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Experience of Secondary Cooling System Modification at Prototype Fast Breeder Reactor MONJU (Translated Document)

(Eds.) Naoyuki KISOHARA and Yoshihiko SAKAMOTO

JSFR Systems Development Planning Office
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September 2010

Japan Atomic Energy Agency

日本原子力研究開発機構

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The prototype fast breeder reactor MONJU has been shut down since the secondary sodium leak accident that occurred in December 1995. After the accident, an investigation into the cause and a comprehensive safety review of the plant were conducted, and various countermeasures for sodium leak were examined. Modification work commenced in September 2005. Since sodium, a chemically active material, is used as coolant in MONJU, the modification work required work methods suitable for the handling of sodium. From this perspective, the use of a plastic bag when opening the sodium boundary, oxygen concentration control in a plastic bag, slightly-positive pressure control of cover gas in the systems, pressing and cutting with a roller cutter to prevent the incorporation of metal fillings, etc. were adopted, with careful consideration given to experience and findings from previous modification work at the experimental fast reactor JOYO and plants abroad. Owing to these work methods, the modification work proceeded close to schedule without incident.

Keywords: MONJU, Sodium Leak, Modification Work, FBR, SFR

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The original Japanese paper was written by the authors below.
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高速増殖原型炉「もんじゅ」における2次冷却系の改造工事経験

（翻訳資料）

日本原子力研究開発機構
次世代原子力システム研究開発部門　炉システム開発計画室
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（2010 年 7 月 5 日 受理）

高速増殖原型炉もんじゅでは、1995 年 12 月に発生した 2 次冷却系ナトリウム漏えい事故により、原子炉が約 10 年停止している。事故後、原因究明とプラント全体の安全総点検を実施して漏えいに対する様々な対応策を検討し、2005 年 9 月より本格的な改造工事を開始した。「もんじゅ」では冷却材に科学的に活性なナトリウムを使用するため、実験炉「常陽」や海外先行プラントの改造工事の経験や知見を参考に、ナトリウムバウンダリを解放する際のプラバック使用、バック内の酸素濃度管理、系統系カバーガスの微正圧制御、切粉混入防止のためのロールカッタによる押し切り工法等を採用した。これらの導入により、本改造工事はトラブルもなくほぼ計画通り進んだ。

本報告書は社団法人 火力原子力発電技術協会発行の機関誌「火力原子力発電」に投稿された論文『高速増殖炉「もんじゅ」における２次冷却系の改造工事経験』（2007 No.610 Vol.58）の内容を、第４世代国際原子力システムフォーラム　ナトリウム冷却高速炉分野　機器設計及びバランス・オブ・プラントに報告するために英訳したものである。論文の原著者は下記の通りである。

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1. Introduction

Japan aims to develop the sodium-cooled fast reactor as a fourth-generation reactor, and has built the experimental reactor JOYO and the prototype reactor MONJU as a part of this plan.

The role of MONJU includes the demonstration of performance, reliability, and safety as the prototype FBR power plant in Japan, and the establishment of sodium handling technologies. In addition, MONJU contributes to research and development toward the realization of future demonstration reactors, and, from a global viewpoint, has an important role as a core facility for the promotion of international cooperation through the Generation-IV International Forum (GIF).

This paper describes the full-scale modification work that commenced in September 2005 with a focus on modification work technologies for sodium components.

2. MONJU overview

MONJU is a prototype fast breeder reactor fueled by uranium-plutonium mixed oxide with a rated power of 280MWe (714MWt). Construction began in 1985, and manufacturing and installation were completed in 1991.

The first criticality was achieved in April 1994 following the completion of the functional test, and power supply to the grid started in August of 1995. However, an accident, in which sodium coolant leaked due to the break of a thermo-couple well in the secondary cooling system, occurred in December 1995, and since then the reactor has been shut down.

3. Modification work overview

After the sodium leak accident, an investigation into the cause was conducted along with a comprehensive review of plant safety. Considering the lessons learned from the accident, it was revealed that the previous design requirements for countermeasures for medium or small-scale sodium leak were not clearly specified in MONJU equipment design. Accordingly, these requirements were clearly specified, and it was decided to perform equipment improvements from the perspective of the prevention, early detection and suppression of a sodium leak, and the mitigation of the effect of any sodium leak.

Modification work for these improvements was started in September 2005 following completion of the national safety assessment and examination for the application for approval of the amendment of the design and construction method, and preparatory work that had started in March 2005.(see Fig. 1).

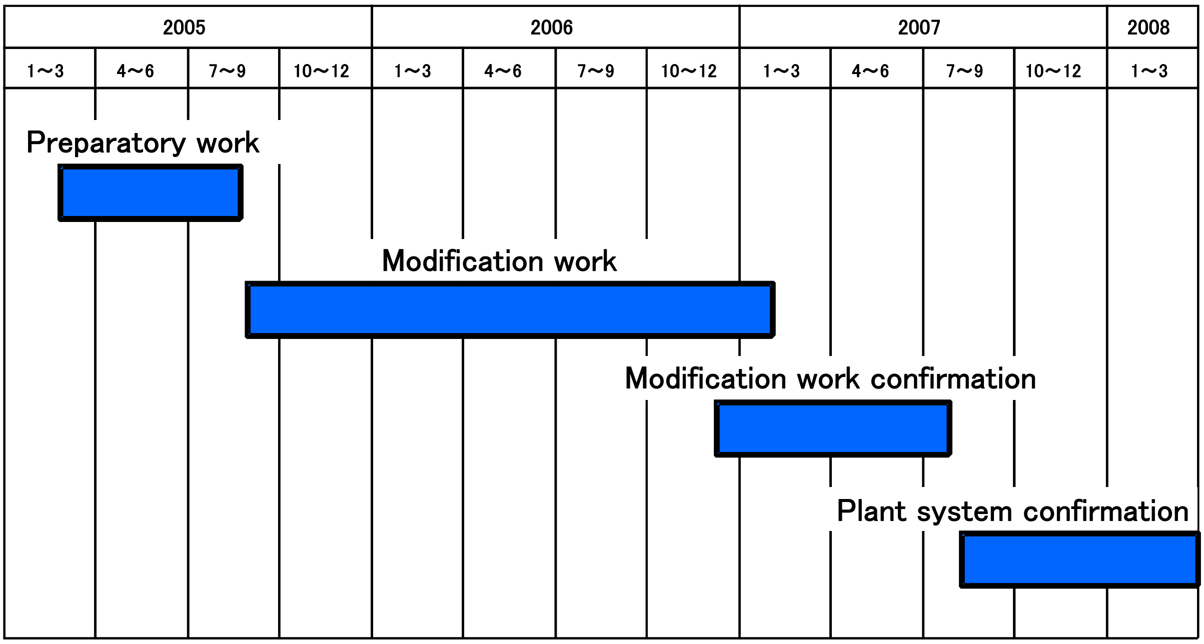


Fig.1　Modification work Schedule at Monju

The main modifications for countermeasures for sodium leak from the secondary cooling system at MONJU are outlined below (see Fig. 2).

(1) Prevention of sodium leaks

○ Improvement in thermo-couple(T/C) well

- Shortening of well and modification in shape
- The total number of T/Cs is reduced from 48 to 42.

(2) Monitoring and early detection of sodium leaks

○ Installation of cell monitors (smoke detector, thermal detector)

○ Installation of TV cameras

○ Installation of an integrated leak monitoring system

(3) Suppression of sodium leaks

○ Modification of sodium drain system equipment

- Increase in drain piping diameter and additional installation of a drain line
- Parallel installation of drain valves
- Use of motor-operated drain valves and its operation at the main control room

○ Modification of the secondary argon gas system equipment

- Addition of a cover gas depressurization line

○ Installation of nitrogen-gas injection equipment

(4) Mitigation of the effects of leaks

○ Installation of heat sink material in the fuel storage vault

○ Installation of heat insulator on the wall and ceiling

○ Improvement in the ventilation and air conditioning equipment

○ Smaller compartmentation of the areas inside buildings

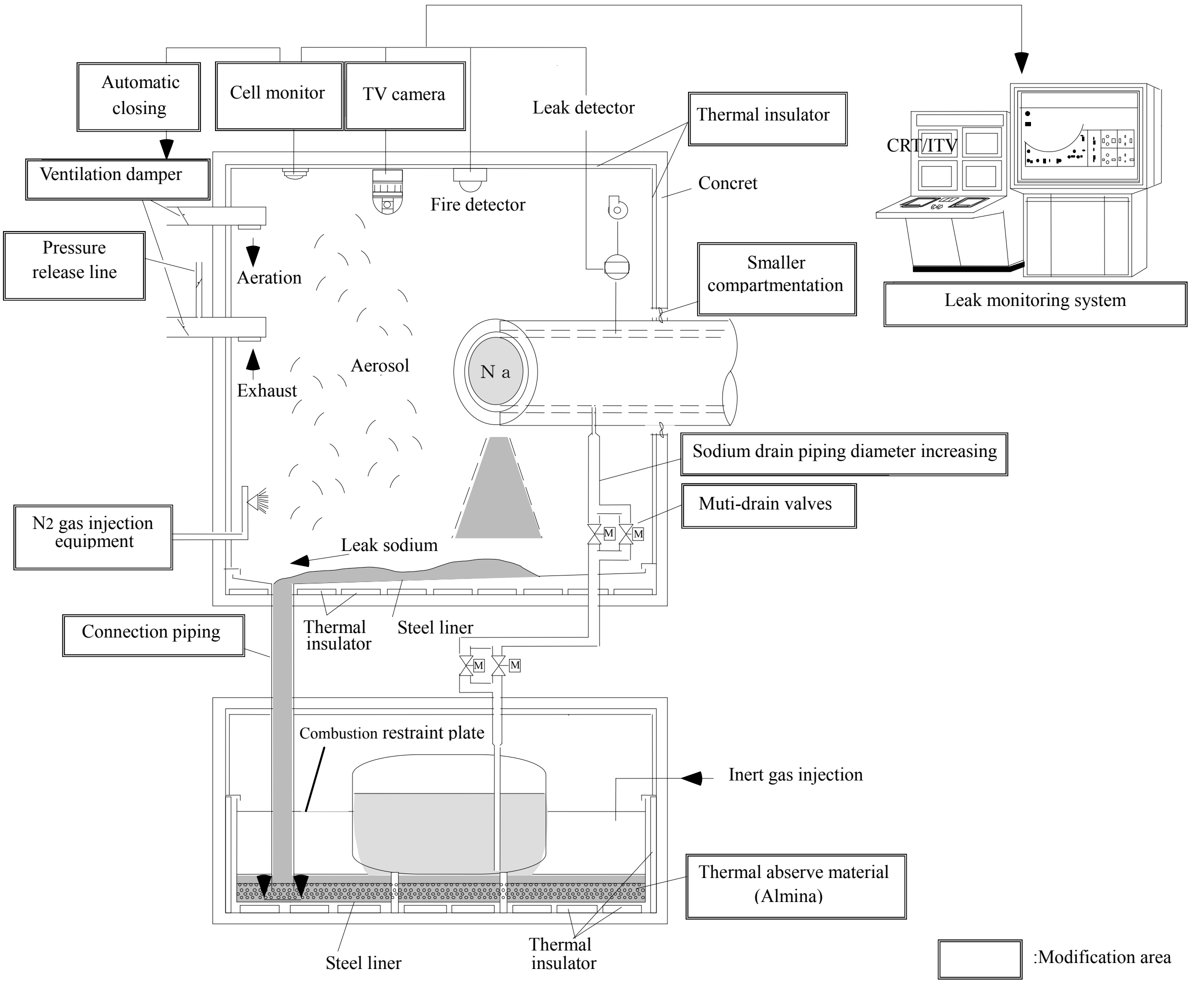


Fig.2　Outline of modification work

3.1 Improvement in the thermo-couple well

The investigation, testing and analysis performed after the sodium leak accident revealed that the failure in the thermo-couple well was caused by high-cycle fatigue due to flow-induced vibration. On the basis of this finding and the experience in the leak accident, the structural design of the thermo-couple well for the secondary cooling system was examined. Specifically, based on due consideration of the temperature measurement capability, workability and maintainability, an evaluation of integrity with regard to flow-induced vibration, strength, etc. was performed by analysis to determine the required dimensions and shape for the thermo-couple well. In addition, the design was validated by impact test and flow-induced vibration test. To eliminate a potential cause of sodium leaks, it was decided to remove thermo-couple whose function could be substituted by other thermo-couple and mount closure caps.

Schematic structure diagrams and photographs of the previous and the improved thermo-couple are shown in Fig. 3 and Photo.1, respectively. To meet the requirement for the prevention of a failure, the thermo-couple well was shortened and the outer shape was changed from a stepped type to a tapered type. The thermo-couple sheath for which good response is required was designed to be long enough for accurate measurement (for system control), and the thermo-couple sheath for which good response is not required was designed to be short to a degree not affected by the sodium piping wall (for system monitoring).

In addition, a seal structure employing a metal gasket was adopted to suppress the leak of sodium inflow to the exterior of the thermo-couple well in the event of a well failure, and a contact-type sodium leak detector was installed inside of the well.

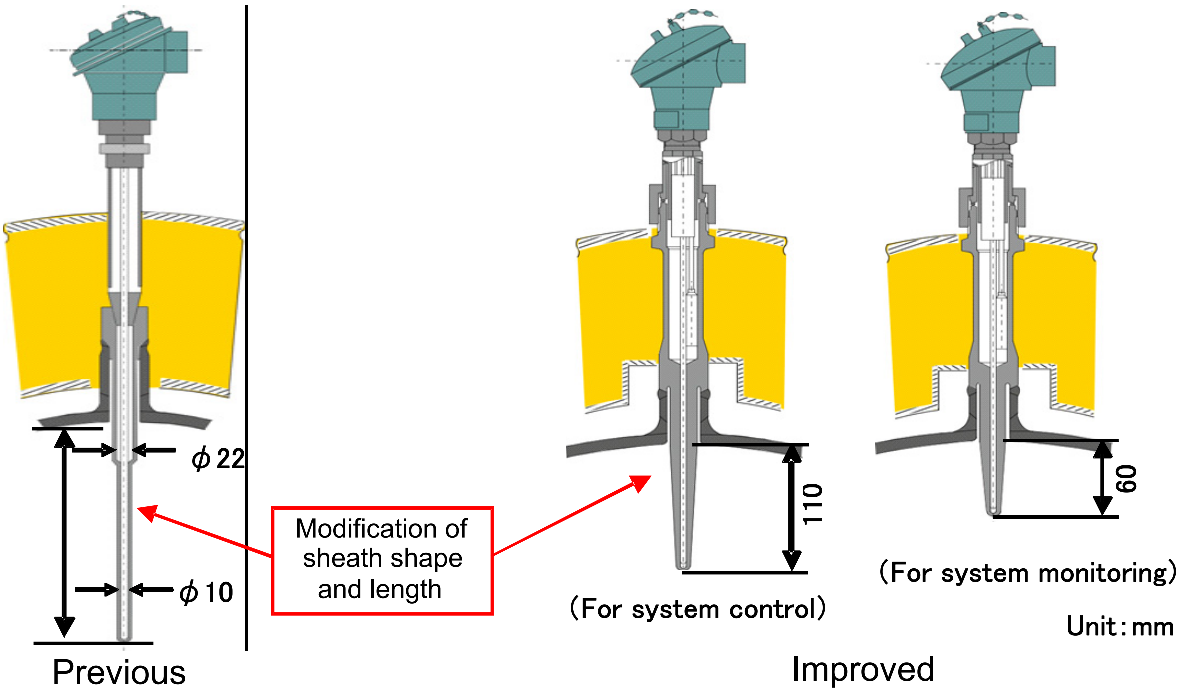
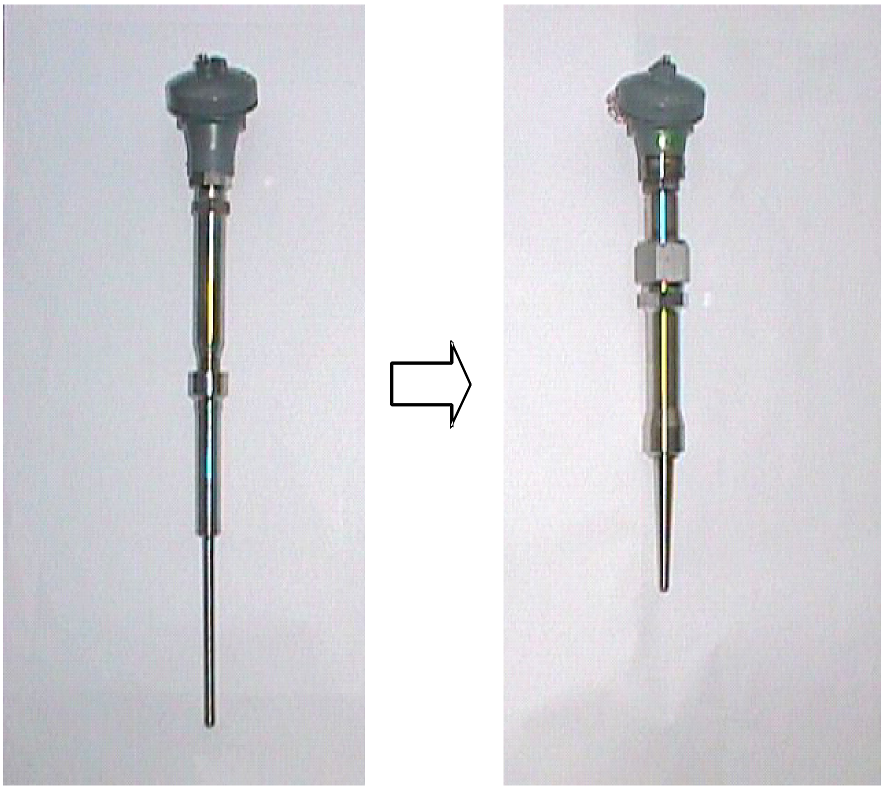


Fig.3　Previous and improved thermo-couple



Previous　T／C　　　　Improved　T／C

Photo.1　　Previous and improved thermo-couple

3.2 Modification of sodium drain system equipment

Based on the lessons learned from the secondary sodium leak accident, it was decided to achieve improvement in equipment to rapidly shut down the reactor in the event of a leak as well as to start the draining of sodium without waiting for the temperature decrease in the secondary cooling system.

(a) Additional installation of a sodium drain line and the increase in diameter of the existing sodium drain piping

To shorten the time required to drain sodium from main piping, work was performed to add a new drain line at the inlet side of each sodium pump in the secondary cooling system (see Fig. 4), and to increase the diameter of the existing sodium drain piping from 3-4 inches to 4-6 inches. This modification would make it possible to shorten the drainage time from approximately 50 minutes to approximately 20 minutes. Thermal stresses are caused at the drain piping, drain tanks, and intermediate heat exchangers in the case where drainage is started under a high temperature condition just after a reactor trip. However, detailed structural evaluation revealed that the structural integrities of these components are not impaired due to the thermal stresses.

(b) Improved reliability by multiplexed sodium drain valves

Two valves were installed in parallel so as to assure sodium drainage from the system piping in the event of the failure of one of the drain valves. In addition, measures to protect the drain valves and driving cables from scattered sodium and the increase in the atmosphere's temperature were enhanced to ensure secure operation of the drain valves even under a sodium leakage environment.

(c) Improved operability of sodium drain valves

For early termination and mitigation of effect in the event of a sodium leak, a drain operation switch was mounted on the control panel in the main control room to speed up sodium drainage.

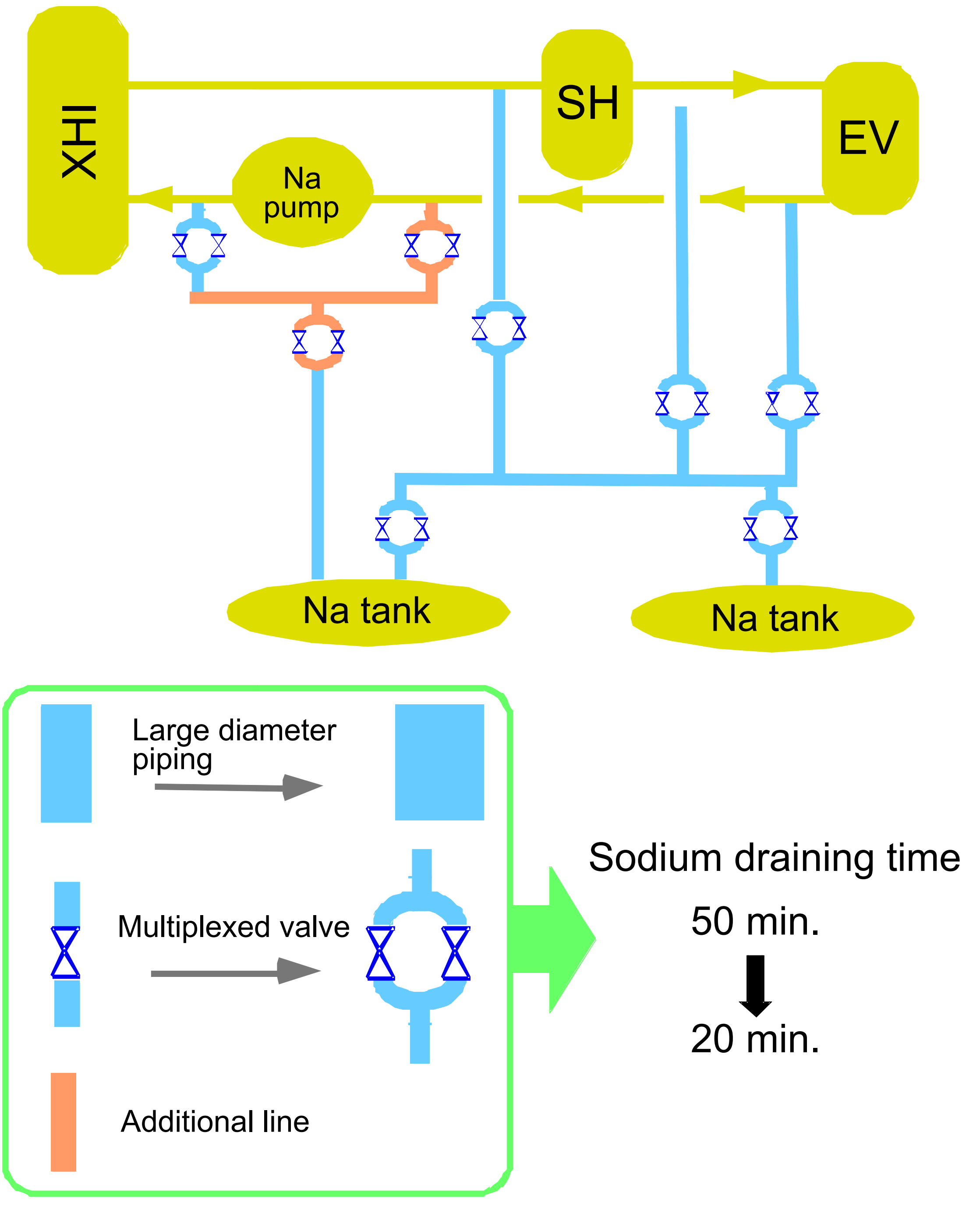


Fig.4 Improvement of sodium drain line

4. Sodium handling technology used during modification work

4.1 Sodium as coolant

Nuclear reactor coolant is directly related to the features of the reactor type, and significantly affects the nuclear characteristics of the core, structural material, including the fuel cladding material, and the design of key components, such as sodium pumps and steam generators. To determine coolant for FBR, it is necessary to make a comprehensive judgment based on discussions on the thermal, fluid dynamic and nuclear characteristics of the coolant and its compatibility with materials, to assure the appropriate removal of heat generated from a core. Taking these factors into consideration, sodium is adopted for the coolant for MONJU since it has a small slowing-down power and an absorption cross-section for fast neutrons, and excellent heat transfer capability.

On the other hand, since sodium generates flammable hydrogen gas when it comes into contact with water and reacts even with the moisture in air, it may generate hydrogen bubbles when it is left as it is in a high-humidity environment. In addition, when sodium comes into contact with human skin or mucous membrane, it reacts with moisture, and the reaction heat or sodium hydroxide may cause burn injury. Because of these characteristics, it is necessary to adopt methods that take into account the characteristics of sodium for the modification work for lessons learned.

For the reasons, experience gained from the experimental reactor JOYO MK-III modification work and plants abroad were used as reference. The methods described in the following sections were applied to the actual work by taking accont of mock-up tests of the modification work.

4.2 Work methods for sodium-containing piping

4.2.1 Plastic bag method and gas seal method

The sodium in the system was already stored in the dump tank; however, solid sodium remained attached to the inner surface of the piping. Due to this and taking into account the above-noted characteristics of sodium, it was necessary to prevent air infusion into the system when cutting piping.

Two methods were adopted in this modification work to prevent air infusion into the system during work that required the opening of the sodium boundary: i) the plastic bag method, a method by which the entire work space is surrounded with a transparent plastic cover to isolate the space from the air, and ii) the gas seal method, a method by which the pressure of argon gas enclosed in the system is maintained at a slightly positive level to prevent air infusion into the system (see Fig. 5).

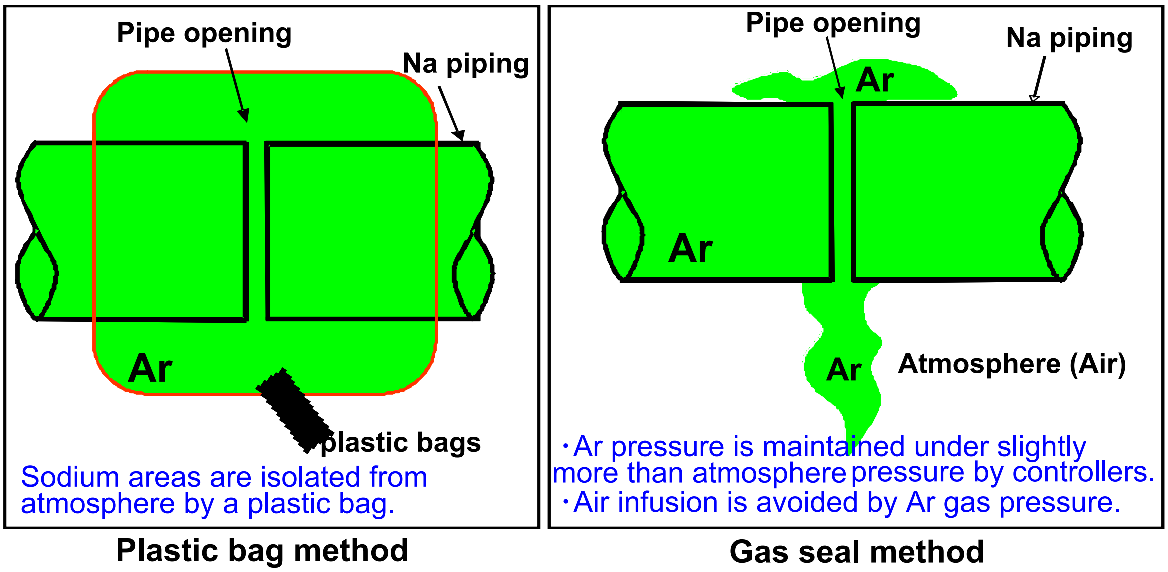


Fig.5 Plastic bag method and seal method

When cutting the drain piping, the plastic bag method was used at positions where there is no gate valve between the position and the dump tank, and at tanks that have no vent valve. The plastic bag method was also used to the area where the sodium leak accident occured. Because the work required a large opening area. On the other hand, when welding, the gas seal method, which was determined to be a more reasonable method, was used.

4.2.2 Plastic bag and cleaning tools

The external view of the plastic bag is shown in Photo. 2. The plastic bag is designed to have good transparency and flexibility to avoid hindering work in the bag. The projected portions are intended for inserting the hands for work and their arrangement was examined taking into account the mock-up test result of the workability.

Photo.2 Plastic bag

The cleaning tools used to remove the sodium attached to the inner surface of the piping were a metallic spatula, rags, and a metallic bucket for used rags. In addition, a sodium fire extinguishing agent (NATREX) was prepared in the event of sodium fire. The rags were wetted with a solution of alcohol diluted with water (degree of dilution: 50%) and used in addition to dry rags.

To assure removal of the sodium attached to the inner surface of the piping, the inner surface was wiped with rags and subsequently sprayed repeatedly with phenolphthalein until the rags ceased turning red.

4.3 Management during the work

4.3.1 Purity control in the plastic bag

When using the plastic bag method, the inner atmosphere of the bag was replaced with argon gas beforehand, and work was started after confirming that the oxygen concentration was reduced to 2% or less (1% or less in reality), which was the work condition.

In addition, when the gas replacement was performed, all lids of the containers in the plastic bag were opened to assure that no air remained in the containers. Attention was also given to the moisture in the plastic bag due to the fact that moisture causes the deliquescence of sodium hydrate that leads to corrosion of structural material.

Agron gas purity monitoring in the secondary system was also performed using a gas chromatograph during the work period.

4.3.2 Cover gas pressure control

Normally, the pressure of the cover gas (argon) in the system is maintained at approximately 100 kPa ± 10%.

However, since it is difficult to control pressure using the existing control equipment during the work in the plastic bag or welding, a new control unit for creating a slightly positive pressure was introduced specifically for this modification work. Here, the pressure was maintained within the range of 20 to 100 Pa as a pressure slightly higher than atmospheric pressure. The system pressure was measured by a manometer installed in the system.

The slightly positive pressure control was employed for both the plastic bag method and the gas seal method. When cutting and welding, the slightly positive pressure control unit was set to adjust the pressure at a cutting zone to approximately 100 Pa and the pressure at a welding zone to approximately 20 Pa.

4.3.3 Welding management

A small amount of sodium remains in several places in sodium piping. Since the melting point of sodium is approximately 98°C, the remaining sodium may melt due to piping welding heat. Accordingly, welding was performed while monitoring the temperature registered on a thermo-couple attached near the piping welding zone to assure that it does not exceed the preset upper limit of 70°C. The weldimg zone pressure was maintained to be within 20Pa in consideration of the atmospheric pressure variation due to weather changes.

4.4 Performance of the modification work

4.4.1 Replacement of the sodium leaking piping

A series of figures to explain the cutting procedure for the piping concerned with the sodium leak accident (the intermediate heat exchanger outlet pipiing of the secondary main cooling system loop C, 22B pipe, outer diameter: 558.8 mm, wall thickness: 9.5 mm) is shown in Fig. 6.

The sodium leaked piping was cut at two positions using a roller cutter and replaced with newly-manufactured piping.

A newly-manufactured thermo-couple well was mounted in advance to this newly-installed piping by welding in the factory manufacturing stage. The cutting work of the sodium leaked piping is shown in Photo. 3.

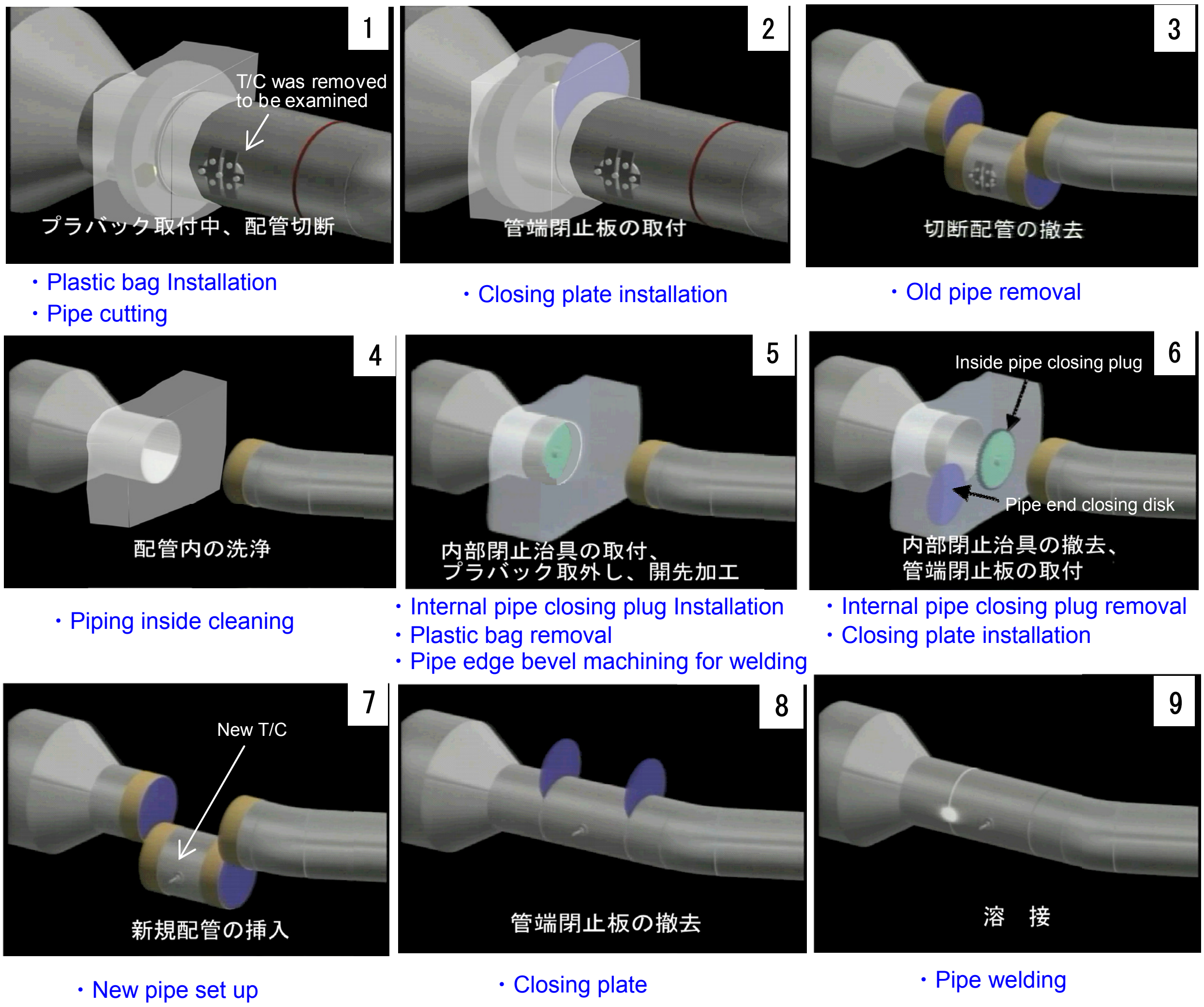


Fig.6　Sodium piping replacement work at leakage point

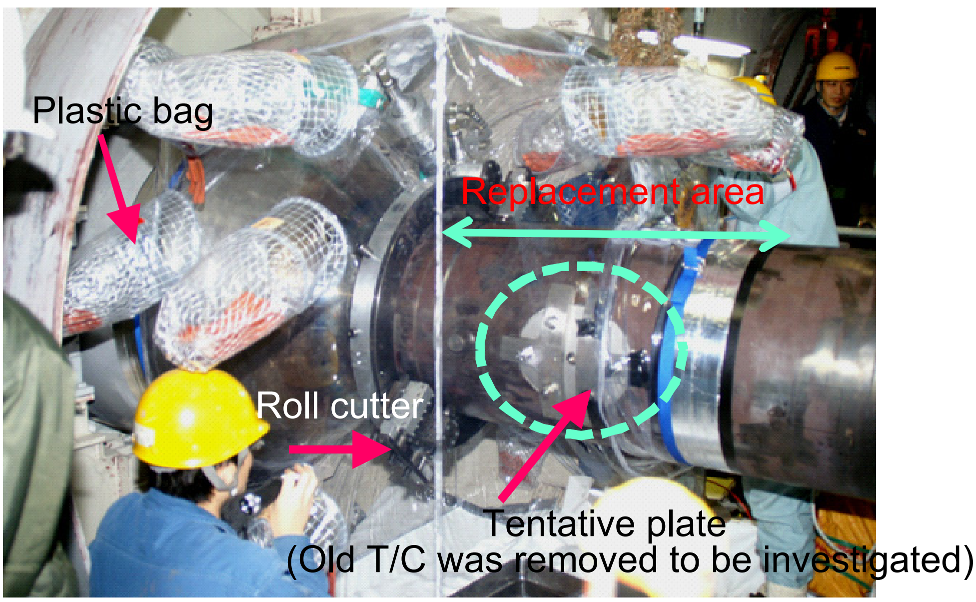


Photo.3　Sodium leaked piping cutting

Firstly, (1) a roller cutter (see Fig. 7) was mounted to the positions of the piping to be cut off, and a plastic bag was installed. Cutting was carried out in two steps: i) the primary cutting, cutting by slowly rotating a turning tool, and ii) the secondary cutting, pressing and cutting with a roller cutter to prevent the ingress of metal fillings. Next, (2) after cutting the piping at two positions, gaps were provided at the cuts on the pipe using a chain block, and closing plates were attached to the end surfaces and then sealed by metal tape. (3) Then, the cut-off pipe section was removed. (4) The plastic bag was again installed, and the sodium remaining in the existing piping was cleaned off. (5) An internal pipe closing plugs were mounted at a position internal to the end surface of the pipe, and then the plastic bag was removed and the edge preparation was made for welding. In this process, since the piping was not perfectly round, a restraining ring was shrinkage-fit to the newly-installed pipe to maintain the perfectly round condition, and with reference to the pipe, the existing piping was adjusted by a circle-making device (see Fig. 8) to achieve a perfect circle to adjust the groove position to that of the new pipe.

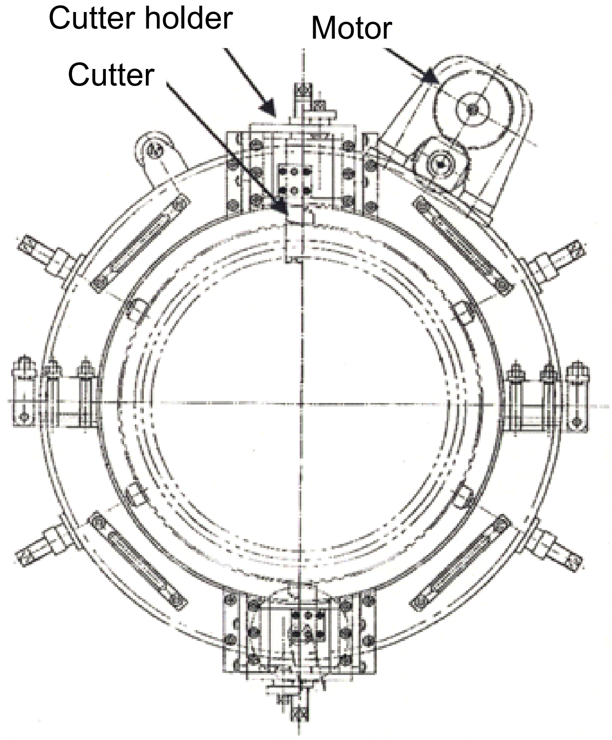


Fig.7　Roller cutter

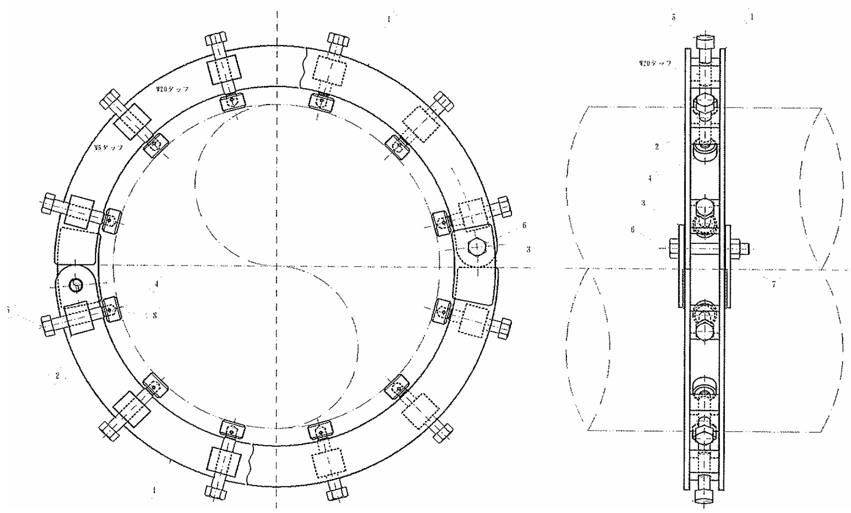


Fig.8　　Circle-making device

After completion of the edge preparation, (6) the internal pipe closing plugs were removed and the closing plates were attached to the pipe ends surface. (7) The new pipe was inserted into the cut section and firmly fixed by a chain block, (8) and then the closing plates were removed. An external view of this condition is shown in Photo. 4. The pipe fixing by a chain block is an important measure to prevent pipe moving during cutting. Subsequently, (9) pipe welding was carried out. The pipe welding is shown in Photo. 5.

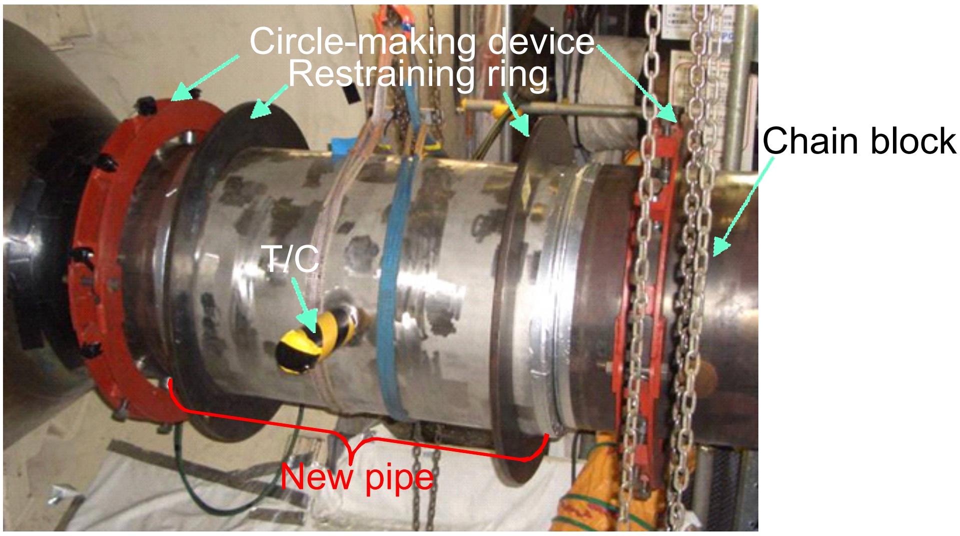


Photo.4　Circle-making device and restraining ring

Photo.5　Main pipe welding

4.4.2 Replacement of thermo-couple

The replacement procedure of thermo-couple is shown in Fig. 9. Firstly, after preparation for cutting, including (1) placement of scaffolding and (2) installation of the plastic bag, the nozzle of the thermo-couple well stand was removed using a pipe cutter, the thermo-couple was pulled out, and then the sodium remaining in the nozzle was cleaned off. After (4) edge preparation using a beveling machine, (5) the edge setter was installed to adjust the groove position to that of the new thermo-couple well. At this point in time, the plastic bag was removed, (6) welding was carried out, and (7) the thermo-couple was installed.

Welding was carried out in a three-step series: spot welding, welding up to half the layer, and full-layer welding (see Photo. 6). In addition, liquid penetrant testing was performed at the half layer and full layer for weld inspection, and no abnormality was identified. Although the inspection provided by law is liquid penetrant testing, radiographic testing was also performed at the final layer to observe the shape of the penetration bead and to confirm whether the gap between the bead and the thermo-couple had been maintained.

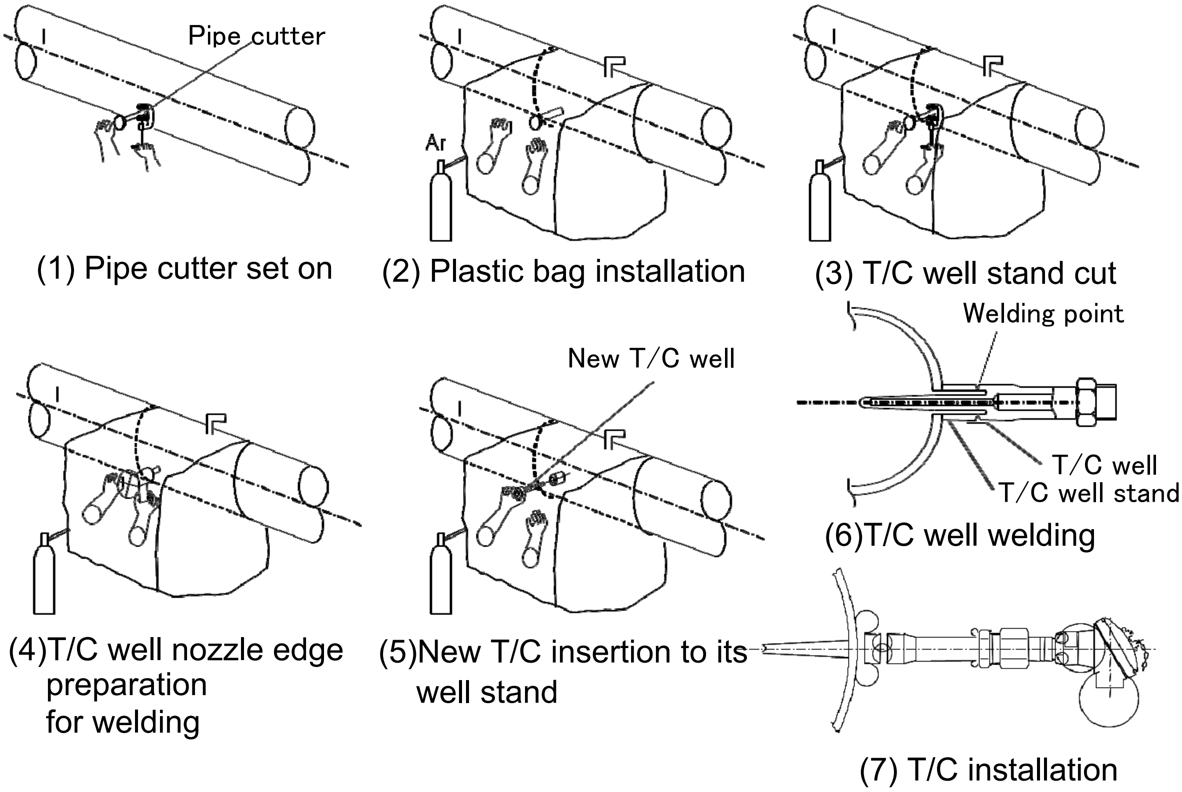


Fig.9 T/C Replacement procedures

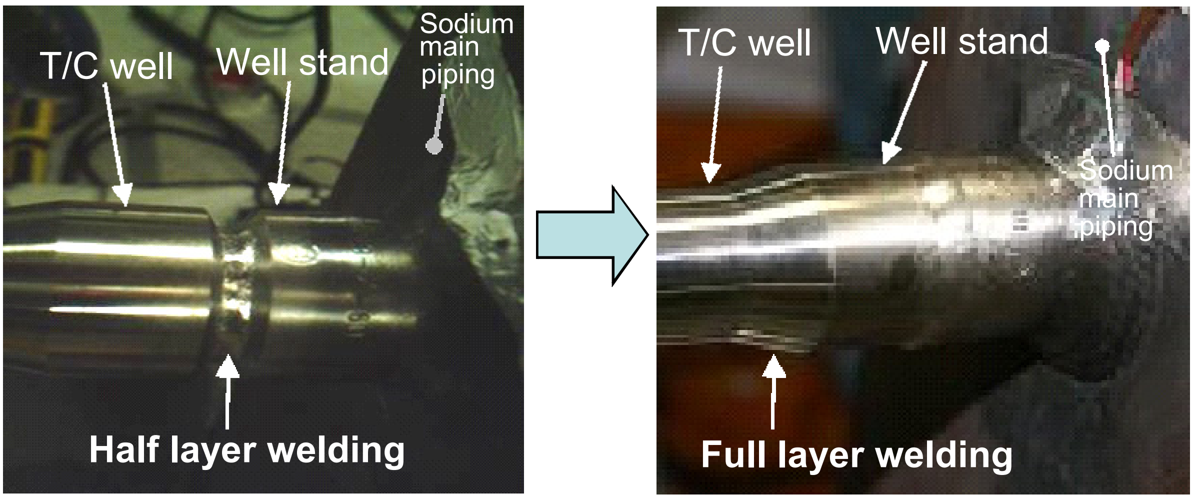


Photo.6 T/C replacement work

4.4.3 Cutting off of the existing sodium drain piping

The piping valves were fixed to prevent the movement of piping associated with cutting first. And the primary cutting was performed up to a depth of 3 mm, approximately half of the pipe thickness, without the plastic bag. Since sodium was attached on the piping, a roller cutter was used to prevent an increase in the cutting surface temperature. After installation of the plastic bag, the secondary cutting (final cutting of piping) was performed using a press-and-cut type roller cutter.

A view of sodium remaining in the piping after completion of the final cutting is shown in Photo. 7. A small amount of sodium was observed on inner surface of the pipe, and in several places, a body of sodium, approximately 50 mm wide and 5 mm high, remained at the bottom of the pipe. Subsequently, the remaining sodium was scraped out, and cleaned off with rags. The cleaned region was specified as 150 mm or greater from the pipe end. This region was specified based on advance test results showing that the pipe temperature at a position 100 mm or more away from the pipe end did not exceed the sodium melting temperature.

After cleaning the sodium, the closing plug was installed inside the piping, the plastic bag was removed and then the closing lid was mounted on the pipe end. A wire to the closing lid was attached to the closing plug to prevent being drawn into the piping. A set value for system pressure during cutting was determined to adjust the pressure at the cut section to approximately 100 Pa, and the control value of the oxygen concentration in the plastic bag was 2% or less, as described above.

In preparation for cleaning, the existing pipe that was cut off from the system was cut into sections of approximately 1m using a band saw. Since this was sodium handling work in air, the work was carried out wearing protective equipment for after sectioning and protection of the work area using a metal pan.

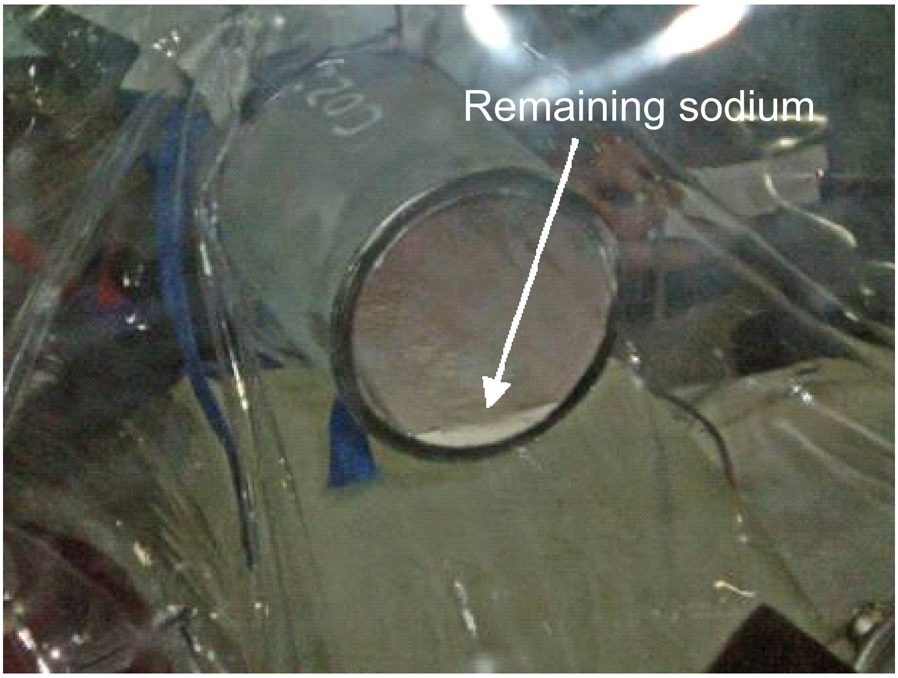


Photo.7　Sodium drain piping cut view

(Photography outside plastic bag)

4.4.4 Addition of the nozzle for additional sodium drain piping

A method to add a nozzle to the sodium main piping (22B pipe, outer diameter: 558.8 mm) was employed to install an additional drain line. The procedure for this work is shown in Fig. 10.

A nozzle was welded to the sodium main piping first, and then a hole was drilled into the piping, including the undercut at the inner side of the nozzle. This method made it possible to avoid cutting out part of the main piping, minimize the workload.

To inspect the integrity of this weld zone, ultrasonic testing was performed in addition to liquid penetrant testing. Since ultrasonic testing had been used only a few times for a nozzle welded by this method, a mock-up test was performed in factory first to verify defect detectability.

After welding the nozzle to the piping, the primary cutting was performed by installing a driller to the nozzle. A plastic bag was installed and the inside atmosphere was replaced by argon gas. Then, secondary cutting, drilling a hole to the piping, was performed and the hole diameter was enlarged (see Photo. 8).

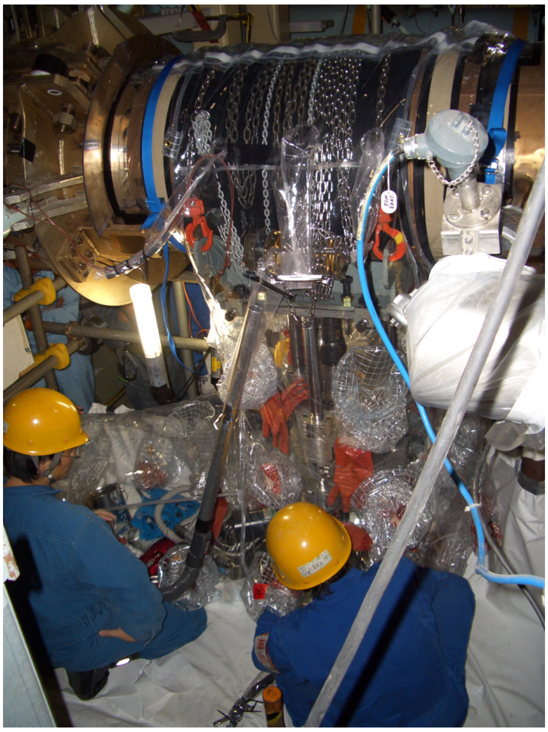


Photo.8 Drill work at sodium main piping opening

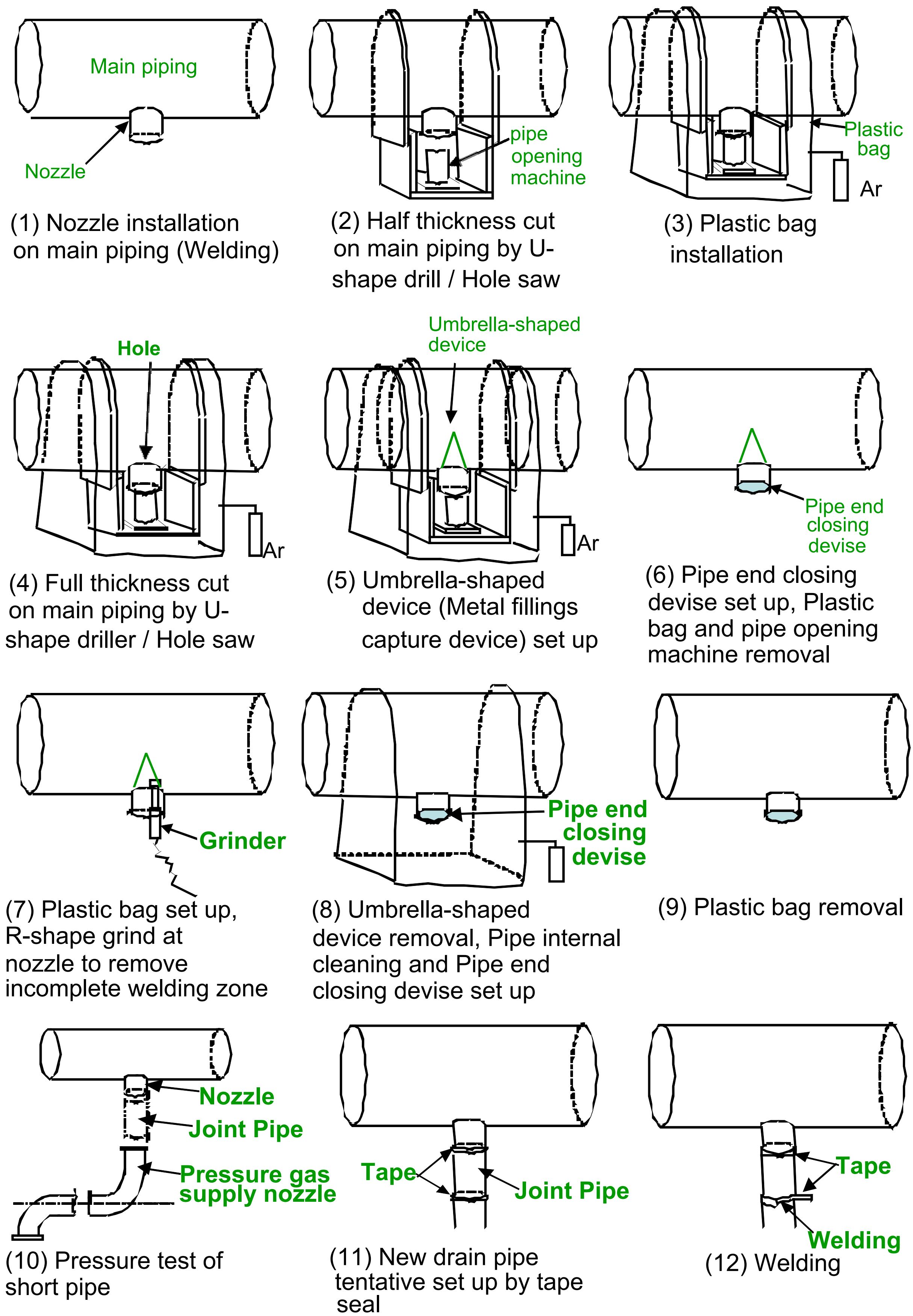


Fig.10 New sodium drain piping addition procedure

After enlarging the hole, the pipe end closing device was mounted, and the finishing of the inner surface was performed manually with a grinder. Subsequently, all work tools were removed and the newly-installed pipe was welded.

To prevent the metal fillings from spreading into the piping during enlargement of the hole and subsequent finishing of the inner surface, an umbrella-shaped device was set on the top surface of the hole.(see Photo. 9).

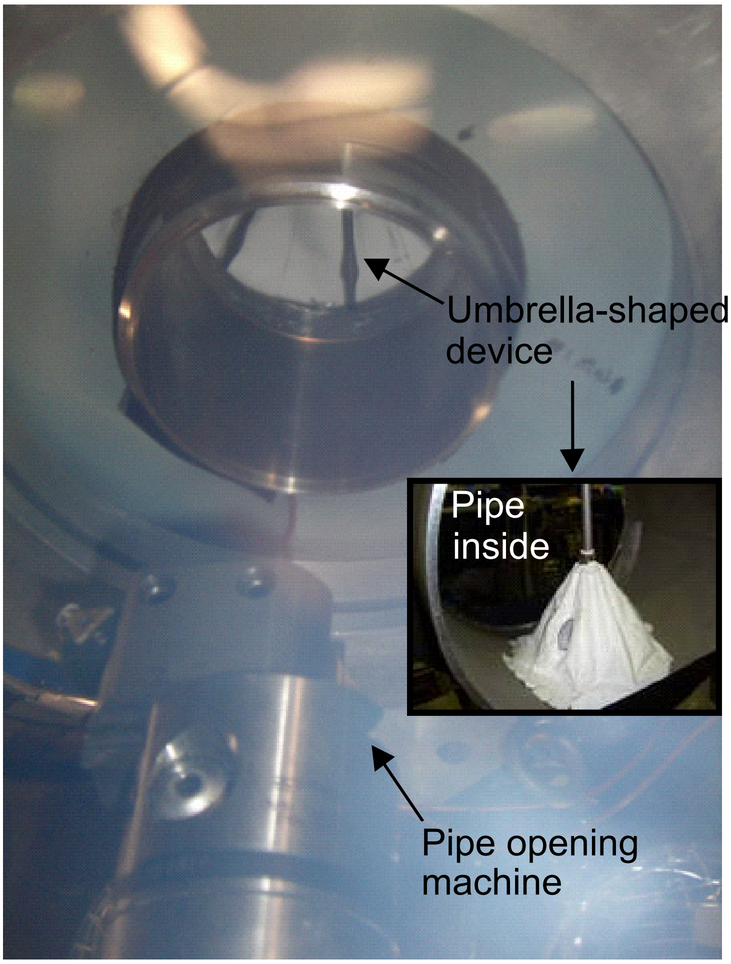


Photo.9　Pipe opening machine and metal fillings capture device

5. Concluding remarks

This report describes the work performed to take countermeasures for sodium leaks, mainly in the secondary cooling system, during MONJU modification work. Modification work to take countermeasures for sodium leaks was also performed in the sodium equipment, such as the secondary maintenance cooling system and the ex-vessel fuel storage equipment cooling system to improve the safety margin of the MONJU facility.

Recently, nuclear energy is considered to be a reliable and cost-effective energy source in various countries, and the Japan Atomic Energy Agency aims to make a contribution to the world through the development of MONJU.

Unfortunately, MONJU has been shut down years due to the sodium leak accident. However, during the shutdown period, engineering knowledge on the leaked sodium has been accumulated. Based on that knowledge, equipment employed to take countermeasures for sodium leaks in MONJU was reexamined and modification work on the sodium components was performed. We believe that great progress was achieved in sodium handling technologies. Hereafter, modification work confirmation testing will be performed and plant verification testing will be also carried out to confirm the function of the equipment. Re-criti cality will be soon achieved,the reactor will be operated,and thereby MONJU fulfils a role as a proto type reactor.

References

K.Itoh, K.Onuki, et al. "Replacement of the Drain System of Secondary Circuit at MONJU", ICONE11-36072, April 2003.

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	$1L=11=1dm^3=10^3cm^3=10^{-3}m^3$
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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