

IAEA EC- FAC Activities

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Nuclear Power Division



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Recent material and related managerial issues on nuclear power plants

15 - 18 February. 2005 at VIC



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Workshop programme

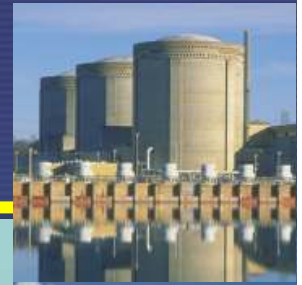
Session 1	Session 2	Session 3	Session 4
Report of Incidents	Technical issues	Managerial issues	Regulatory Aspects
Recent real incidents involving mat. & mana. Issues	Technical update and outstanding material issues	Management system and outstanding managerial issues	Roles and responsibilities among parties involved & polices on reg. aspects.
Canada, Japan Finland, France, Spain, Sweden Russia, USA	Czech, France, Hungary Germany Japan Mexico, Spain, EC- JRC	Armenia, France, Germany, Japan, Netherlands, Switzerland	Argentina, Canada, Japan, Netherlands, Slovakia, South Africa, USA

uction of Participants

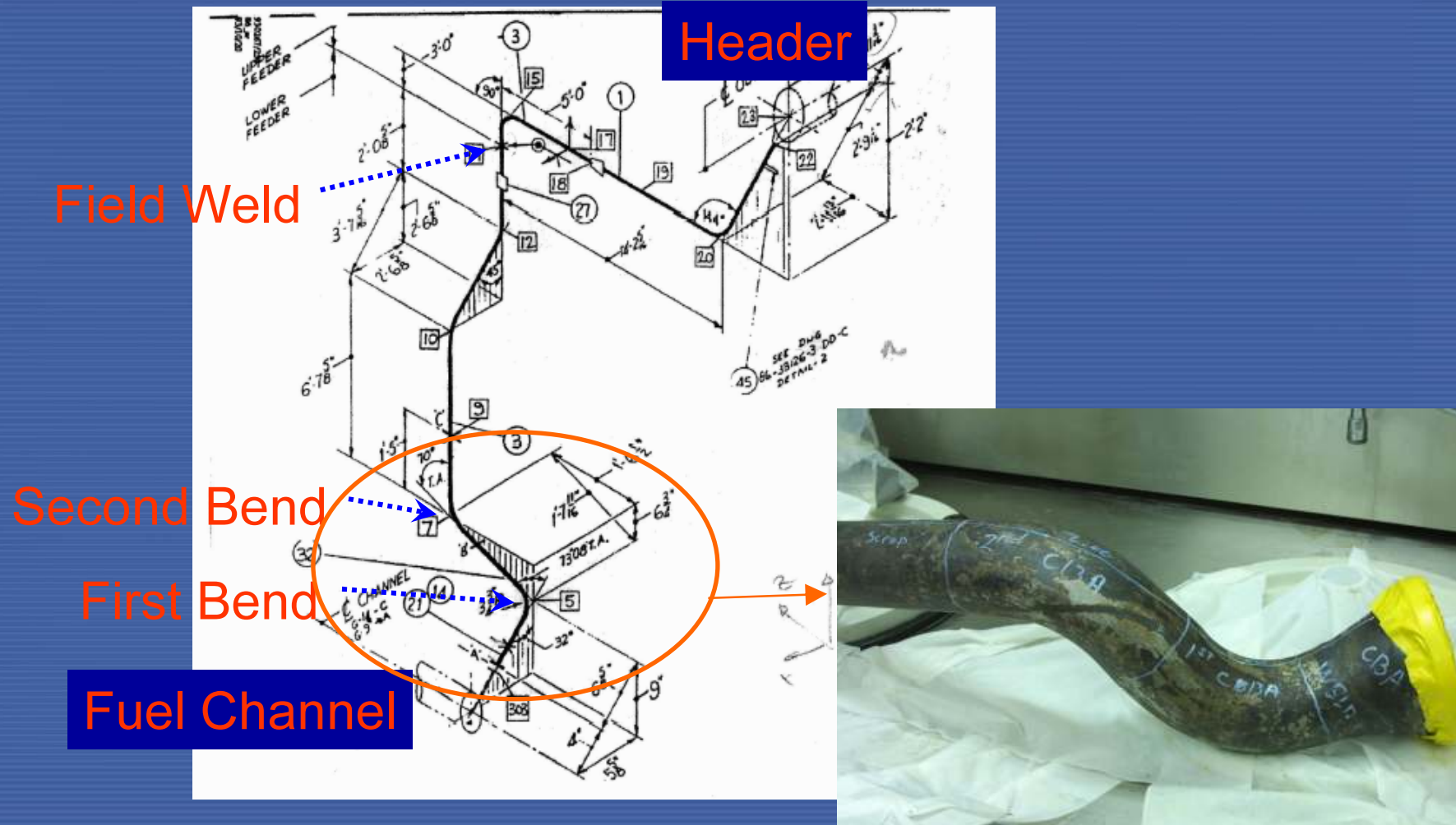
Argentina,
Armenia,
Canada,
China,
Czech Rep.
Finland,
France,
Germany,
Hungary,
Iran,
Japan,
Korea,
Mexico,
Netherlands,
Romania,
Russia,
Slovakia,
South Africa,
Spain
Sweden,
Switzerland,
USA,
EC- JRC,
IAEA



Belgium, Brazil, Bulgaria, India, Pakistan, Lithuania, UK.

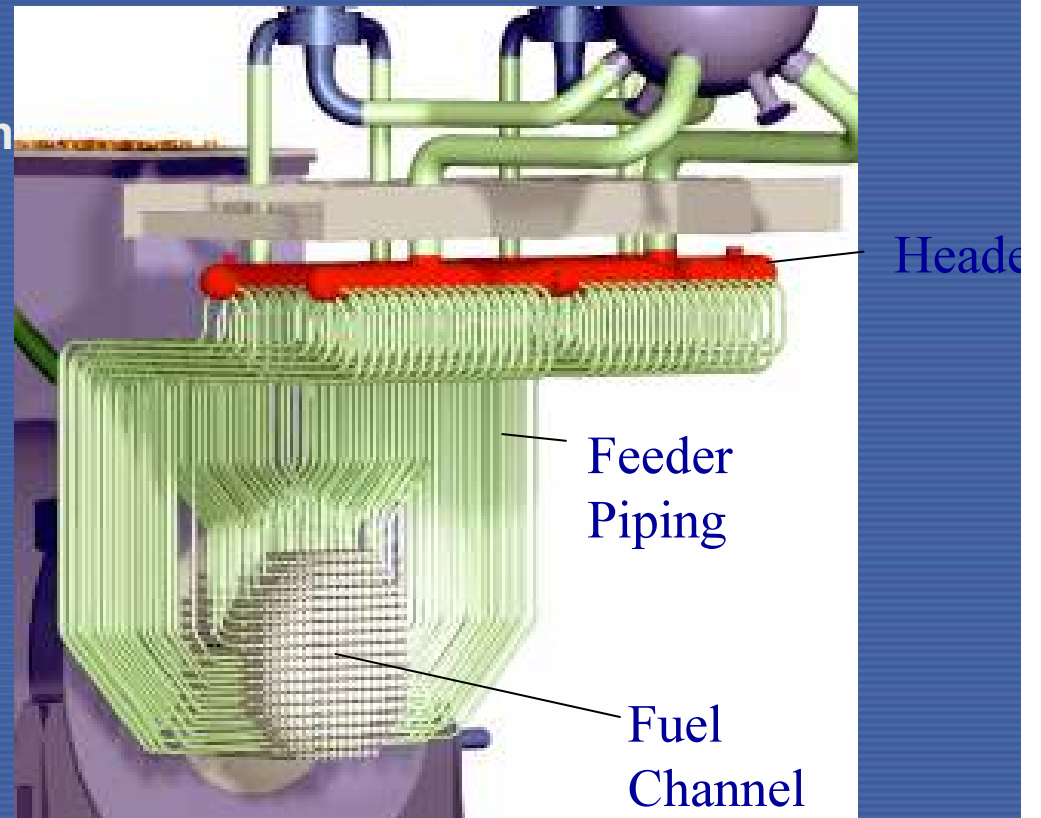
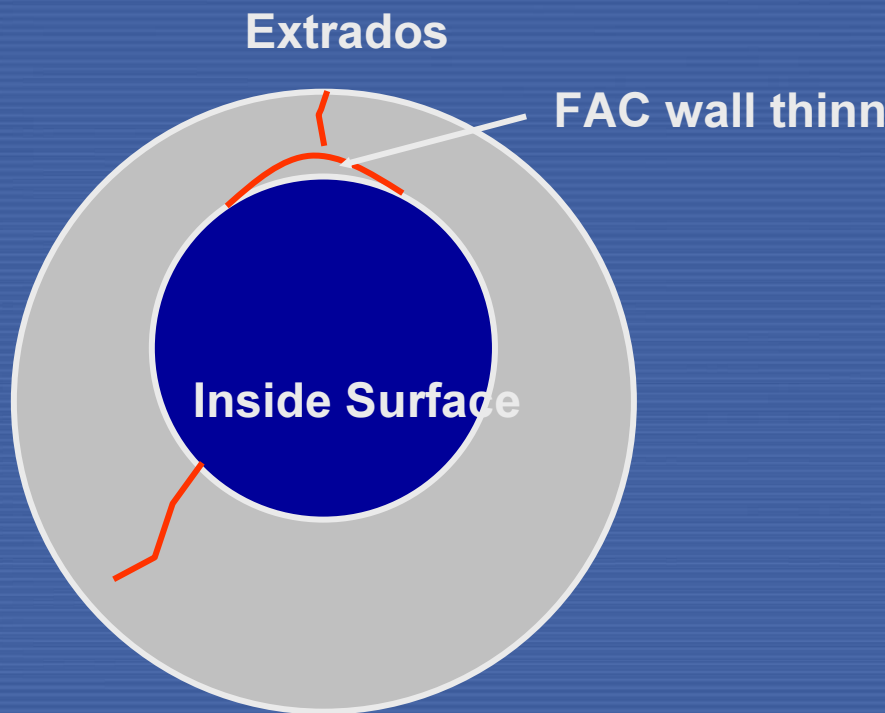


Service Induced Degradations of CANDU feeder piping - FAC wall thinning and cracking



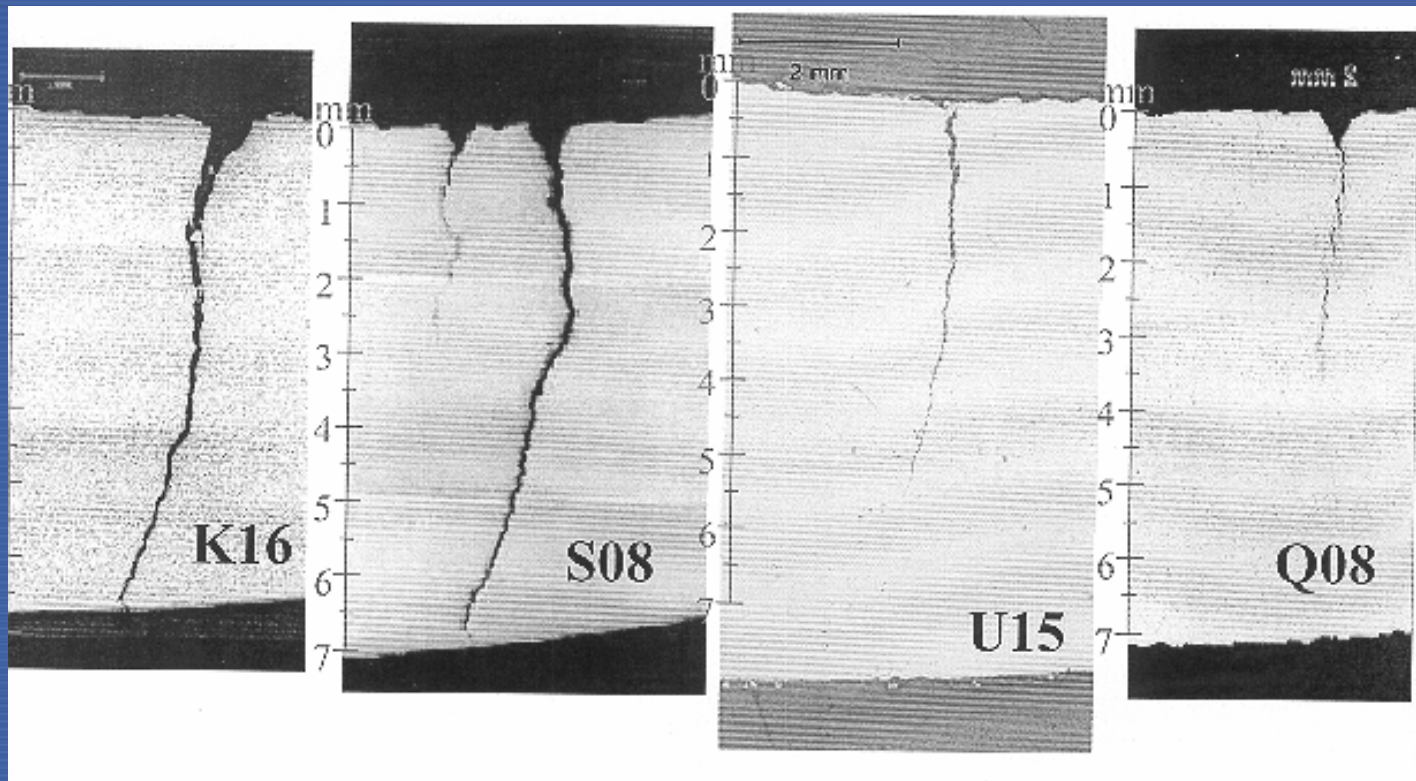
Service Induced Degradations of CANDU feeder piping - FAC wall thinning and cracking

Feeder Bend



Intrados
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Metallographic Images Cross-Sections of the Cracks - Canada

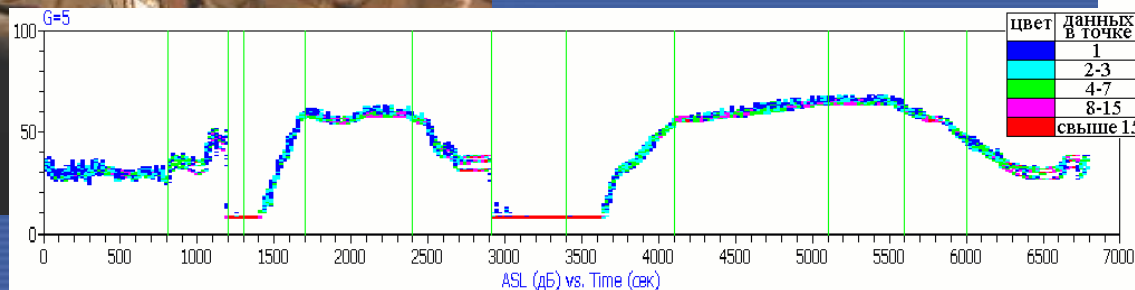
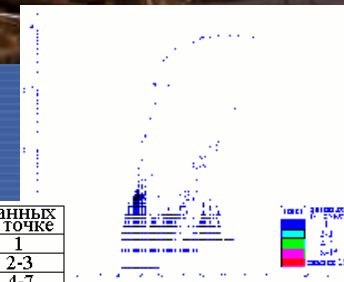


Intergranular

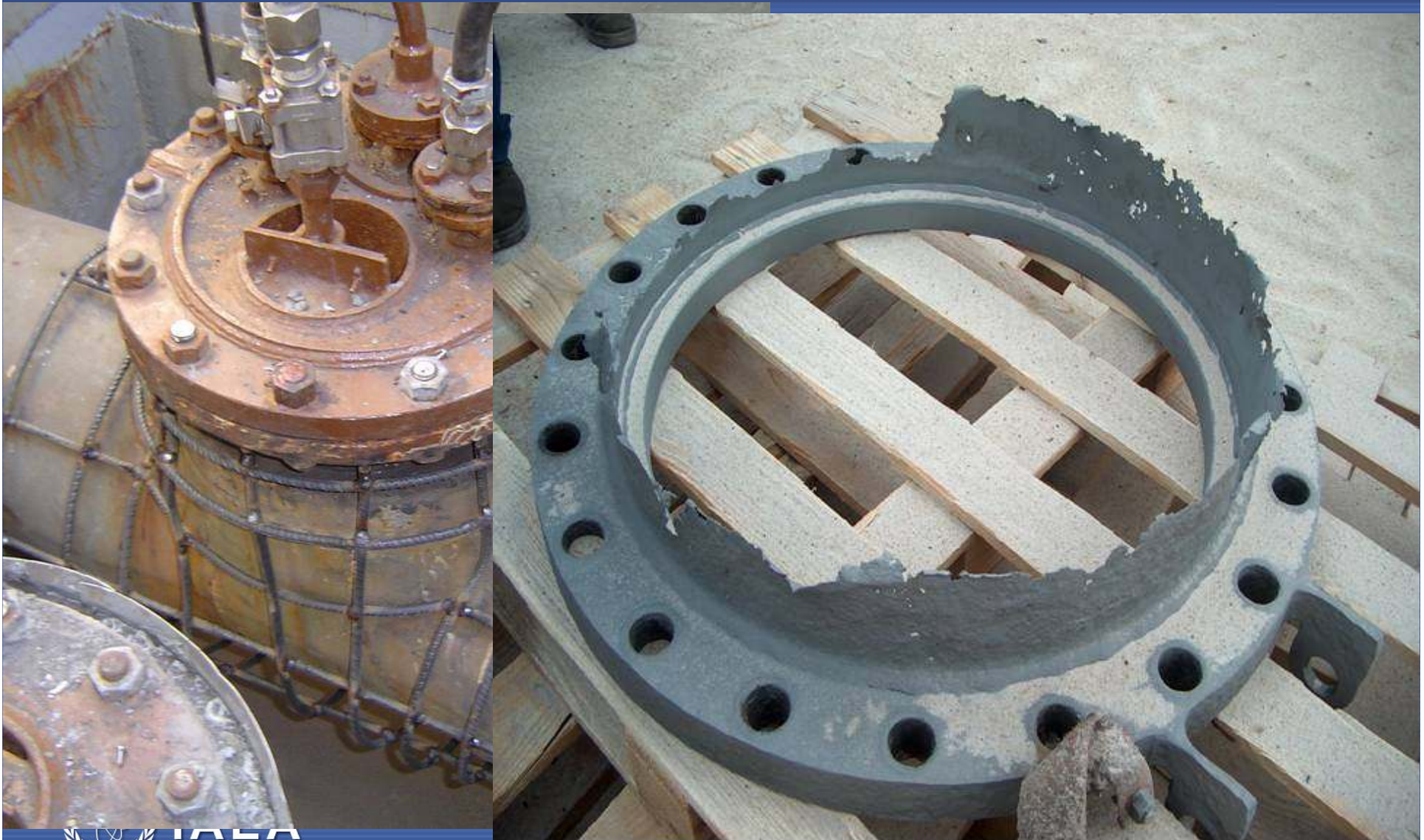
Inspection of the microstructure and of the magnetic properties - Russia



Examination of the potential defect growth by use acoustic-emission method - Russia



Vandellós II - Essential Service Water System Pipe Degradation - Spain



Pipe Rupture Accident at Mihama-3 NPP - Japan



Ruptured Opening



Spring hanger

Rust in stagnant water

Investigation on pipe rupture mechanism– Mihama 3

- The pipe is of carbon steel and the rupture occurred downstream of the orifice where unsteady boundary layer flow occurs
- Water chemistry conditions(pH, dissolved oxygen, etc.) have been maintained within control values
- Normal operating temperature is 140°C that is favorable for erosion/corrosion
- Pipe inner surface shows considerable thinning with overall fish-scale like pattern, which is specific to erosion/corrosion
- At the corresponding portion of B-line, pipe inner surface shows the same aspects as A-line

- Pipe wall thickness had been reduced gradually by erosion/corrosion during long operating time.
- Thinning rate: 0.47×10^{-4} mm/hr)
- The pipe rupture occurred finally by operating loads because of insufficient pipe strength

Main Root causes (Mihama # 3, 2004)

- **Mihama #3** : there was the omission of the ruptured portion in the check list from the beginning and the omission had never been corrected until the accident took place.
- **Root cause** : Managerial mistakes in secondary pipe wall thinning management involving three parties, KEPCO, MHI and Nihon Arm Co.
- **Locations screened according to susceptibility**
 - 43,183 locations subject to inspect for 11 PWRs at KANSAI.
 - 16 locations : Ruptured location + 4 locations (all 4 in heating steam line to Steam Converter) + 11 locations (integrity estimated from similar inspections in other plants)

Davis Besse NPP – Reactor Vessel Head



Main Root causes (Davis Besse NPP, 2002)

- **Throughout 1990's, Davis-Besse's Operational Performance was Exceptional.**
 - **Less than adequate safety focus**
 - **Corrective action program implementation shortcomings**
 - **Ineffective use of industry information**
 - **Boric Acid Program weaknesses**

Main Root causes (Unreported Cracks in Reactor Components in TEPCO, 2002)

- **Production Oriented Culture**
- **Overconfidence in Engineering Decision**
- **Complacency on Operational Performance**
- **Weak independent Verification and Oversight**

Main Root causes (Loviisa 1 & 2 – 1990, 1993)

- **Lack of Knowledge**
 - **Wrong assumption of the effect of small pressure drop over the orifice (~0.5 bar) on erosion - corrosion**
 - **No flow control orifices in the inspection programme**
 - **Inadequate inspection technique for flanges**
 - **Misinterpretation of the previous inspection results**
 - **Disregarding of the flange from the inspection programme in 1993**

Lessons Learned from experiences

Technical points:

- **A strong corrective action program is essential for safe plant operation**
- **Equipment and materiel problems and anomalies must be rigorously addressed in a thorough and timely manner**
- **Minimal compliance with regulatory standards is unacceptable**
- **Better material management program**
- **Organizational learning through benchmark studies and self-assessment**
- **Active involvement in several international projects/groups on AM (IAEA, OECD, EC....)**
- **Ageing documentation not optimal and therefore potential problems on AM knowledge transfer**
- **Process improvement and enhanced commonality of the processes throughout the fleet.**

Lessons Learned from experiences

Managerial points:

- Past plant operating successes can lead to complacency and failure to maintain and advance standards of excellence
- Having a heavy production focus rather than a safety focus is a costly and wrong choice
- Oversight organizations must be involved and unbiased.
- Independent quality assurance organization
- Effects of trend for cost reduction
- Ethics programs including behavioral standards
- Organizational transparency
- Leadership development

Main Root Causes to recent material issues (Managerial Point of View)

1	Over-confidence	Good past performance leading to self-satisfaction
2	Complacency	Occurrence of minor events that are subjected to minimum self-assessment, and delay in improvement programmes
3	Denial	Number of minor events increases with possibly a more significant event.
4	Danger	Several potentially serious events occurred but management and employees reject criticism from audits or regulators, by considering their views biased.
5	Collapse	Management is overwhelmed and may need to be replaced.

Summary of basic Information on FAC

Reference: Hiromi Shihara, Research Institute Nippon Kaiji Kyokai (ClassNK), "Current Wall Thinning Measured on Piping System of Main & Aux. Boiler Plant in Ships", ASME-PVP 2008, Chicago, USA(2008)

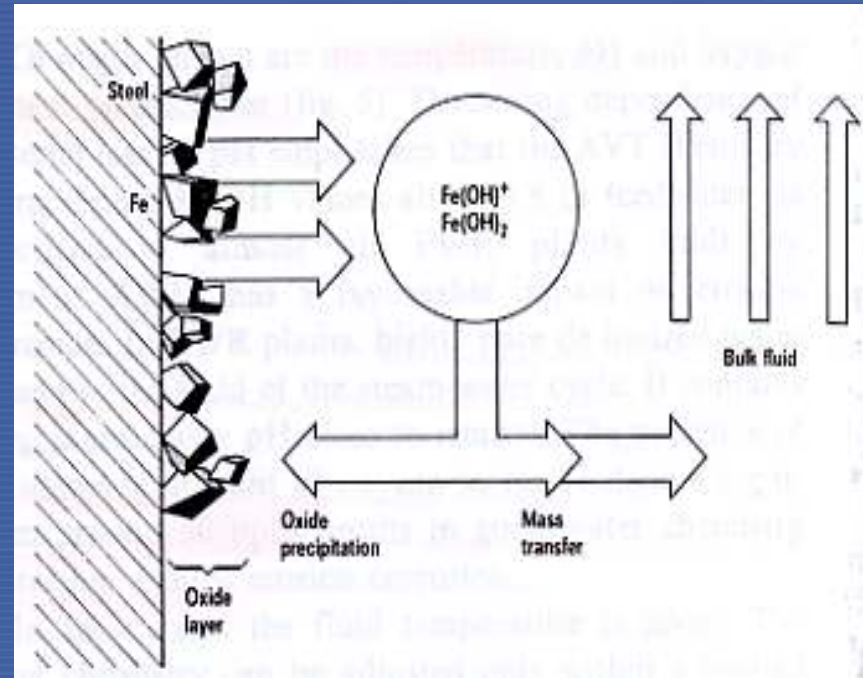


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Erosion-Corrosion Definition

- Erosion-corrosion is a flow-induced degradation. This phenomenon can affect metallic materials which owe their corrosion resistance to the formation of oxide process of material films.
- Wearing away of the oxide films by turbulent water or wet steam flow is followed by dissolution corrosion of the unprotected metal.



Oxide precipitation process

Mass Transport process in flow

What is Flow Accelerated Corrosion ?

Flow Accelerated Corrosion is caused by turbulent flow at elbow, bent part or T-junction, behind valve or orifice etc.

FAC has other name as Flow Induced Localized Corrosion. There are similar damage as cavitations-erosion, droplet impingement erosion or different flow velocity corrosion.

Factors influencing to FAC

Temperature

Temperature is a very important factor. There is peak point at around 150°C and temperature between 100°C and 250°C to be paid attention to.

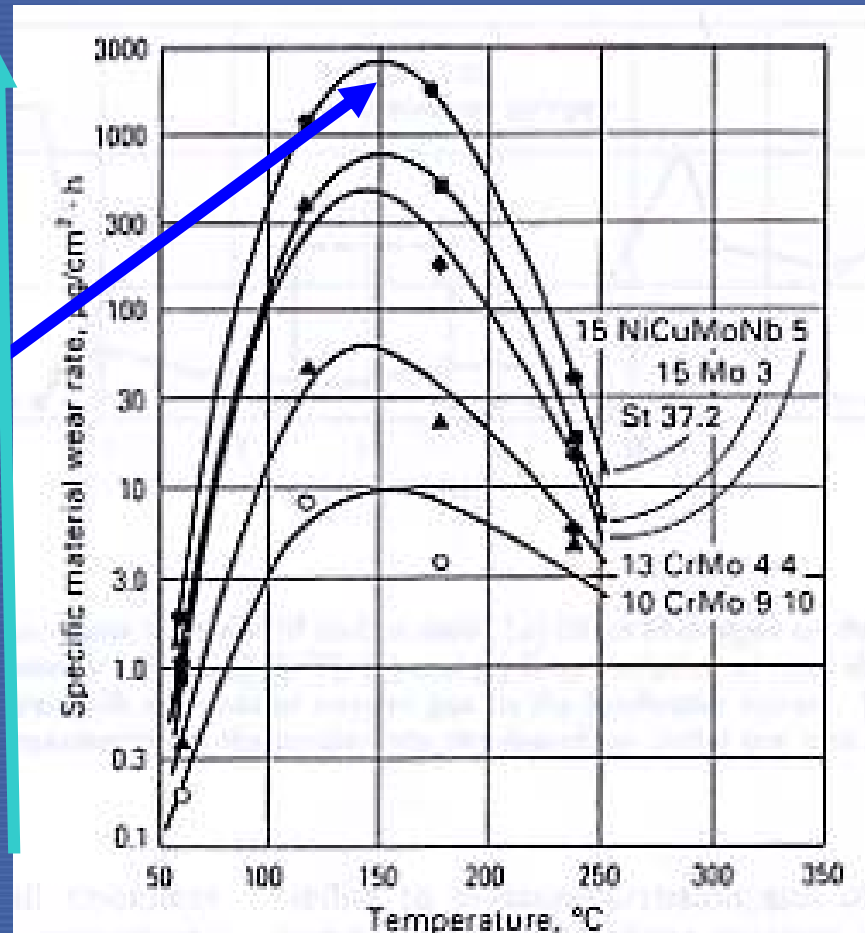


Fig. 73 Temperature effect on material wear due to erosion-corrosion. P : 40 bar, v : 35 m/s, pH: 7, O_2 content: <40 ppb, period of exposure: 200 h. See Fig. 71 for material composition. Source: Ref 137

Factors influencing to FAC

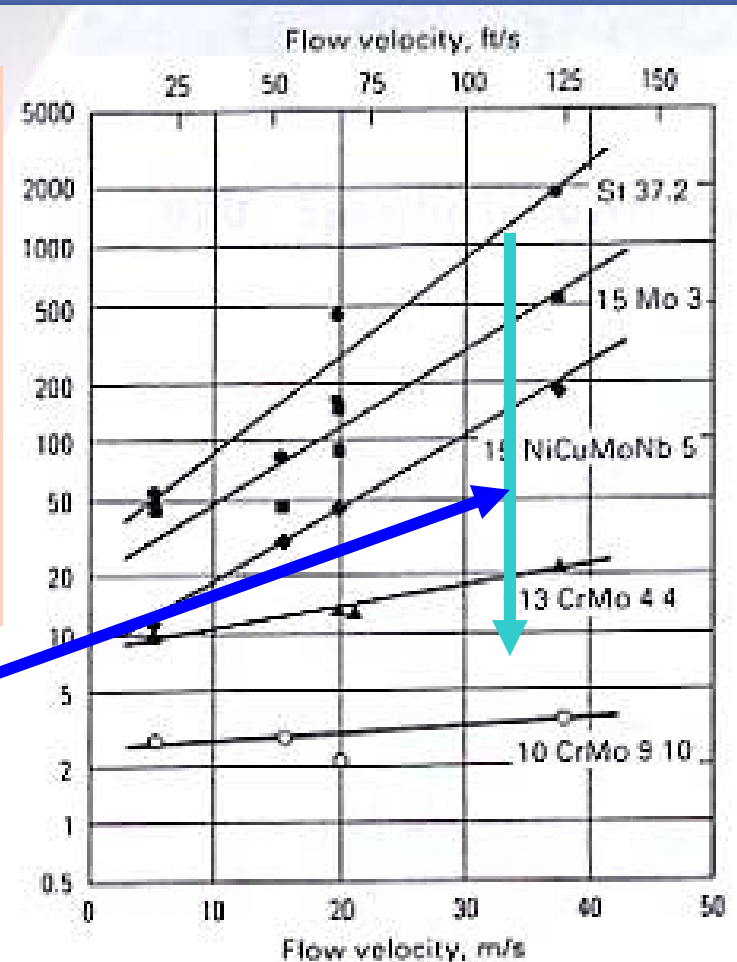
Flow Velocity

Flow velocity is also a very important factor. As Flow velocity increases, reduction rate in pipe wall thickness by FAC increases.

However as amount of Cr and Mo in pipe material increases, the rate decreases.



Reduction rate in pipe wall thickness



ig. 78 Effect of flow velocity on material wear due to single-phase erosion-corrosion. P : 1 bar (4000 kPa, or 580 psi), T : 180 °C (355 °F), pH: oxygen content: <5 ppb, period of exposure: 200 h. See Fig. 71 for material composition. Source: Ref 137

Factors influencing to FAC

pH

pH is also a very important factor. Reduction rate in pipe thickness by FAC decreases over pH 9.5.

This reduction rate is depending upon content of Cr and Mo in pipe materials.

Reduction rate in pipe wall thickness

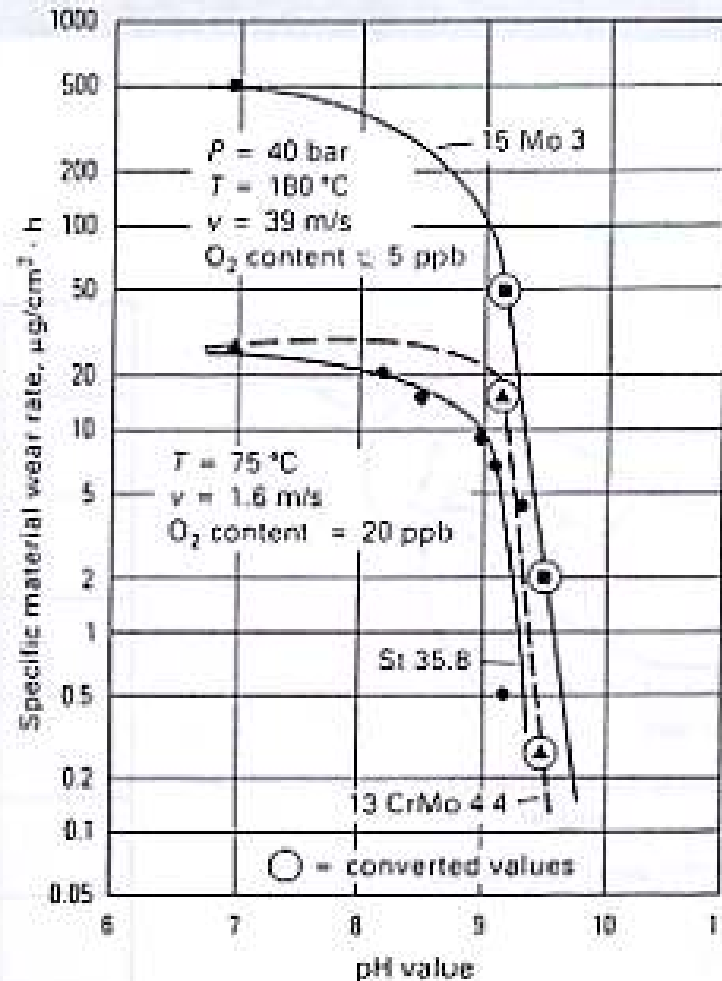


Fig. 72 Effect of pH value on material wear due to erosion-corrosion. *P*, pressure; *T*, temperature; *v*, velocity. For material composition, see Fig. 71. Source: Ref 137

Factors influencing to FAC

Oxygen Content

Oxygen content in fluid water is also a very important factor.

Reduction rate in pipe thickness by FAC increases below 200ppb and especially increases suddenly below 15ppb.

Reduction rate in pipe wall thickness

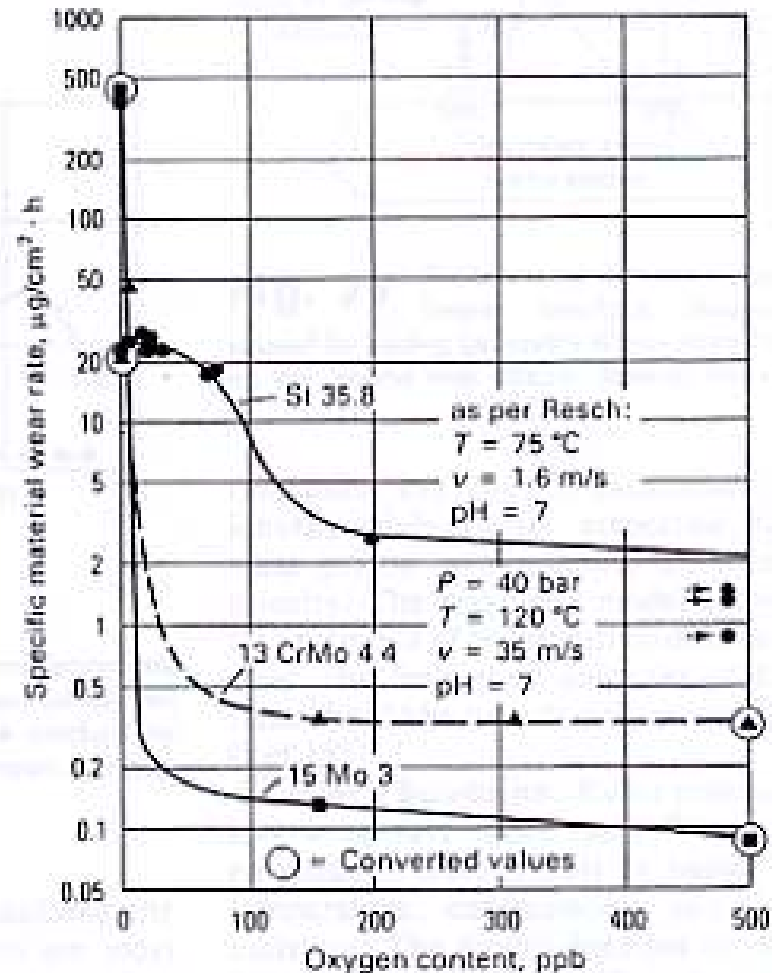


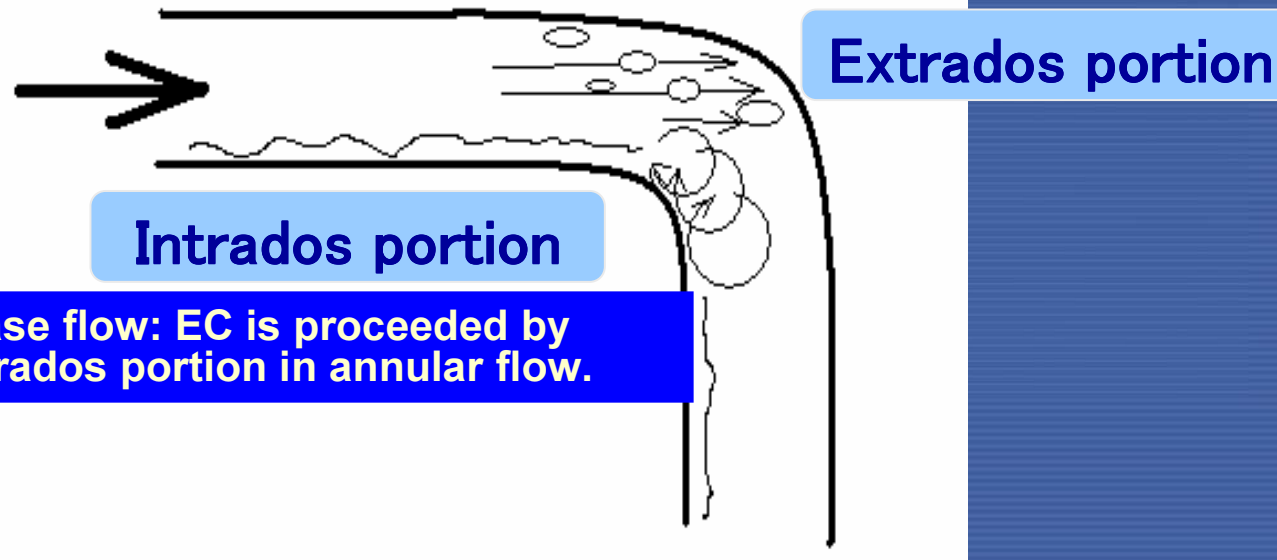
Fig. 74 Effect of oxygen content on material wear due to erosion-corrosion. See Fig. 71 for material composition. Source: Ref 137

Factors influencing to FAC

Flow Phase

There are completely different corrosion process between single phase flow and two phase flow.

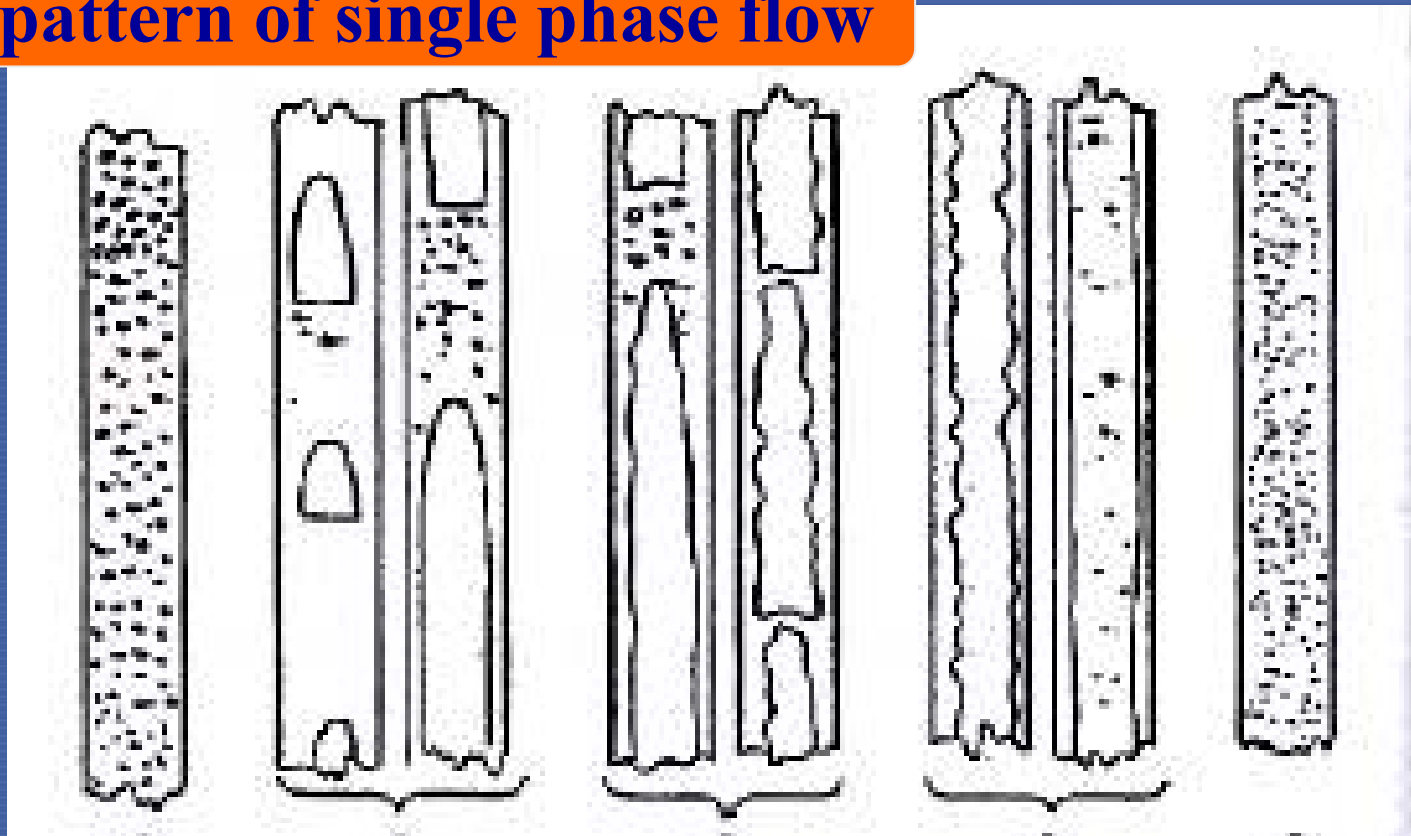
In case of two phase flow: Erosion is proceeded by collision of water masses to the corner of bent wall surface at extrados portion in vapor or mist flow.



In case of single phase flow: EC is proceeded by turbulent flow at intrados portion in annular flow.

Factors influencing to FAC

Flow pattern of single phase flow

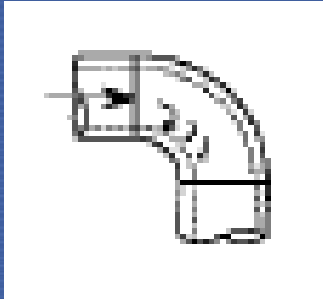
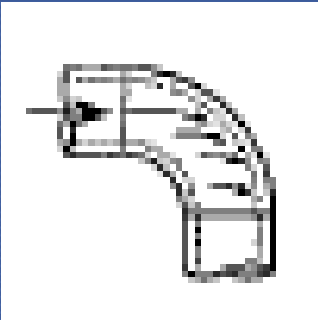
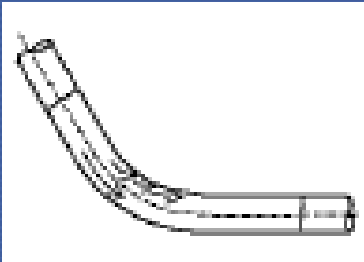
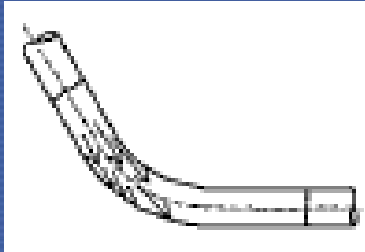


water flow -> air bubble flow -> slug flow -> annular flow -> single phase - increase flow velocity → steam flow.

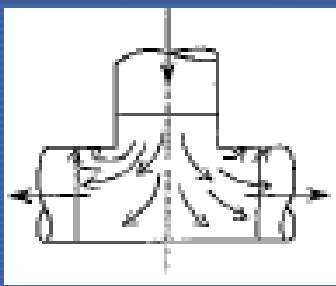
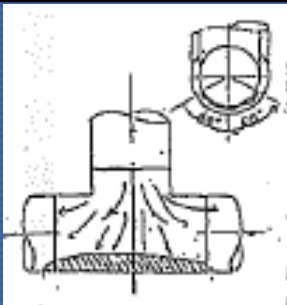
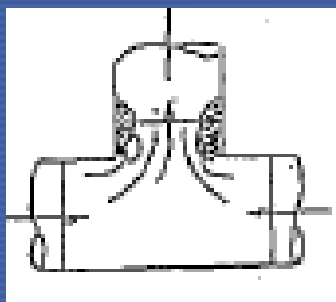
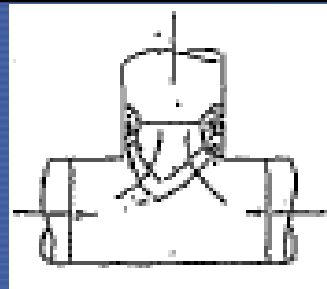
————— Increasing Gas Flow —————→



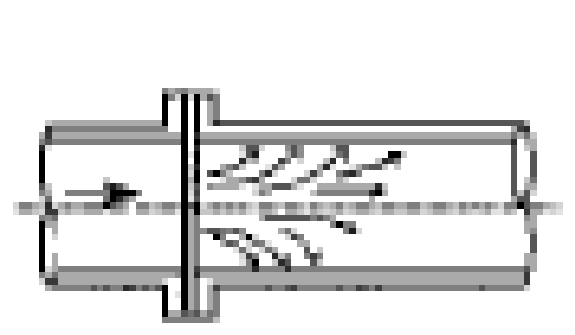
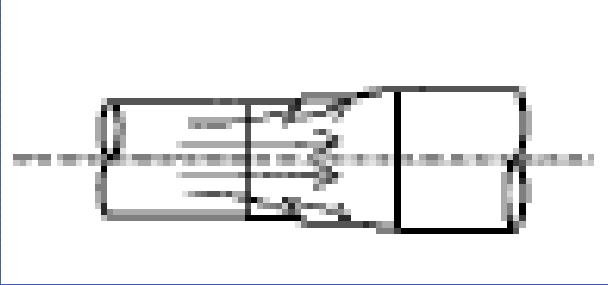
Corrosion feature on Elbow and Pipe Bend

	Elbow		Pipe bend	
Flow	Single phase water flow	Water and steam two-phase flow	Single phase water flow	Water and steam two-phase flow
Sketch of flow state				
Mechanism generating flow accelerated corrosion	Generated when an eddy occurs on the inside (anterior side) of the flow.	Generated when mist or water mass in wet steam impinges on the rear side of the pipe wall.	Thickness reduction advances when eddy is formed on the inside (anterior side) of flow.	Generated when mist or water mass in wet steam impinges on the rear side of the pipe wall.

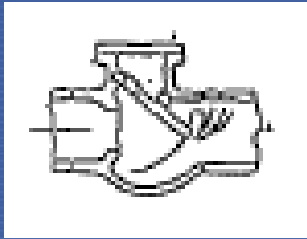
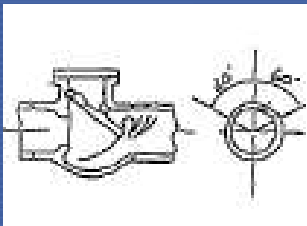
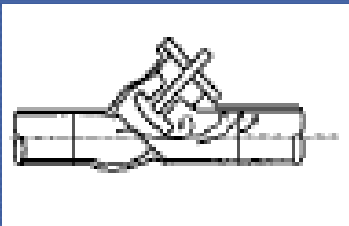
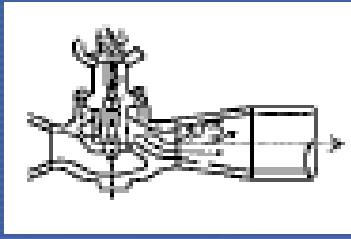
Corrosion Feature on T- Junction

	T-joint (branch)		T-joint (merge)	
Flow	Single phase water flow	Water and steam two-phase flow	Single phase water flow	Water and steam two-phase flow
Sketch of flow state				
Mechanism generating flow accelerated corrosion	Generated when an eddy occurs due to the flow.	Generated when mist or water mass in wet steam impinges on the surface of the pipe wall.	Generated when an eddy occurs internally due to the flow.	Generated when mist or water mass in wet steam impinges on the surface of the pipe wall.

Corrosion feature on Orifice & Reducer

	Downstream of orifice	Reducer
Flow	Single phase water flow	Water and steam two-phase flow
Sketch of flow state		
Mechanism generating flow accelerated corrosion	Generated when an eddy occurs in downstream parts in the flow constricting elements.	Generated when mist or water mass in wet steam impinges on the surface of the pipe wall.

Corrosion Feature on Valves

	Downstream of swing check valve		Downstream of ball check valve	Downstream of control valve
Flow	Single phase water flow	Water and steam two-phase flow	Single phase water flow	Single phase water flow Water and steam two-phase flow
Sketch of flow state				
Mechanism generating flow accelerated corrosion	Generated when an eddy occurs downstream of the valve.	Generated when mist or water mass in wet steam impinges on the surface of the pipe wall.	Generated when an eddy occurs downstream of the valve.	Generated when an eddy occurs downstream of flow constricting elements, or when flushing occurs.

Troubles on Large Pipe Diameter in NPPS

1986	Surry Unit 2	USA	18 in. Pipe	Trouble
1987	Doel	Belgium	Large DiaPipe	Rupture
1990	Loviisa VVER 1	Finland	12 in. Pipe	Rupture
1990	Millstone Unit 3	USA	6 in. Pipe	Rupture
1990	Millstone Unit 2	USA	8 in. Pipe	Rupture
1993	Loviisa VVER 2	Finland	12 in. Pipe	Rupture
1993	Sequoyah Unit 2	USA	10 in. Pipe	Rupture
1996	Maanshan Unit 2	Taiwan	12 in. Pipe	Rupture
1997	Fort Calhoun	USA	12 in. Pipe	Rupture
1999	Point Beach 1	USA	4 in. Vessel	Rupture
1999	PWR	Korea	16 in. Pipe	Severe Thinning
2001	Callaway Unit 1	USA	14 in. Pipe	Severe Thinning
2001	unknown	USA	Vessel Nozzle	70% Thinning
2004	Ooi Unit 1	Japan	16 in. Pipe	42% Thinning
2004	Mihama Unit 3	Japan	22 in. Pipe	Rupture

Troubles on Small Pipe Diameter in NPPs (Since Aug., 2004)

Date	Type	Unit	Diameter	Remarks
Aug. 18, 2004	Thermal	Souma	12 inch	Burst
Sept. 24, 2004	PWR	Sendai-2	508 mm	Equal to tmin
Sept. 29, 2004	BWR	Onagawa-2	-	304 SS
Oct. 12, 2004	BWR	Fukushima	165.5 mm	Shut down
Oct. 18, 2004	PWR	Tsuruga-2	160 mm	Leak
Oct. 25, 2004	PWR	Mihama-1	114 mm	Less than tmin
Nov. 1, 2004	PWR	Ooi-4	12 inch	Less than tmin
Jan. 31, 2005	BWR	Shimane-2	76.3 mm	Leak
Feb. 5, 2005	BWR	Kashiwazaki-1	60.5 mm	Leak
Feb. 16, 2005	BWR	Hamaoka-3	90 mm	Leak
March 11, 2005	BWR	Fukushima	22 mm	Less than tmin
March 11, 2005	BWR	Fukushima	115 mm	Leak

Whether pipe will be burst or leaked after proceeding wall thinning ?

A following tendency can be observed:

Pipe of Large Diameter

⇒ high possibility of **burst** of pipe

Pipe of small diameter

⇒ Low possibility of burst of pipe
High possibility of **leakage** through
a hole generated on pipe

What may be taken against pipe wall thinning not avoidable?

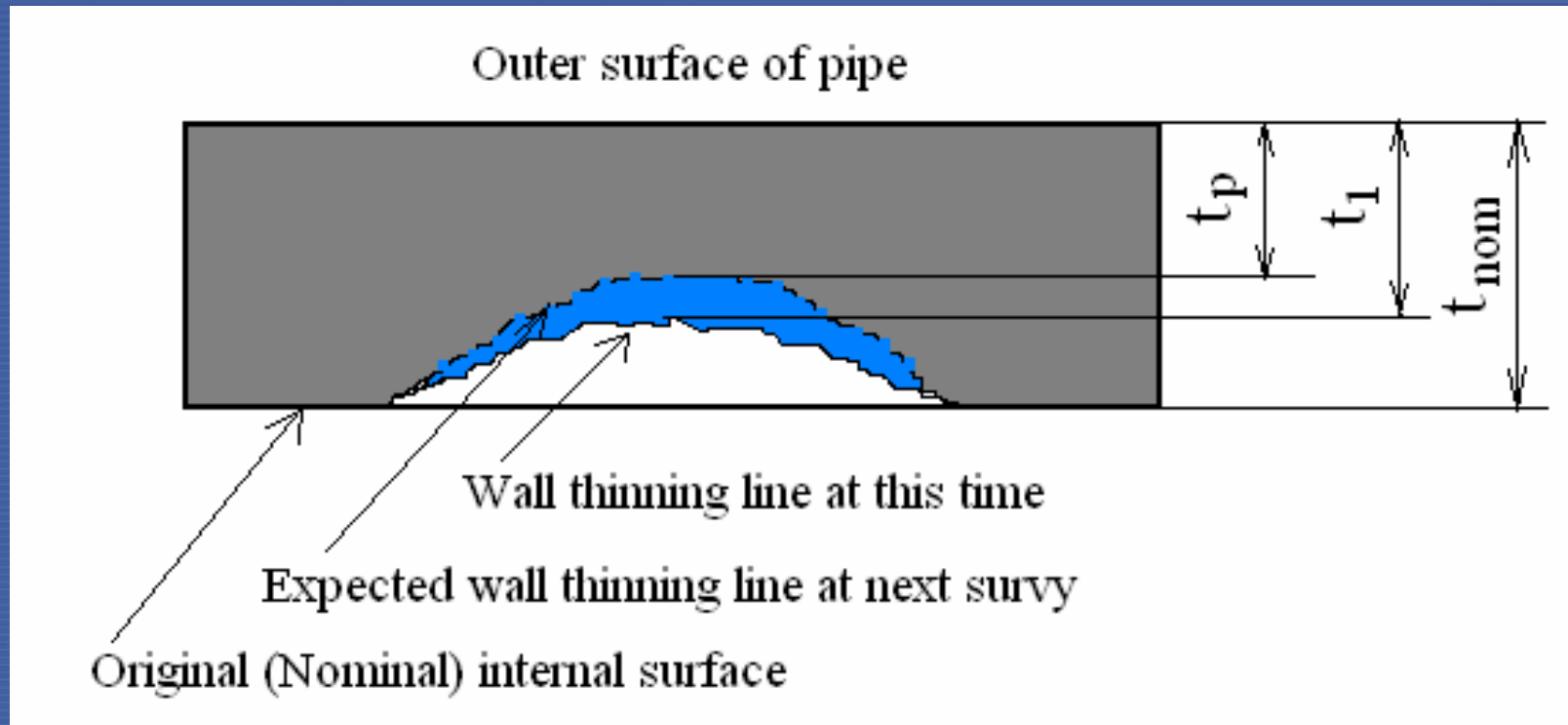
Following countermeasures may be taken:

- (1) Enough corrosion allowance for expected pipe wall thinning \Rightarrow too thick pipe?
- (2) Usage of low alloy steel contained Cr & Mo \Rightarrow high initial cost ?
- (3) Periodical thickness measurement \Rightarrow high running cost ?

Countermeasures depending on pipe pressure and diameter

	High burst possibility	High leakage possibility
High pressure pipe	Large Dia. Pipe	Small Dia. Pipe
Low pressure pipe	Periodical thickness measurement	Run to failure or check at Special Survey
	Enough Corrosion Allowance	

How to decide repairing work for wall thinned pipe



$t_p > 0.9t_{min}$: Pipes may be used.

$t_p < 0.9t_{min}$: Pipes to be repaired or replaced,

How to calculate residual thickness at next survey

T_p Supposed thickness at next survey

$$T_p = T_1 - Z \cdot h$$

Where each parameter have following meanings

Z [mm/hr] : Wall thinning rate = $(T_0 - T_1)/H$

T_0 : Measured thickness at last survey,

T_1 : Measured thickness at this time

T_{min} : Required minimum thickness excluded by corrosion allowance

T_{nom} : Nominal thickness

H : Running hour from last survey to this time

h : Running hour from now to next survey

How to calculate required minimum thickness of the pipe

$$t_{\min} = \frac{pD}{2fJ + p} + b + C$$

t_{\min} : Required minimum thickness (mm)

p : Design internal pressure (Mpa)

D : Outer diameter of pipe (mm)

f : Allowable stress (N/mm²)

J : Junction efficiency

b : Bending allowance

$$b = \frac{1}{2.5} \cdot \frac{D}{R} \cdot t_0$$

R : Bending radius at center line of pipe (mm)

C : Corrosion allowance (mm)

Reduction rate in this table may be used if there is no actual available measured data – in Japan

Table 10 Maximum reduction rate ($\times 10^{-4}$ mm/hr) (carbon steel (Cf. STPG370)) 1)

Flow rate (m/s)		Temp. (°C)			
		100 to 150	150 to 200	200 to 250	Above 250
Single phase water flow	Below 3	0.45 ^{*)}		0.90 (Downstream of control valve and ball check valve)	
	3 to 6				
	Above 6				
Two-phase flow (wetness greater than 15%)	Below 30	0.90	0.95 ^{*)}		
	30 to 50		1.15 ^{*)}		
	Above 50				
Two-phase flow (wetness 5 to 15%)	Below 30		0.95 ^{*)}		
	30 to 50		1.15 ^{*)}		
	Above 50				
Two-phase flow (wetness below 5%) (Possibility of drain inclusions)	Below 30		0.95 ^{*)}		
	30 to 50		1.15 ^{*)}		
	Above 50				

Remark *): Down stream of Control valve to be 5 times and down stream of ball check valve to be 2 times.

