach is widely used in the design of MCs considering cost effect.

Typical safety classification of MCs

Safety Class		Typical SSCs
Safety Class	Class 1	Reactor, RCPB
	Class 2	Safety Injection Sys. Containment Penetration
	Class 3	Diesel Generator
Non Nuclear Safety Class	Class NNS	BOP, Turbine

Guidelines on the safety classification

- Guidelines on the safety classification
  - Korea: NSSC Notice Reactor.15
  - USA: USNRC Reg. Guide 1.26
  - IAEA : SSG-30

IAEA Safety Standards

for protecting people and the environment

Safety Classification of Structures, Systems and Components in Nuclear Power Plants

Specific Safety Guide

No. SSG-30

IAEA

International Atomic Energy Agency

IAEA SSG-30 : Safety Classification of SSC in NPP

IAEA SSR-2/1 Requirement 22: Safety classification

All items important to safety shall be identified and shall be classified on the basis of their function and their safety significance.

IAEA SSG-20 GENERAL RECOMMENDATIONS

Safety classification should be performed during the plant design, system design and equipment design phases, and should be reviewed for any relevant changes during construction, commissioning, operation and subsequent stages of the plant' s lifetime.

Safety Class 1

- Safety class 1 (SC-1)
  - Safety Function
    - Reactor Coolant Pressure Boundary (RCPB)
  - Components & Systems
    - Reactor Vessel
    - Pressurizer
    - Steam Generator
    - Reactor Coolant Pump
    - Reactor Coolant Piping

Safety Class 2

- Safety class 2 (SC-2)
  - Safety Functions
    - emergency core cooling
    - emergency heat removal
    - fission product barrier
    - emergency negative reactivity
  - Components and Systems
    - emergency core cooling system (ECCS/SIS)
    - heat removal system (HRS/SCS)
    - Containment Penetration

Safety Class 3

- Safety class 3 (SC-3)
  - Safety Functions (sample)
    - To maintain sufficient reactor coolant inventory
    - To Maintain geometry within the reactor to ensure core reactivity control or core cooling capability
    - Provide actuation or motive power for SC-1, SC-2, or SC-3 equipment
  - Components & Systems
    - reactor coolant normal makeup system
    - core support structures
    - Emergency Diesel Generator

Non Nuclear Safety Class

- Non-nuclear safety (NNS)
  - Non-nuclear safety (NNS) shall be assigned to equipment not included in SC-1, SC-2, or SC-3
  - Systems & Components
    - Secondary System (BOP, Balance of Plant)
    - Turbine Generator

Comparison of Safety Class and NNS Class

Safety Class		Requirement and Cost
Safety Class	Class 1	– Severe Design Rule – Certified Material – Controlled Manufacturing – Augmented Inspection – Enhanced QA requirement
	Class 2	
	Class 3	
Non Nuclear Safety Class	Class NNS	The cost of Class NNS components is very low compared to similar Safety Class components.

ASME Boiler and Pressure Vessel Code (ASME Code)

- ASME Code consists of 11 sections
  - ASME: American Society of Mechanical Engineer
  - ASME Code shall be applied in nuclear component by regulations and guides.

- Localization of ASME Code
  - Korea : KEPIC Code
  - France : RCC Code
  - Japan : JSME Code

ASME Code (1)

1. Section I: Power Boilers

2. Section II: Material Specifications:

   Part A: Ferrous Material Specifications

   Part B: Non-ferrous Material Specifications

   Part C: Specifications for Welding Rods, Electrodes, and Filler Metals

   Part D: Material Properties

   => Safety class components should be constructed of ASME Sec. II material.

ASME Code (2)

3. Section III: Rules for Construction of Nuclear Facility Components

Division 1: Metallic Components

a. NCA: General Requirements

b. NB: Class 1 Components

c. NC: Class 2 Components

d. ND: Class 3 Components

e. NE: Class MC Components

f. NF: Component Supports

g. NG: Core Support Structures

Division 2: Concrete Reactor Vessel and Containment

ASME Code (3)

4. Section IV: Rules for Construction of Heating Boilers
5. Section V: Nondestructive Examinations (NDE)
6. Section VI: Recommended Rules for the Care and Operation of Heating Boilers
7. Section VII: Recommended Guidelines for Care of Power Boilers
8. Section VIII : Pressure Vessel
9. Section IX: Welding and Brazing Qualifications
10. Section X: Fiberglass-Reinforced Plastic Pressure Vessels
11. Section XI: Rules for In-Service Inspection of Nuclear Power Plant Components (ISI)

Relation Between Safety Class and ASME Code

Safety Class	ASME Code
Safety Class 1	Sec. III NB
Safety Class 2	Sec. III NC
Safety Class 3	Sec. III ND
Non-nuclear safety	Sec. VIII and other Codes (ANSI etc.)

III. Concluding Remark

Concluding Remark

- To maintain the integrity of mechanical components is very important to assure nuclear safety.

- Comprehensive approach to maintain the integrity of mechanical components is required
  - Design & Construction stage: design, material, manufacturing, installation, inspection and test
  - Operation stage: in-service inspection, repair & replacement, and aging management