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Investigation on Integrity of Heat Exchanger and Tanks in Primary Cooling System of JMTR

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(Received October 6, 2010)

The Japan Materials Testing Reactor (JMTR) is a light water moderated and cooled tank-type reactor using LEU silicide plate-type fuels. First criticality was achieved in March 1968, and its operation was stopped from August, 2006 for the refurbishment. The refurbishment is scheduled from the beginning of FY2007 to the end of FY2010.

An investigation on aged components was carried out for concrete structures of the JMTR building and for aged components of tanks in the primary cooling system, heat exchangers and so on, in order to identify their integrity. The investigation was carried out from the beginning of FY2007. In this paper, the aged-investigations for heat exchangers and tanks in the primary cooling system are presented.

The integrity of three heat exchangers was confirmed by the eddy current testing for heat exchanger tubes, visual observation using endoscope, liquid penetration test of tube plates and thickness measurement of the main body.

The visual inspection test and liquid penetration test were carried out to confirm the integrity of tanks in the primary cooling system.

The heat exchangers and tanks in the primary cooling system will be continuously used in the future operation of the JMTR by appropriate maintenance activities based on the long-term maintenance program.

Keywords : JMTR, Testing Reactor, Refurbishment, Aged-Investigation, Primary Cooling System, Heat Exchanger, Tanks

一次冷却系熱交換器及びタンク類の健全性調査

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JMTR は、低濃縮シリサイド板状燃料を用いた軽水減速・冷却のタンク型原子炉である。熱出力は 50MW である。1968 年 3 月に初臨界を達成した後に、2006 年 8 月に改修作業のために運転を停止した。改修作業は、2007 年度初頭から 2010 年に予定されている。

2007 年度当初に、JMTR 建屋のコンクリート構造物、一次冷却系統のタンク類、熱交換器、等について、健全性を確認するために、高経年化設備について調査を行った。本報では、一次冷却系統の熱交換器及びタンク類の高経年化調査について述べる。

一次冷却系統に供えられた 3 基の熱交換器について、渦流探傷試験、内視鏡を用いた外観検査、浸透探傷試験、胴部の減肉検査を行い、健全性を確認した。一次冷却系統のタンク類に対しては、外観検査及び溶接線に対する浸透探傷検査を行い、健全性を確認した。

一次冷却系統の熱交換器及びタンク類は、長期的な保全計画に基づく適切な点検を行い、JMTR の今後の運転で継続使用する。

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1. Introduction

The Japan Materials Testing Reactor (JMTR) is a light water moderated and cooled tank-type reactor using LEU silicide plate-type fuels with thermal power of 50 MW.

First criticality was achieved in March 1968, and its operation was stopped from August, 2006 for the refurbishment. The refurbishment is scheduled from the beginning of FY2007 to the end of FY2010. The renewed and upgraded JMTR will be re-started from FY2011.

An investigation on aged components was carried out for concrete structures of the JMTR building and for aged components of tanks in the primary cooling system, heat exchangers and so on, in order to identify their integrity. The investigation was carried out from the beginning of FY2007. In this paper, results of the investigation on the aged-investigations for heat exchangers and tanks are presented.

2. Outline of primary cooling system

The JMTR was constructed to perform irradiation tests, for fuels/materials to establish domestic technology for developing nuclear power plants, and to produce radioisotopes. Its specification is summarized in Table 1. The reactor pressure vessel, 9.5 m in hight with 3 m in inner diameter, is made of low carbon stainless steel (SUS304L), and is located in the reactor pool. The control rod drive mechanisms are placed under the pressure vessel to make an easy handling of the irradiation facilities and fuels from the top of the core as shown in Figure 1. The core of the JMTR is a cylindrical shape with 1.56 m in diameter and 0.75 m in height. The core consists of 24 standard fuel elements, five control rods with fuel followers, reflectors and H-shaped beryllium frame.

A primary cooling system consists of a main circulating system and a purification system. Cooling water in the primary cooling system is pressurized at about 1.5 MPa to avoid local boiling in the core during rated power operation of 50 MW. Figure 2 shows a diagram of the primary cooling system.

The main circulating system consists of main circulating pumps, emergency pumps, primary coolant system heat exchangers, a pressure surge tank, pipes and valves. The cooling water flows downwards in the core to transfer the heat from the core. The main circulating system circulates the primary cooling water to remove heat generated in the core to the secondary cooling system through 3 units of shell-and-tube heat exchangers. Finally, the heat transferred to the secondary cooling system is removed away into the atmosphere by cooling towers. The primary cooling water flows inside of heat transfer tubes, and the secondary cooling water flows outside of the tubes. Purified water is used as the primary cooling water. The number of tubes of each heat exchanger is 1,152, and heat transfer area is 1,100m^2. Specifications of the heat exchangers are shown in Table 2. The surge tank has the function of suppression of pressure variation of the reactor vessel. Specifications of the surge tank are shown in Table 3.

The purification system consists of a degas tank, a purify water tank, charging pumps, transfer pumps, ion exchange towers, filters, pipes and valves. This system removes corrosion products, and dissolved gas in the primary cooling water, and keeps the quality of water. The role of degas tank is to prevent separation of radiolytic hydrogen and oxygen generated in the reactor. The purify water tank temporarily stores purified primary cooling water. Table 3 shows also the specifications of the degas tank and the purify water tank.

3. Investigation items

3.1 Heat exchanger

The inside tube walls of heat exchangers in primary coolant system are prevented from rusting and stress corrosion cracking (SCC), with following reasons; the tubes are made of austenite stainless steel, the quality of primary cooling water is kept and the temperature of water is low (below 49 degrees C). On the other hand, it has a possibility of pitting corrosion or SCC by chloride ion, because hypochlorite is used as sterilizer in the secondary cooling water. However, it is considered that degree of corrosion is inhibited by an anticorrosion additive in the secondary cooling water. It has a potential for thinning of baffle plates with fluid oscillation. Therefore, following investigations are carried out to identify the integrity of heat exchangers.

(1)Eddy current testing for heat exchanger tubes

Thinning of heat exchanger tubes was measured by the eddy current testing. The investigation covered throughout the length of straight tube and U-tube (Refer to Figure 3). We could not insert an ETC probe into 151 tubes within total 3456 tubes.

(2)Visual observation using endoscope

Visual observation was carried out with an endoscope to the heat exchanger tubes that had been evaluated as the thinning rate 20% or more by the eddy current testing and that had not been measured.

(3)Penetration test of tube plates

Penetration test was carried out for the depressed parts that had been observed by photograph of the tube plate surface.

(4)Thickness measurement of the main body

Wall thickness of main body of the heat exchanger was measured by an ultrasonic thickness gauge at installation intervals of baffle plate in a longitudinal direction (HX-1~HX-10) and at every 45 degree in circumferential direction (A~H) as shown in figure 4. Wall thickness of the tank head was measured at three points in radial direction at every 45 degree in circumferential direction. Wall thickness of the heat affected zone of welding part was measured at intervals of 20mm.

3.2 Surge tank, degas tank, purified water tank

Investigations were carried out for the surge tank, degas tank and purify water tank. All tanks will be used during reoperation period. Though the surge tank was replaced in 1997, visual inspection was carried out for the inner surface in order to confirm the long term utilization. The degas tank and purify water tank have been used for about 40 years since the beginning of JMTR operation. Visual inspection and penetration testings for welding region were carried out for these two tanks to confirm their integrity.

4. Investigation result

4.1 Heat exchanger

(1)Eddy current testing for heat exchanger tubes

It was observed that signals which indicate thinning and dent by the eddy current testing. All dents were small. Total 23 tubes were evaluated to have the thinning rate 20% or more by the eddy current testing in heat exchanger tubes. All of thinnings were observed at the inner surface of the tube wall. From low incidence of thinning, heat exchangers are kept in a good condition.

(2)Visual observation using endoscope

According to the result of eddy current testing, we observed tube surfaces using an endoscope, and confirmed color change and pitting corrosion. Some observed results are shown in figure 5. It is observed that there are minor corrosion, color change, pitting corrosion, deformation and separation of oxide film ((a) ~ (d) in figure 5). Photo (c) shows a pipe in which ETC prove could not insert. Photo (e) shows a step part of inner surface. Photo (f) shows a sample of reference specimen which is adjusted to the thinning rate at 30%. We evaluated that there is no significant corrosion and decrease of tube thickness from the result of the comparative testing using some reference specimens.

(3)Penetration test of tube plates

No defect indication was found where depressed position had been observed by photograph of surface of the tube plate.

(4)Thickness measurement of the main body

Table 4 shows minimum thickness of body and heat affected zone of welding part. All measured thickness was greater than required minimum thickness of 6 mm. The integrity of the main body of heat exchangers was confirmed by the measurement.

4.2 Surge tank, degas tank, purified water tank

There was no abnormal condition (such as, flaws, cracks and corrosion) on the inner surface of the surge tank. The surge tank was maintained in good condition. Figure 6 shows a part of investigation results. The condition of the inner surface of the degas tank and the purified water tank was fine without flaws, cracks and corrosion and so on. No abnormal condition was observed for all three tanks from the result of visual inspection.

In the penetration testing for welding region, defect indications were observed in the welding lines of the purified water tank and degas tank. However, after grinding, no defect indication was found in the re-inspection. A sample photograph for the degas tank is shown in figure 7, and figure 8 for the purified water tank. It was concluded that there were not progressive defects. The inspection result shows that these tanks will keep structural integrity during prolonged periods after the re-operation of JMTR.

5. Conclusions

We confirmed the integrity of the three heat exchangers, surge tank, degas tank and purified water tank in the primary system by the inspections and information of current status of these components. Based on the information, we will continue to assess the integrity on thinning parts of the heat exchangers by a periodical overhaul. For the three tanks, we will continue applicable maintenance programs such as an annual visual inspection, an annual leak testing, and a periodical overhaul. The heat exchangers and three tanks in the primary cooling system will be used continuously in the future operation of the JMTR.

References

1) H.Ebisawa et al., “The Outline of Investigation on Integrity of JMTR Concrete Structures, Cooling System and Utility Facilities”, JAEA-Technology 2009-030(2009).(in Japanese).

Table 1 Major Specifications of JMTR

Reactor Thermal Power	50	(MW)
Fast Neutron Flux (Max.)	4 x 10^{18}	(n/m^2s)
Thermal Neutron Flux (Max.)	4 x 10^{18}	(n/m^2s)
Primary Coolant Flow Rate	6000	(m^3/h)
Coolant Temperature(In/Out)	49 / 56	(°C)
Active Core Length	750	(mm)
Fuel	Plate type, 19.75% ^{235}U	
Irradiation Capability (Max.)	60 (20*) capsules	
dpa of Stainless Steel (Max.)	4	(dpa/y)
Diameter of Capsule	30 – 65	(mm)
Temperature Control (Max.)	2000	(°C)

* Capsule with in-situ measurement

Table 2 Major Specifications of heat exchanger

type	shell-and-tube
dimensions	11,390^H×1,650$^\phi$ (mm) / units
material	shell SS41
	tube SUS27TB
Number of units	3
Number of tubes	1,152 / units
Heat transfer area	1,100m^2 / units
Date of manufacture	1967.3

Table 3 Major Specifications of surge tank, degas tank, purify water tank

	Surge tank	Degas tank	Purify water tank
type	Cylindrical tank	Cylindrical tank	Cylindrical tank
capacity	3 (m^3)	Total content 10 (m^3) Holding water quantity 5 (m^3)	5 (m^3)
dimensions	$3{,}950^{H} \times 1{,}028^{\phi}$ (mm)	$6{,}200^{H} \times 1{,}566^{\phi}$ (mm)	$3{,}160^{H} \times 1{,}756^{\phi}$ (mm)
material	SUS	SUS	SUS
Number of tank	1	1	1
Date of manufacture	1997.6	1966.12	1966.11

Table 4 Thickness measurement of the main body (minimum thickness)

body and tank head		heat affected zone	
No.1(HX-1-A)	7.0 mm	No.1	7.0 mm
No.2(tank head-F)	8.9 mm	No.2	8.0 mm
No.3(HX-2-F)	8.7 mm	No.3	8.1 mm

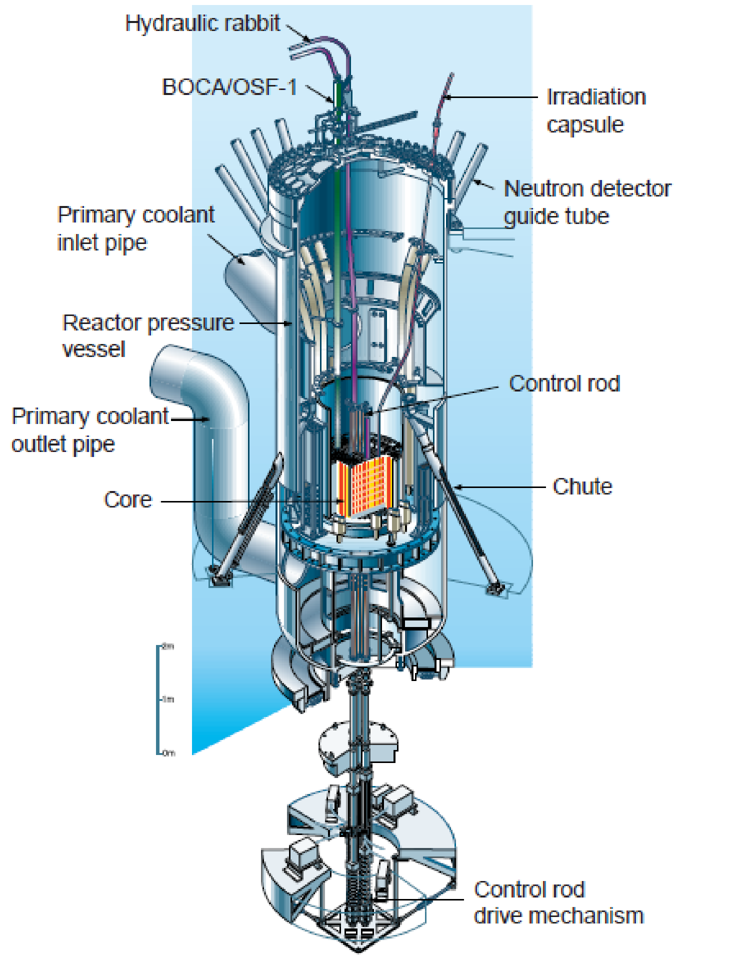


Figure 1　Cutaway view of Reactor core with pressure vessel

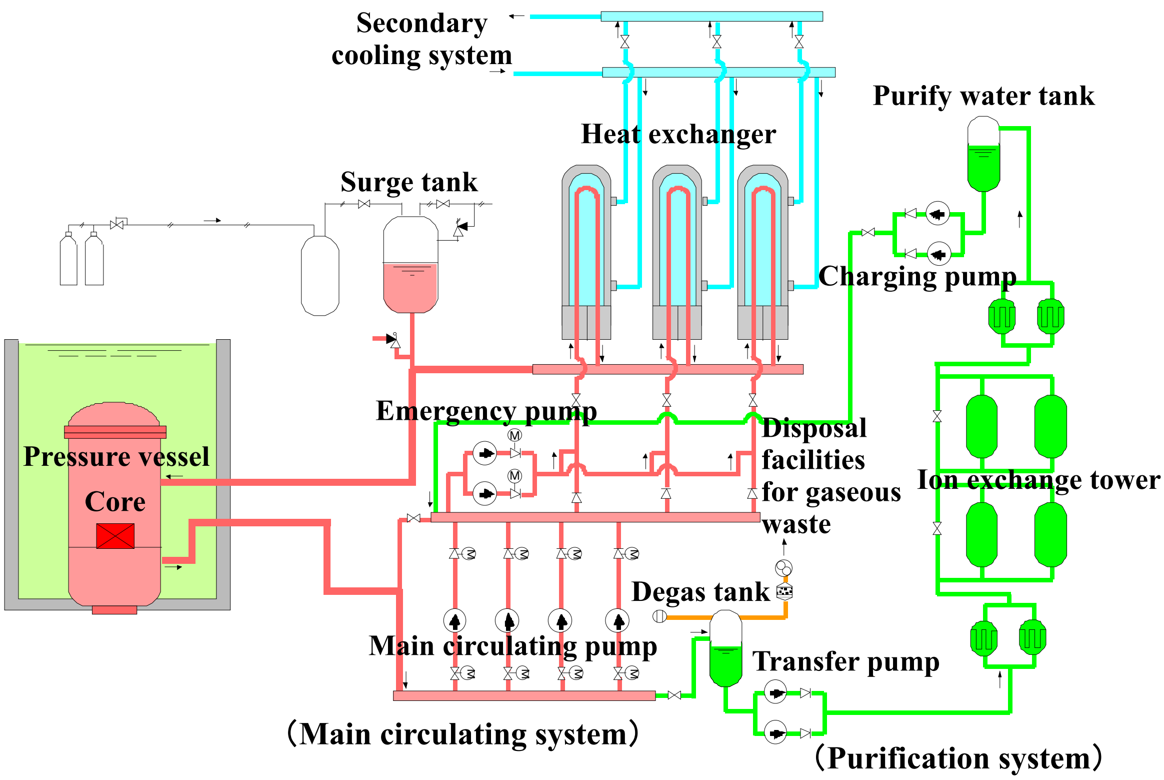


Figure 2 Diagram of the primary cooling system

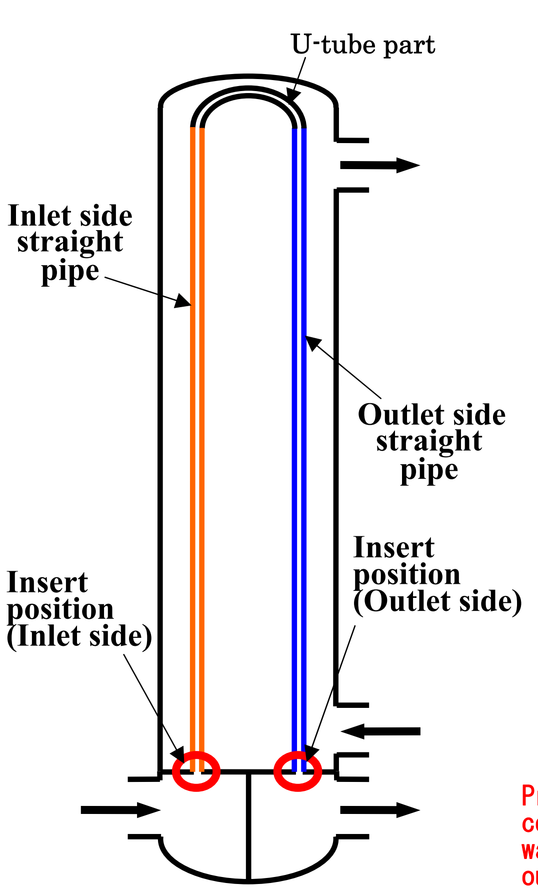


Figure 3 Inspected parts in Eddy current testing

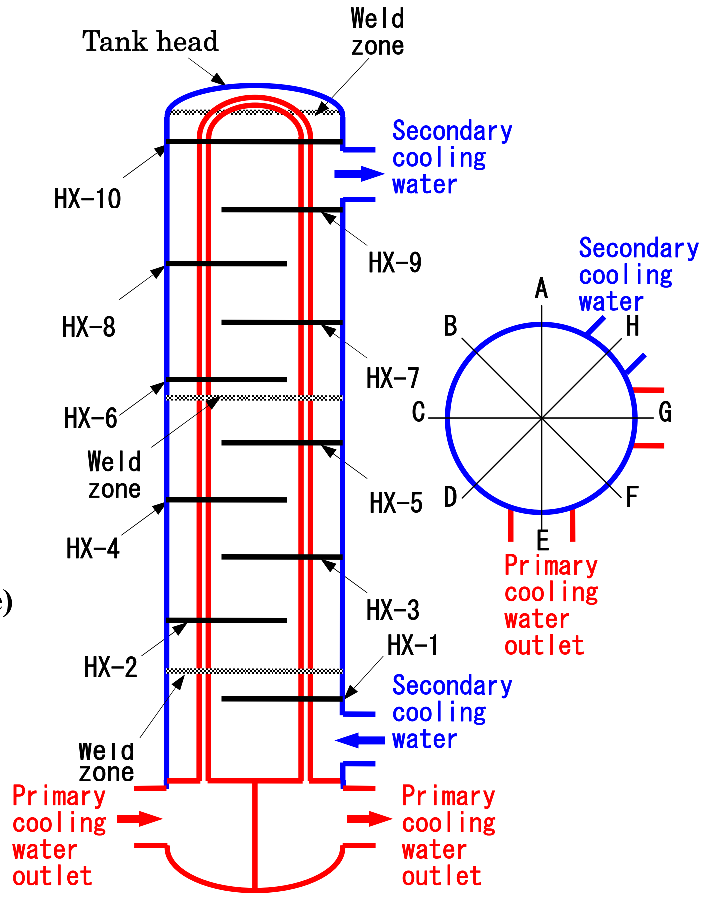
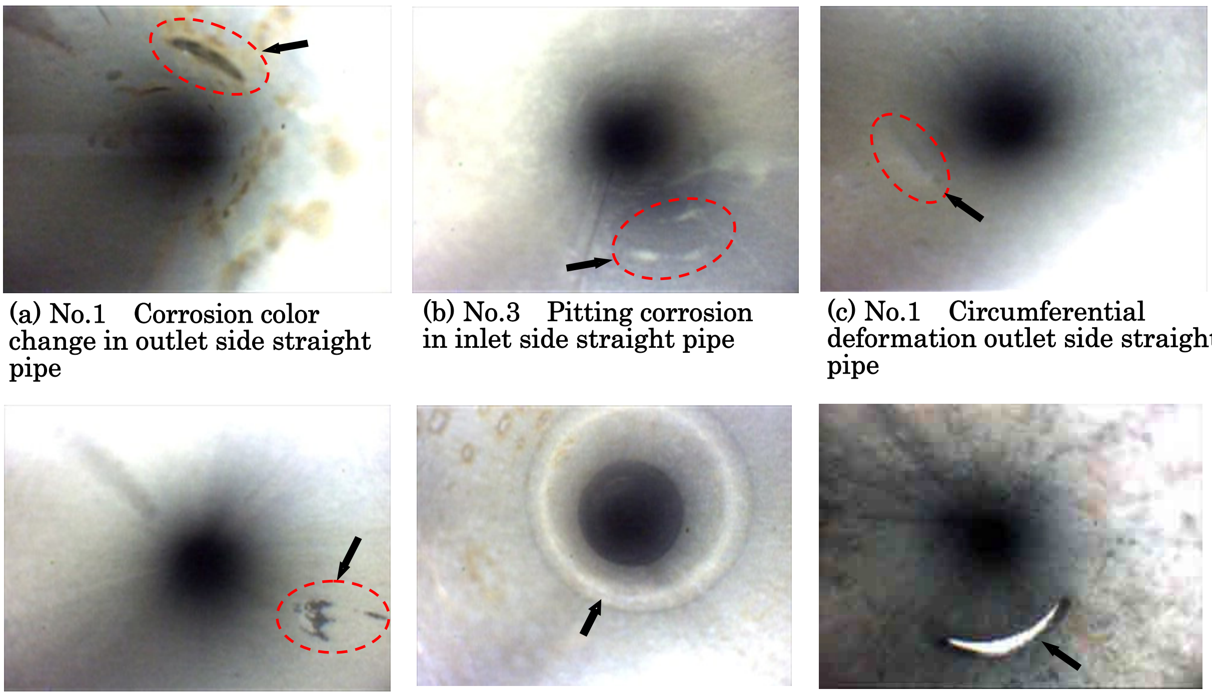


Figure 4 Thickness measured parts of the main body



(a) No.1 Corrosion color change in outlet side straight pipe

(b) No.3 Pitting corrosion in inlet side straight pipe

(c) No.1 Circumferential deformation outlet side straight pipe

(d) No.2 Separation of oxide film from outlet side straight pipe

(e) No.1 Step part of inner surface outlet side straight pipe

(f) Reference specimen (thinning rate at 30%)

Figure 5 Visual observation result

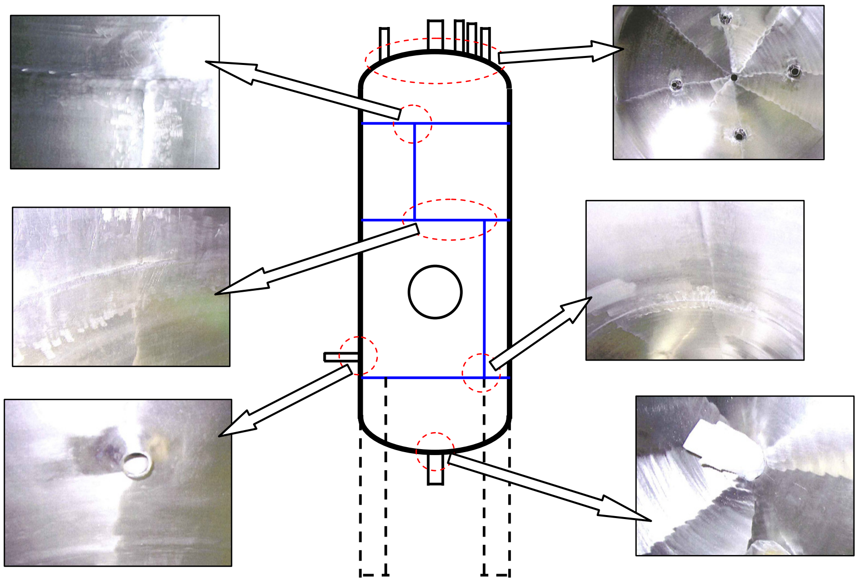


Figure 6　Sample of investigation results for the surge tank

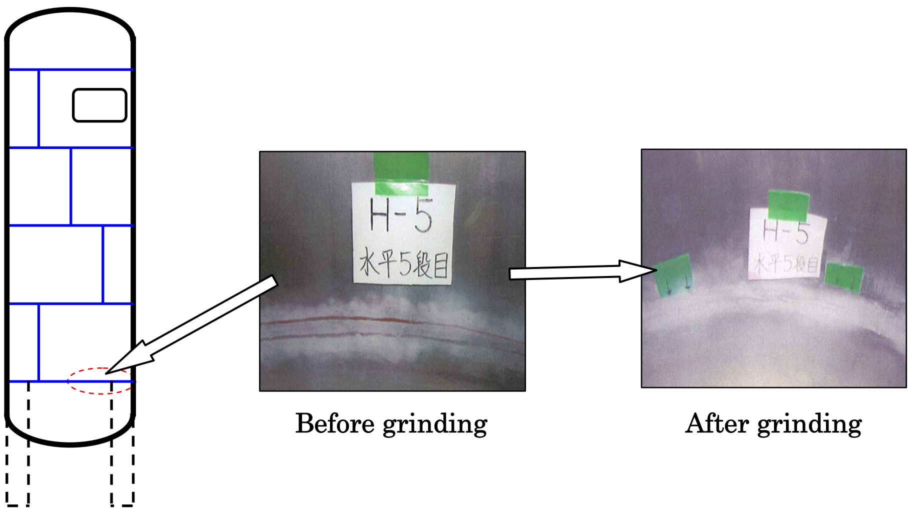


Figure 7　Sample of investigation results for the degas tank

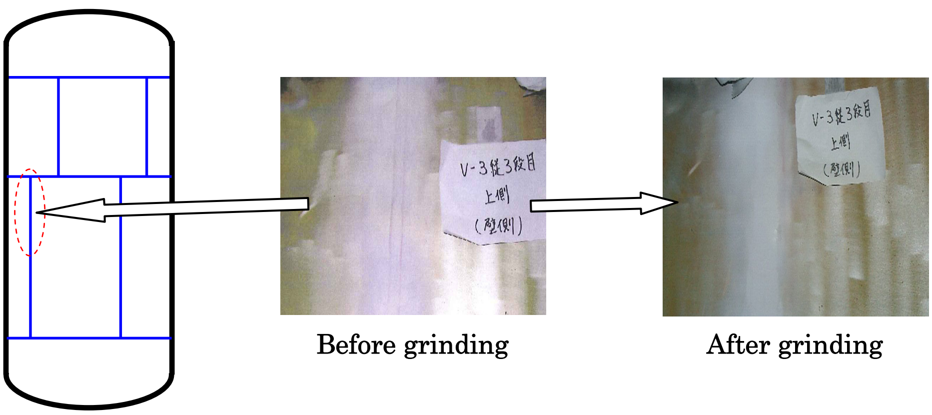


Figure 8　Sample of investigation results for the purify water tank

Appendix Presentation materials at 3rd International Symposium on Material Test Reactor

The 3rd International Symposium on Material Test Reactor was held June 21-23, 2010 at the Nuclear research Institute Rez plc. and Research centre Rez Ltd., Czech Republic. The objective of the meeting was to provide an opportunity for technical and operational information exchange among materials testing reactors.

The presentation materials related in “Investigation on integrity of heat exchanger and tanks in primary cooling system of JMTR” are attached as an appendix.

Investigation on Integrity of heat exchanger and tanks in Primary Cooling System of JMTR

Ryuji ONOUE, Hiroyuki EBISAWA,
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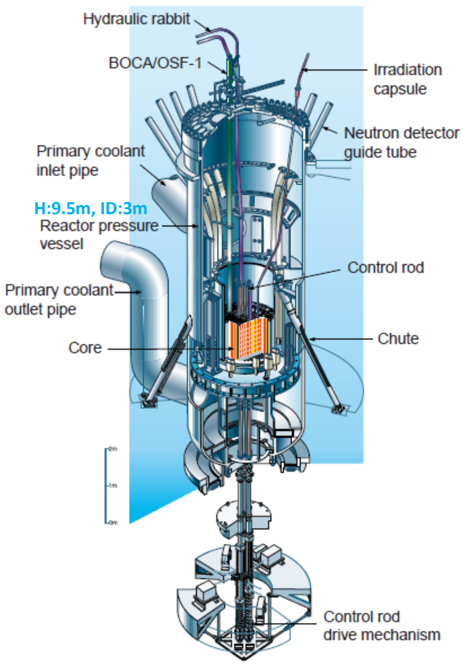
Japan Atomic Energy Agency

1. Outline of the Aged-Investigation

- **First criticality of JMTR was achieved in March 1968**
- **Operation was stopped from August, 2006 for the refurbishment.**
- **The refurbishment is scheduled from the beginning of FY2007 to the end of FY2010.**
- **The renewed and upgraded JMTR will be re-started from FY2011.**
- **An investigation on aged components was carried out for concrete structures of the JMTR building and for aged components of tanks in the primary cooling system, heat exchangers and so on, in order to identify their integrity.**
- **The aged-investigations for heat exchangers and tanks are presented here.**

2.Outline of JMTR

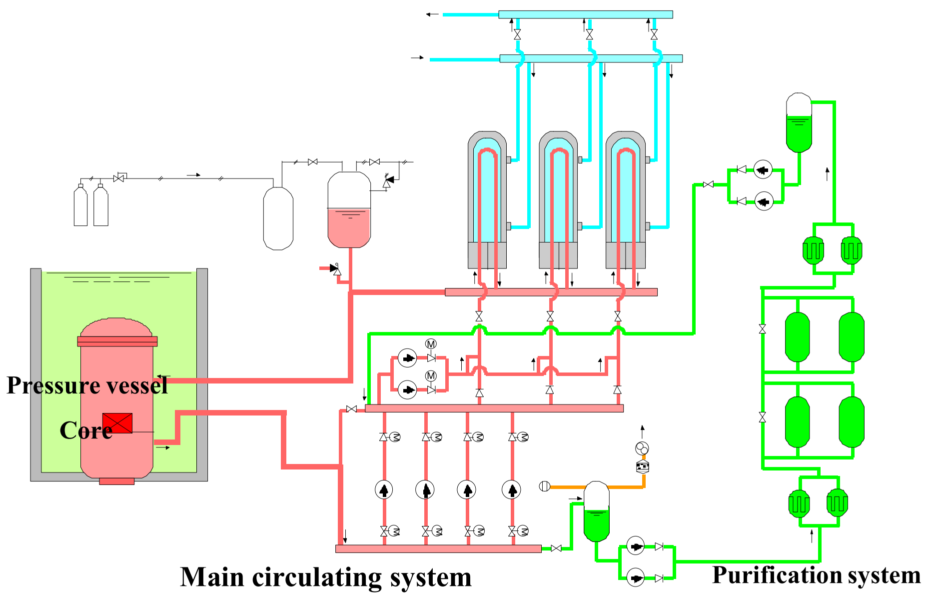


- **The JMTR was constructed to perform irradiation tests, materials and produce radioisotopes in order to establish domestic technology for developing nuclear power plants.**
- **The reactor pressure vessel is made of low carbon stainless steel and is located in the reactor pool.**
- **The CRDMs are placed under the pressure vessel to make an easy handling of the irradiation facilities and fuels from the top of the core.**
- **The core of the JMTR has a cylindrical shape with 1.56 m in diameter and 0.75 m in height.**

Major Specifications of JMTR

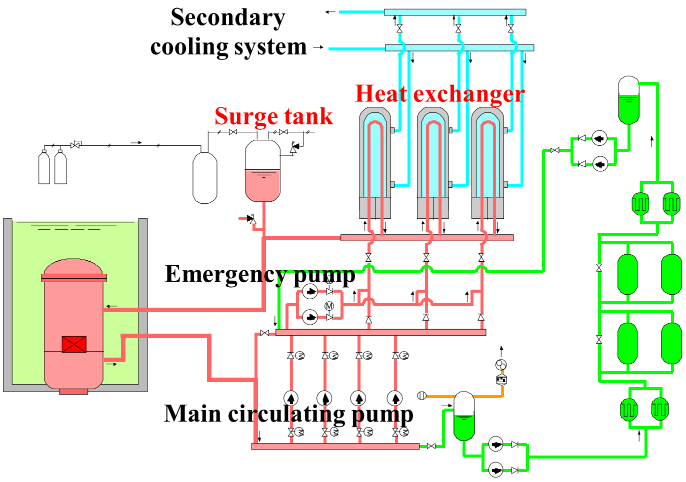
Reactor Thermal Power	50(MW)	
Fast Neutron Flux (Max.)	4 x 10^{18}	(n/m^2s)
Thermal Neutron Flux (Max.)	4 x 10^{18}	(n/m^2s)
Primary Coolant Flow Rate	6000	(m^3/h)
Coolant Temperature	49 / 56	(° C)
Active Core Length	750	(mm)
Fuel	Plate type, 19.75% ^{235}U	
Irradiation Capability (Max.)	60 (20*) capsules	
dpa of Stainless Steel (Max.)	4	(dpa)
Diameter of Capsule	30 – 65	(mm)
Temperature Control (Max.)	200	(° C)

3. Outline of primary cooling system



- **This figure shows a diagram of the primary cooling system.**
- **Cooling water in the primary cooling system is pressurized at about 1.5 MPa to avoid local boiling in the core during rated power operation of 50 MW.**

4.Main circulating system



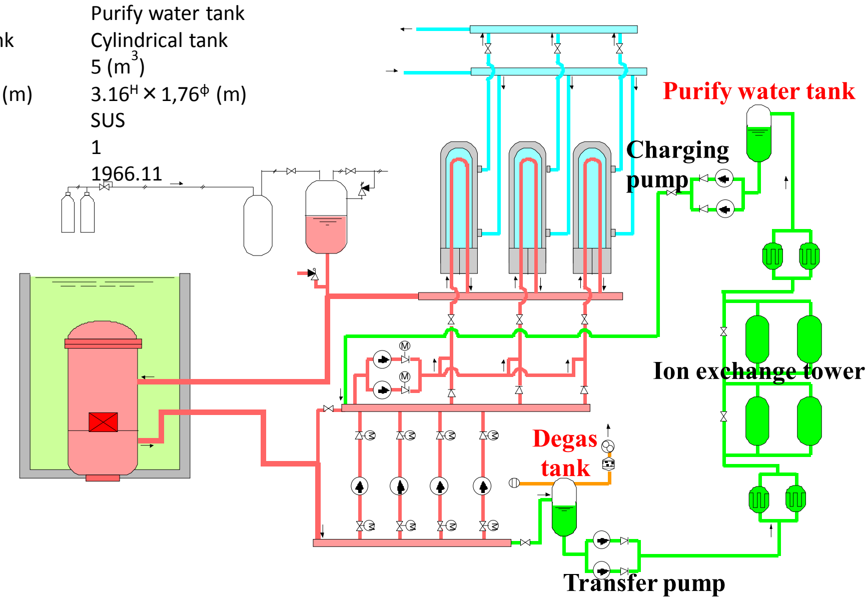
heat exchanger	
Type	shell-and-tube
Dimensions	$11.39^{H} \times 1.65^{\phi}$ (m) / units
Material	shell SS41
	tube SUS27TB
Number of units	3
Number of tubes	1,152 / units
Heat transfer area	1,100m^2 / units
Date of manufacture	1967.3

surge tank	
Type	Cylindrical tank
Capacity	3 (m^3)
Dimensions	$3.95^{H} \times 1.03^{\phi}$ (m)
Material	SUS
Number of tank	1
Date of manufacture	1997.6

- **The MCS circulates the primary cooling water to remove thermal energy generated in the core to the secondary cooling system through 3 units of shell-and-tube heat exchangers.**
- **The primary cooling water flows inside of heat transfer tubes, and the secondary cooling water flows outside of the tubes. Purified water is used as the primary cooling water**
- **The surge tank has the function of suppression of pressure variation of the reactor vessel.**

5. Purification system

	Degas tank	Purify water tank
Type	Cylindrical tank	Cylindrical tank
Capacity	10 (m^3)	5 (m^3)
Dimensions	$6.20^{H} \times 1{,}57^{\phi}$ (m)	$3.16^{H} \times 1{,}76^{\phi}$ (m)
Material	SUS	SUS
Number	1	1
Manufacture	1966.12	1966.11



- **This system removes corrosion products, and dissolved gas in the primary cooling water, and keeps the quality of water.**
- **The role of degas tank is to prevent separation of radiolytic hydrogen and oxygen generated in the reactor.**
- **The purify water tank temporarily stores purified primary cooling water in.**

6. Investigation Items for heat exchangers

- The inside tube walls of primary coolant system heat exchangers are prevent from rusting and SCC.
  - Because ;
  - the tubes are made of austenite stainless steel
  - the quality of primary cooling water is kept
  - the temperature of water is low (below 49 degrees C)
- On the other hand, it has possibility of pitting corrosion or SCC by chloride ion
  - Because :
  - hypochlorite is used as sterilizer in the secondary cooling water.
- But degree of corrosion is inhibited by an anticorrosion additive in the secondary cooling water.
- It has a potential for thinning of baffle plates with fluid oscillation.
- We carried out following investigations to identify the integrity of heat exchangers for the reason stated above.

（1）Eddy current testing for heat exchanger tubes

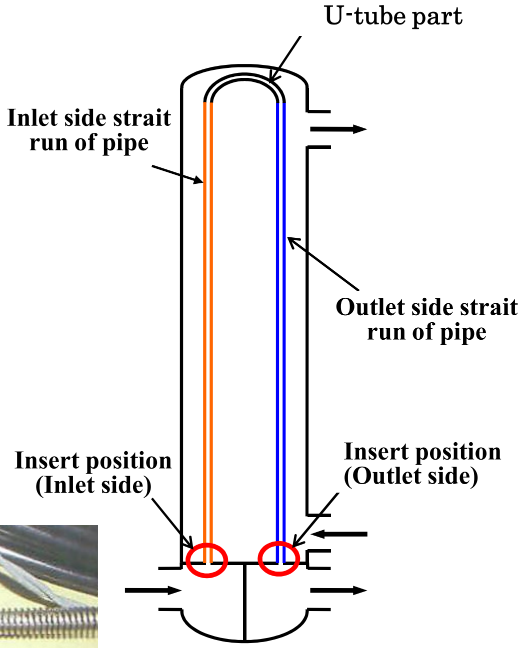
（2）Visual observation using endoscope

（3）Penetration test of tube plates

（4）Thickness measurement of the main body

7.Eddy current testing for heat exchanger tubes

- Thinning of heat exchanger tubes was measured by the eddy current testing.
- The investigation covered throughout the length of straight run and U-tube of tubes .
- We could not insert an ETC probe on 151 tubes out of 3456 tubes.



ETC prove for strait run of pipe

ETC prove for U-tube

8. Result of eddy current testing

- **It was observed the signals that meant thinning and dent according to the eddy current testing.**
- **All dents were minor. A total of 23 tubes were evaluated to have the thinning rate 20% or more in eddy current testing for heat exchanger tubes.**
- **All of these thinning were observed at the inner surface of the tube wall.**
- **It has a low incidence of thinning and the heat exchangers are kept in a good condition as a whole.**

9. Visual observation using endoscope

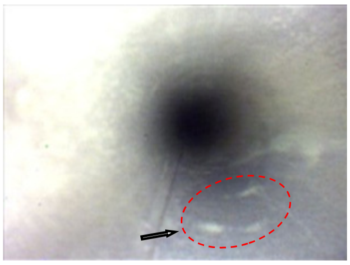
- **Visual observation was carried out.**
- **Using an endoscope for the heat exchanger tubes .**
- **Target ;**
  - **Evaluated part as the thinning of the thinning rate 20% or more according to the eddy current testing**
  - **Part that had not been measured by eddy current testing.**

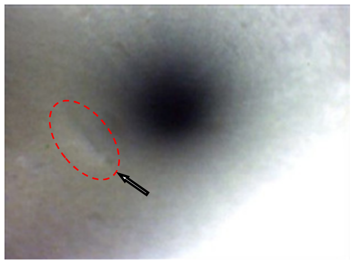
Whole apparatus

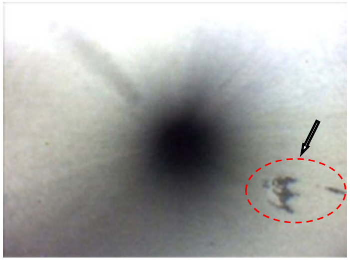
Inspection situation

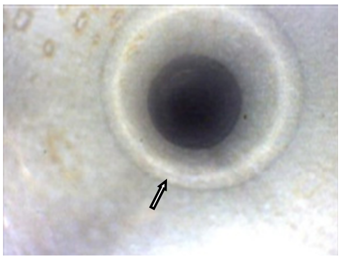
10. Result of Visual observation


No.1 Outlet side strait pipe corrosion, color change


No.3 Inlet side strait pipe pitting corrosion


No.1 Outlet side strait pipe circumferential deformation


No.2 Outlet side strait pipe separation of oxide film


No.1 Outlet side strait pipe step part of inner surface


Reference specimen thinning rate 30%

- **According to the result of eddy current testing, we observed surface of these tubes using an endoscope. Some observed results are shown here.**
- **We evaluated that there is no significant corrosion and decrease of tube thickness**

11. Penetration test of tube plates

- **Penetration test was carried out for the depressed portion**
- **that had been observed by photography of surface of the tube plate.**

- **No defect indication was found at the positions that depressed portion had been observed by photography of surface of the tube plate.**

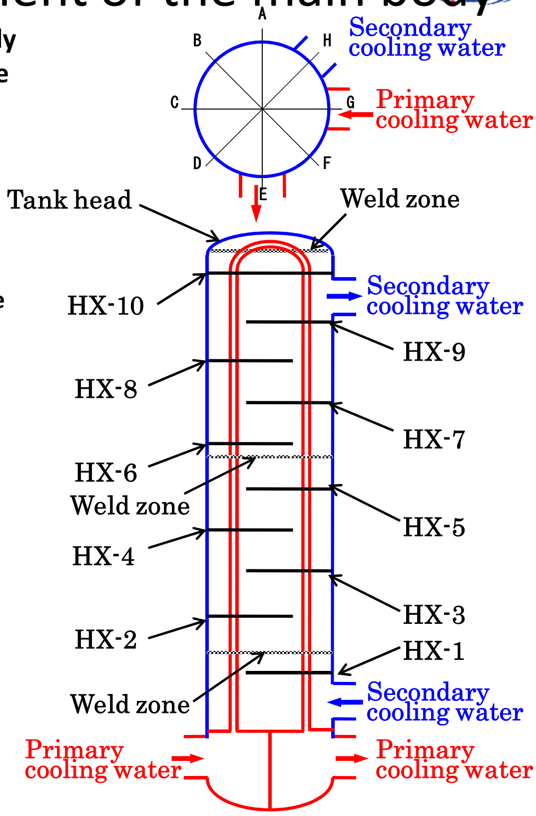
12. Thickness measurement of the main body

- Wall thickness of the heat exchanger main body was measured by an ultrasonic thickness gauge
  - Installation intervals of baffle plate;
  - in a longitudinal direction(HX-1~HX-10)
  - at every 45 degree in circumferential direction (A~H)
- Wall thickness of the tank head was measured
  - at 3 points in radial direction at every 45 degree in circumferential direction
- Wall thickness of the heat affected zone of welding part was measured
  - at intervals of 20mm

Minimum thickness

body and tank head		heat affected part	
No.1(HX-1-A)	7.0 mm	No.1	7.0 mm
No.2(tank head-F)	8.9 mm	No.2	8.0 mm
No.3(HX-2-F)	8.7 mm	No.3	8.1 mm

- All measured thickness was greater than required minimum thickness of 6 mm.

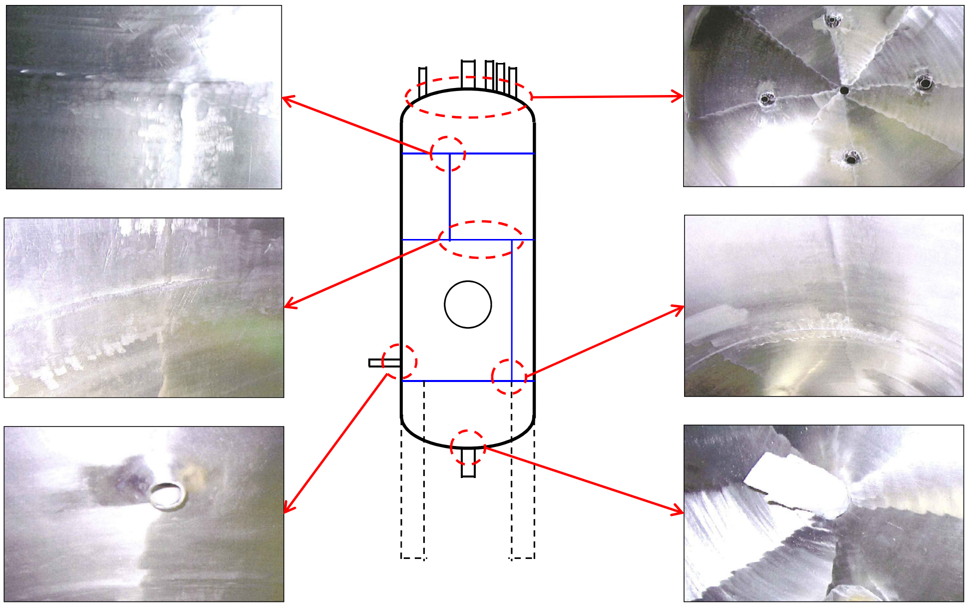


13. Investigation items for tanks

	surge tank	degas tank	purify water tank
Visual Inspection	O	O	O
penetration testing	-	O	O

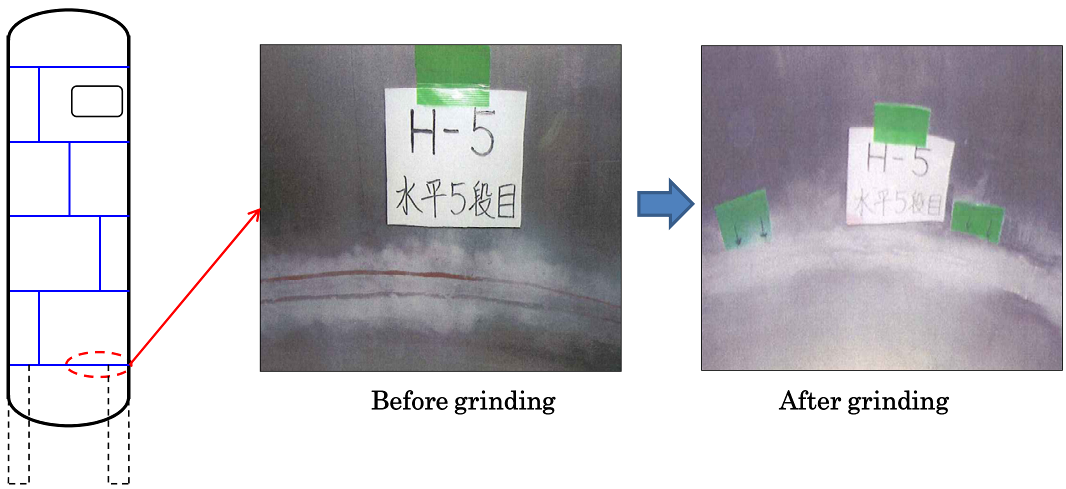
- Though the surge tank was replaced in 1997, visual inspection was carried out for the inner surface in order to confirm that it is able to use the tank over the long term.
- The degas tank and the purify water tank have been used for about 40 years.
- Visual inspection and penetration testing for welding region were carried out for the degas tank and the purify water tank to confirm their integrity.

14. Result of inspection (surge tank)



- The surge tank was maintained in good condition.
- The condition on the inner surface of the surge tank was fine without flaws, cracks and corrosion and so on.
- There was no abnormal condition of all 3 tanks from the result of visual inspection.

15. Result of inspection (degas tank)

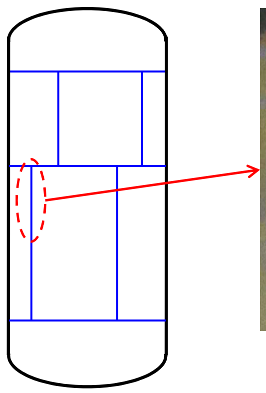


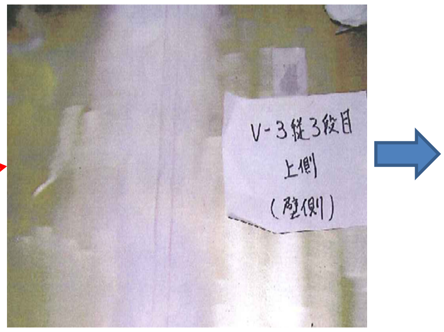
Before grinding

After grinding

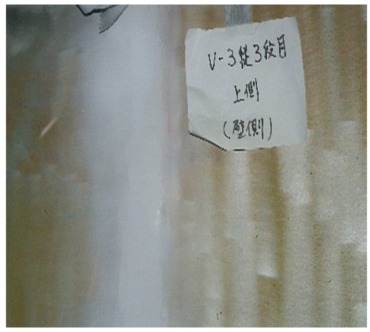
- In the penetration testing for welding region, defect indications were observed in the welding.
- After grinding, no defect indication was found in the re-inspection.
- It was considered that they were not progressive defect.

16. Result of inspection (purify water tank)





Before grinding



After grinding

- In the penetration testing for welding region, defect indications were observed in the welding.
- After grinding, no defect indication was found in the re-inspection.
- It was considered that they were not progressive defect.
- The result shows that these tanks endure prolonged periods after the re-operation of JMTR.

17. Conclusion

- **It was confirmed the integrity of the three heat exchangers, the surge tank, the degas tank and the water purified tank.**
- **Information of current status of these components was obtained.**
- **Based on the information, we will continue to assess the integrity on thinning parts of the heat exchangers in a periodic overhaul.**
- **For the three tanks, we will continue an applicable maintenance operation such as an annual visual inspection, an annual leak testing, and a periodical overhaul.**

国際単位系（SI）

表１．SI 基本単位

基本量	SI 基本単位 名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd

表２．基本単位を用いて表されるSI組立単位の例

組立量	SI 基本単位 名称	記号
面積	平方メートル	m^2
体積	立法メートル	m^3
速さ，速度	メートル毎秒	m/s
加速度	メートル毎秒毎秒	m/s^2
波数	毎メートル	m^{-1}
密度，質量密度	キログラム毎立方メートル	kg/m^3
面積密度	キログラム毎平方メートル	kg/m^2
比体積	立方メートル毎キログラム	m^3/kg
電流密度	アンペア毎平方メートル	A/m^2
磁界の強さ	アンペア毎メートル	A/m
量濃度(a)，濃度	モル毎立方メートル	mol/m^3
質量濃度	キログラム毎立法メートル	kg/m^3
輝度	カンデラ毎平方メートル	cd/m^2
屈折率(b)	（数字の）1	1
比透磁率(b)	（数字の）1	1

(a) 量濃度（amount concentration）は臨床化学の分野では物質濃度（substance concentration）ともよばれる。
(b) これらは無次元量あるいは次元１をもつ量であるが、そのことを表す単位記号である数字の１は通常は表記しない。

表３．固有の名称と記号で表されるSI組立単位

組立量	SI 組立単位 名称	記号	他のSI単位による表し方	SI基本単位による表し方
平面角	ラジアン(b)	rad	1 (b)	m/m
立体角	ステラジアン(b)	sr(c)	1 (b)	m^2/m^2
周波数	ヘルツ(d)	Hz		s^{-1}
力	ニュートン	N		$m\ kg\ s^{-2}$
圧力，応力	パスカル	Pa	N/m^2	$m^{-1}\ kg\ s^{-2}$
エネルギー，仕事，熱量	ジュール	J	N m	$m^2\ kg\ s^{-2}$
仕事率，工率，放射束	ワット	W	J/s	$m^2\ kg\ s^{-3}$
電荷，電気量	クーロン	C		s A
電位差（電圧），起電力	ボルト	V	W/A	$m^2\ kg\ s^{-3}\ A^{-1}$
静電容量	ファラド	F	C/V	$m^{-2}\ kg^{-1}\ s^4\ A^2$
電気抵抗	オーム	Ω	V/A	$m^2\ kg\ s^{-3}\ A^{-2}$
コンダクタンス	ジーメンス	S	A/V	$m^{-2}\ kg^{-1}\ s^3\ A^2$
磁束	ウエーバ	Wb	Vs	$m^2\ kg\ s^{-2}\ A^{-1}$
磁束密度	テスラ	T	Wb/m^2	$kg\ s^{-2}\ A^{-1}$
インダクタンス	ヘンリー	H	Wb/A	$m^2\ kg\ s^{-2}\ A^{-2}$
セルシウス温度	セルシウス度(e)	℃		K
光束	ルーメン	lm	cd sr(c)	cd
照度	ルクス	lx	lm/m^2	$m^{-2}\ cd$
放射性核種の放射能(f)	ベクレル(d)	Bq		s^{-1}
吸収線量, 比エネルギー分与, カーマ	グレイ	Gy	J/kg	$m^2\ s^{-2}$
線量当量, 周辺線量当量, 方向性線量当量, 個人線量当量	シーベルト(g)	Sv	J/kg	$m^2\ s^{-2}$
酸素活性	カタール	kat		$s^{-1}\ mol$

(a)SI接頭語は固有の名称と記号を持つ組立単位と組み合わせても使用できる。しかし接頭語を付した単位はもはやコヒーレントではない。
(b)ラジアンとステラジアンは数字の１に対する単位の特別な名称で、量についての情報をつたえるために使われる。実際には、使用する時には記号rad及びsrが用いられるが、習慣として組立単位としての記号である数字の１は明示されない。
(c)測光学ではステラジアンという名称と記号srを単位の表し方の中に、そのまま維持している。
(d)ヘルツは周期現象についてのみ、ベクレルは放射性核種の統計的過程についてのみ使用される。
(e)セルシウス度はケルビンの特別な名称で、セルシウス温度を表すために使用される。セルシウス度とケルビンの単位の大きさは同一である。したがって、温度差や温度間隔を表す数値はどちらの単位で表しても同じである。
(f)放射性核種の放射能（activity referred to a radionuclide）は、しばしば誤った用語で”radioactivity”と記される。
(g)単位シーベルト（PV,2002,70,205）についてはCIPM勧告2（CI-2002）を参照。

表４．単位の中に固有の名称と記号を含むSI組立単位の例

組立量	SI 組立単位 名称	記号	SI 基本単位による表し方
粘度	パスカル秒	Pa s	$m^{-1}\ kg\ s^{-1}$
力のモーメント	ニュートンメートル	N m	$m^2\ kg\ s^{-2}$
表面張力	ニュートン毎メートル	N/m	$kg\ s^{-2}$
角速度	ラジアン毎秒	rad/s	$m\ m^{-1}\ s^{-1}=s^{-1}$
角加速度	ラジアン毎秒毎秒	rad/s^2	$m\ m^{-1}\ s^{-2}=s^{-2}$
熱流密度，放射照度	ワット毎平方メートル	W/m^2	$kg\ s^{-3}$
熱容量，エントロピー	ジュール毎ケルビン	J/K	$m^2\ kg\ s^{-2}\ K^{-1}$
比熱容量，比エントロピー	ジュール毎キログラム毎ケルビン	J/(kg K)	$m^2\ s^{-2}\ K^{-1}$
比エネルギー	ジュール毎キログラム	J/kg	$m^2\ s^{-2}$
熱伝導率	ワット毎メートル毎ケルビン	W/(m K)	$m\ kg\ s^{-3}\ K^{-1}$
体積エネルギー	ジュール毎立方メートル	J/m^3	$m^{-1}\ kg\ s^{-2}$
電界の強さ	ボルト毎メートル	V/m	$m\ kg\ s^{-3}\ A^{-1}$
電荷密度	クーロン毎立方メートル	C/m^3	$m^{-3}\ sA$
表面電荷	クーロン毎平方メートル	C/m^2	$m^{-2}\ sA$
電束密度，電気変位	クーロン毎平方メートル	C/m^2	$m^{-2}\ sA$
誘電率	ファラド毎メートル	F/m	$m^{-3}\ kg^{-1}\ s^4\ A^2$
透磁率	ヘンリー毎メートル	H/m	$m\ kg\ s^{-2}\ A^{-2}$
モルエネルギー	ジュール毎モル	J/mol	$m^2\ kg\ s^{-2}\ mol^{-1}$
モルエントロピー, モル熱容量	ジュール毎モル毎ケルビン	J/(mol K)	$m^2\ kg\ s^{-2}\ K^{-1}\ mol^{-1}$
照射線量（Ｘ線及びγ線）	クーロン毎キログラム	C/kg	$kg^{-1}\ sA$
吸収線量率	グレイ毎秒	Gy/s	$m^2\ s^{-3}$
放射強度	ワット毎ステラジアン	W/sr	$m^4\ m^{-2}\ kg\ s^{-3}=m^2\ kg\ s^{-3}$
放射輝度	ワット毎平方メートル毎ステラジアン	$W/(m^2\ sr)$	$m^2\ m^{-2}\ kg\ s^{-3}=kg\ s^{-3}$
酵素活性濃度	カタール毎立方メートル	kat/m^3	$m^{-3}\ s^{-1}\ mol$

表５．SI 接頭語

乗数	接頭語	記号	乗数	接頭語	記号
10^{24}	ヨタ	Y	10^{-1}	デシ	d
10^{21}	ゼタ	Z	10^{-2}	センチ	c
10^{18}	エクサ	E	10^{-3}	ミリ	m
10^{15}	ペタ	P	10^{-6}	マイクロ	µ
10^{12}	テラ	T	10^{-9}	ナノ	n
10^{9}	ギガ	G	10^{-12}	ピコ	p
10^{6}	メガ	M	10^{-15}	フェムト	f
10^{3}	キロ	k	10^{-18}	アト	a
10^{2}	ヘクト	h	10^{-21}	ゼプト	z
10^{1}	デカ	da	10^{-24}	ヨクト	y

表６．SIに属さないが、SIと併用される単位

名称	記号	SI 単位による値
分	min	1 min=60s
時	h	1h =60 min=3600 s
日	d	1 d=24 h=86 400 s
度	°	1°=(π/180) rad
分	’	1’=(1/60)°=(π/10800) rad
秒	”	1”=(1/60)’=(π/648000) rad
ヘクタール	ha	$1ha=1hm^2=10^4m^2$
リットル	L，l	$1L=1l=1dm^3=10^3cm^3=10^{-3}m^3$
トン	t	$1t=10^3$ kg

表７．SIに属さないが、SIと併用される単位で、SI単位で表される数値が実験的に得られるもの

名称	記号	SI 単位で表される数値
電子ボルト	eV	$1eV=1.602\ 176\ 53(14)\times10^{-19}J$
ダルトン	Da	$1Da=1.660\ 538\ 86(28)\times10^{-27}kg$
統一原子質量単位	u	1u=1 Da
天文単位	ua	$1ua=1.495\ 978\ 706\ 91(6)\times10^{11}m$

表８．SIに属さないが、SIと併用されるその他の単位

名称	記号	SI 単位で表される数値
バール	bar	$1\ bar=0.1MPa=100kPa=10^5Pa$
水銀柱ミリメートル	mmHg	1mmHg=133.322Pa
オングストローム	Å	$1\ Å=0.1nm=100pm=10^{-10}m$
海里	M	1 M=1852m
バーン	b	$1\ b=100fm^2=(10^{-12}cm)^2=10^{-28}m^2$
ノット	kn	1 kn=(1852/3600)m/s
ネーパ	Np	SI単位との数値的な関係は、対数量の定義に依存。
ベル	B	
デジベル	dB	

表９．固有の名称をもつCGS組立単位

名称	記号	SI 単位で表される数値
エルグ	erg	$1\ erg=10^{-7}\ J$
ダイン	dyn	$1\ dyn=10^{-5}N$
ポアズ	P	$1\ P=1\ dyn\ s\ cm^{-2}=0.1Pa\ s$
ストークス	St	$1\ St\ =1cm^2\ s^{-1}=10^{-4}m^2\ s^{-1}$
スチルブ	sb	$1\ sb\ =1cd\ cm^{-2}=10^4cd\ m^{-2}$
フォト	ph	$1\ ph=1cd\ sr\ cm^{-2}\ 10^4lx$
ガル	Gal	$1\ Gal\ =1cm\ s^{-2}=10^{-2}ms^{-2}$
マクスウェル	Mx	$1\ Mx = 1G\ cm^2=10^{-8}Wb$
ガウス	G	$1\ G\ =1Mx\ cm^{-2}\ =10^{-4}T$
エルステッド(c)	Oe	$1\ Oe \triangleq (10^3/4\pi)A\ m^{-1}$

(c) ３元系のCGS単位系とSIでは直接比較できないため、等号「 ≙ 」は対応関係を示すものである。

表10．SIに属さないその他の単位の例

名称	記号	SI 単位で表される数値
キュリー	Ci	$1\ Ci=3.7\times10^{10}Bq$
レントゲン	R	$1\ R = 2.58\times10^{-4}C/kg$
ラド	rad	$1\ rad=1cGy=10^{-2}Gy$
レム	rem	$1\ rem=1\ cSv=10^{-2}Sv$
ガンマ	γ	1γ=1 nT=10-9T
フェルミ		1フェルミ=1 fm=10-15m
メートル系カラット		1メートル系カラット = 200 mg = 2×10-4kg
トル	Torr	1 Torr = (101 325/760) Pa
標準大気圧	atm	1 atm = 101 325 Pa
カロリー	cal	1cal=4.1858J（「15℃」カロリー），4.1868J（「IT」カロリー）4.184J（「熱化学」カロリー）
ミクロン	µ	$1\ \mu\ =1\mu m=10^{-6}m$

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