SODIUM LEAKAGE EXPERIENCE AT THE PROTOTYPE FBR MONJU

A. MIYAKAWA, H. MAEDA, Y. KANI, K. ITO
Monju Construction Office,
Japan Nuclear Cycle Development Institute,
Fukui-ken, Japan

XA0056252

Abstract

Monju is Japan's prototype fast breeder reactor : 280 MWe (714MWt), fueled with mixed oxides of plutonium and uranium, cooled by liquid sodium. Construction was started in 1985 and initial criticality was attained in April 1994

On 8th December 1995, sodium leakage from a secondary circuit occurred in a piping room of the reactor auxiliary building. The secondary sodium leaked through a temperature sensor, due to the breakaway of the tip of the thermocouple well tube installed near the secondary circuit outlet of the intermediate heat exchanger (IHX). The reactor remained cooled and thus, from the viewpoint of radiological hazards, the safety of the reactor was secured. There was no release of radioactive material. There were no adverse effects for personnel and the surrounding environment. The thermocouple well tube failure resulted from high cycle fatigue due to flow induced vibration. It was found that this flow induced vibration was not caused by well-known Von Karman vortex shedding, but a symmetric vortex shedding. The design of the thermocouple well, which was subject to avoid this phenomenon, was reviewed. A new design guide against the flow-induced vibration was prepared by JNC (Japan Nuclear Cycle Development Institute). That is more comprehensive and definitive than the existing guide "ASME N-1300" (Flow-induced vibration of tube and tube banks). New thermocouple well designs were proposed consistent with this design guide.

To prevent a recurrence of the secondary sodium leakage incident, comprehensive design review activities were started for the purpose of checking the safety and reliability of the plant. As a result, several aspects to be improved were identified and improvements and countermeasures have been studied. The main improvements and countermeasures are as follows:

- To enable the operators understand and react to incidents quickly, new sodium leakage detectors (TV monitors, smoke sensors) and a new surveillance system will be installed.
- To reduce the amount of sodium leakage and damage by spilt sodium, the drain system will be remodeled to shorten the drain time.
- To extinguish a sodium fire in the secondary circuit, a nitrogen gas injection system will be installed.
- To limit the spread of aerosol, the secondary circuit area will be divided into four smaller zones.

These countermeasures will enhance the safety and reliability of the plant with regard to sodium leakage incidents.

1. INTRODUCTION

The construction of Monju is a major milestone in the Japanese national FBR development project which is based on the Atomic Energy Commission's long-term nuclear energy program. The Japan Nuclear Cycle Development Institute (JNC) is responsible for the management of the project. Construction of Monju began in October 1985 at a site near the Tsuruga city. The principal data on plant design and performance are shown in TABLE 1. Loading of the fuel assemblies into the core started in October 1993 and the reactor attained initial criticality in April 1994. Monju achieved

TABLE 1. PRINCIPLE DESIGN AND PERFORMANCE DATA OF MONJU

Reactor type	loop-type	Reactor vessel	
Number of loops	3	height / diameter	18 / 7 m
Thermal output	714 Mwt	Primary coolant systems	
Electrical output	280 Mwe	Primary coolant sodium mass	760 ton
Fuel material	PuO2-UO2	Inlet / outlet reactor temperature	397 / 529 ℃
Core dimensions		Primary coolant flow rate	5.1×10^6kg/h/loop
Equivalent diameter	1,790 mm	Primary coolant flow velocity	6m/s(inlet),4m/s(outlet)
Height	930 mm	Secondary coolant systems	
Plutonium enrichment (inner core / outer core)		Secondary coolant sodium mass	760 ton
(Pu fissile %)		Inlet / outlet IHX temperature	325 / 505 ℃
Initial core	15 / 20	Secondary coolant flow rate	3.7×10^6kg/h/loop
Equilibrium core	16 / 21	Secondary coolant flow velocity	5 m/s
Fuel inventory		Water - steam systems	
Core (U+Pu metal)	5.9 t	Feed water flow rate	113.7×10^4kg/h
Blanket (U metal)	17.5 t	Steam temperature (turbine inlet)	483 ℃
Average burnup	80,000 MWD/T	Steam pressure (turbine inlet)	12.7 MPa
Cladding material	SUS316	Type of steam generator	Helical coil
Cladding outer diameter/thickness	6.5 / 0.47 mm	Refueling system	Single rotating plug with fixed arm FHM
Blanket thickness			
Upper / lower / radial	30 / 35 / 30 cm	Refueling interval	6 months
Breeding ratio	1.2		

Japan's first generation of electricity by an FBR in August 1995 and the electric power was raised gradually for a program of power buildup tests to be carried out; the rated power test planned for June 1996. It was in the course of this program that the tip of a thermocouple well tube in the secondary circuit (loop C) broke away causing a sodium leak on 8th December 1995.

This paper summarizes the sodium leak incident, the cause of thermocouple well tube failure, and the improvement and countermeasure programs against sodium leakage incidents.

2. SUMMARY OF THE ACCIDENT AND POST-ACCIDENT RESPONSE

After a plant trip test, Monju restarted operation on 6th December 1995. On 8th December, power was being raised for the next plant trip tests, part of 40% electric power tests. The thermal power had reached 43% when an alarm sounded at 19:47 due to an off-scale sodium temperature at the outlet of IHX in the secondary circuit loop C. A fire alarm (smoke detector) sounded at the same time. A sodium leak alarm in the secondary circuit followed. The plant conditions of Monju at that time are shown in Fig.1. The presence of smoke was confirmed when the door of the piping room was opened. The plant operators decided to begin normal shutdown operations because they judged it was a small sodium leak had occurred. Reactor power-down operations began at 20:00.

The state inside the piping room (C) was checked again and an increase in white fume was observed. Accordingly, the reactor was manually tripped at 21:20. After the trip, the reactor was cooled down by the auxiliary cooling system (ACS) and was maintained in the low-temperature shutdown state. To minimize leakage, sodium in the secondary circuit (loop C) was drained at 22:55 and drain operations were complete at 00:15, the following day.

As it was in the secondary circuit, there was no release of radioactive material. There were no adverse effects for personnel and the surrounding environment.

An inspection of the affected piping room on 9th December confirmed the presence of solidified materials associated with the sodium leak around and near the thermocouple well of the outlet of the secondary side of IHX. The state of the piping room after the sodium leak is shown in Fig.2. Approximately 1 m^3 of a sodium oxide on the 6 mm thick steel floor liner formed a semicircular mound, nearly 3 m in diameter and 30 cm high. Sodium aerosol was lightly diffused over and accumulated on the floor and walls of the room. The ventilation duct directly under the

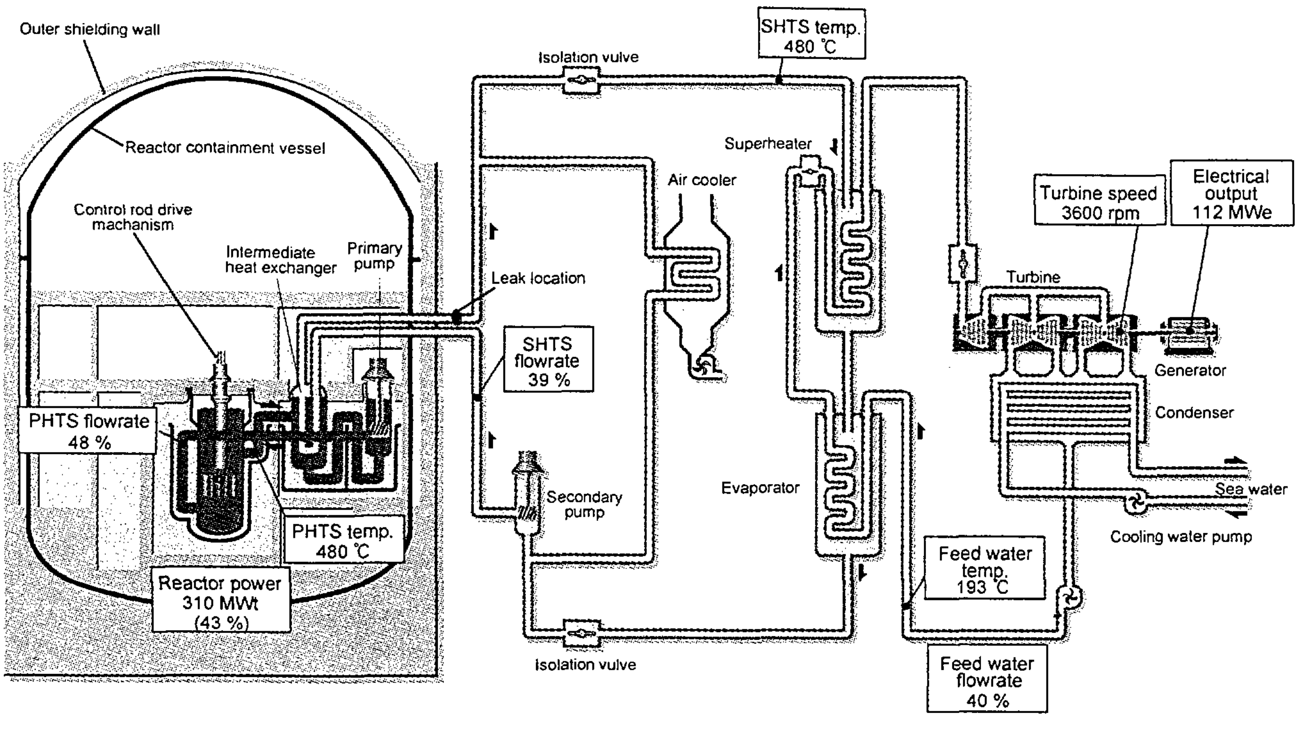

Fig. 1. MONJU plant condition (just before the sodium leak).

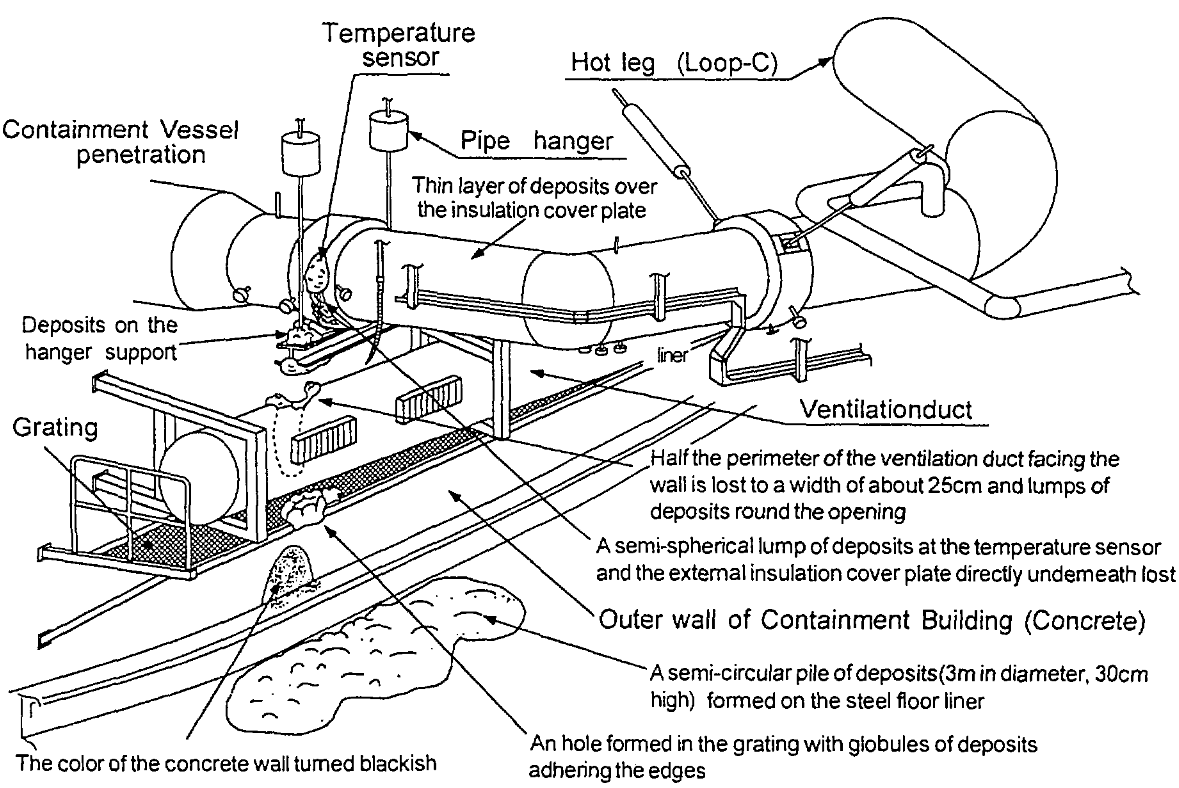

Fig. 2. Sketch of the affected area.

thermocouple well developed a hole extending over half the perimeter facing the wall with lumps of deposits around the opening. On the steel walkway grating under the thermocouple well, an opening was formed with globules of deposits stuck around the edges. There were no further anomalies observed in the piping of the secondary circuit. Sodium compounds covered the entire floor of the loop C steam generator (SG) room adjacent to the piping room and the passages on the first and second floors.

Temperature sensor and the well tube which leaked was examined to investigate the cause. On 7th and 8th January, radiographs were taken of areas close to the temperature sensor in order to estimate the extent of adherent sodium compounds around the temperature sensor and to assess its structural condition. The thermocouple (3 mm diameter) was found to be bent at 45 degrees toward the downstream flow direction. The protective tube of the temperature sensor was found to be filled with sodium compounds. On 9th February, the temperature sensor was cut out for detailed investigation.

On 28th March, the sleeve tip, a cylinder 1 cm in diameter and 15 cm in length, was located in the sodium-inlet part of the superheater, and JNC recovered the broken sleeve tip on April 24.

3. INVESTIGATION OF THE CAUSE

A taskforce was formed to direct the investigation of the incident. This taskforce was organized by Science and Technology Agency (STA) and the members consisted of STA's Nuclear Safety Technology Panel experts. JNC performed its own work under the direction of the Taskforce.

The outline of the investigation works was as follows ;

A. The affected temperature sensor

The thermocouple wires are enclosed by a sheath which is itself housed within the well tube. The tip of well tube is inserted horizontally into the center of the pipe. This tip (some 15 cm in length) is thinner in diameter than the base of the sensor. (Fig.3)

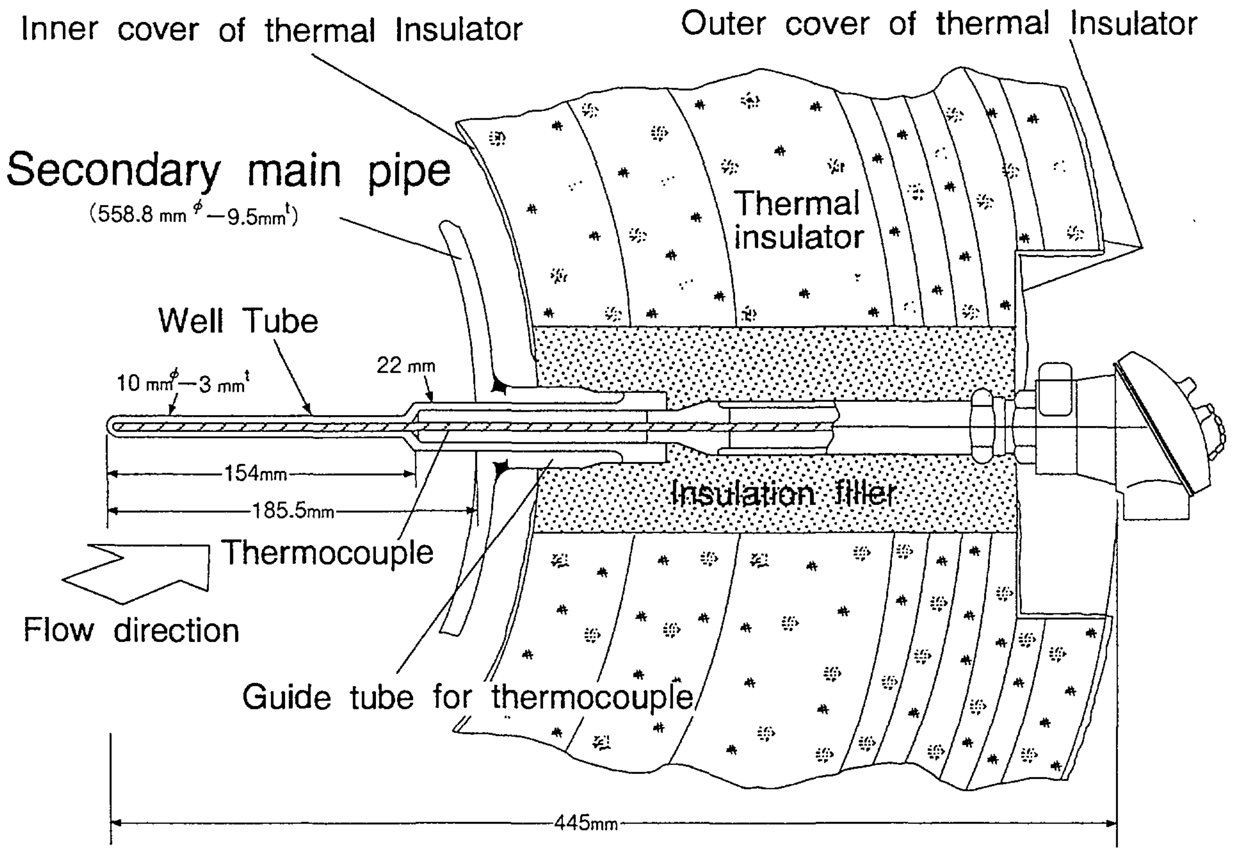

Fig. 3. The thermocouple well of the secondary circuit.

X-ray photographs were taken to estimate the extent of adherent sodium compounds around the temperature sensor and to assess structural condition. These revealed that the tip of the well tube was missing and the sheath containing the thermocouple wires was bent downstream. Other anomalies were not observed by the photographs. At that time, it was clear that the sodium leaked into the temperature sensor through the broken well tube. (Fig.4)

Temperature sensor, together with a small section of the adjacent pipe wall, was cut out for the detailed investigation and transported to the Japan Atomic Energy Research Institute (JAERI).

B. The cause of the well tube breakage

Detailed microscopic and metallographical examinations of the well tube and the fracture surface, examination of welded parts of the well, detailed examination of the sheathed thermocouple were carried out at JAERI and the National Research Institute of Metals (NRIM). The detailed measurement of the damaged part (fracture surface) was undertaken with microscopes and laser microscopes. As a result of these inspections, it was found that the fracture surface showed the typical features of high cycle fatigue with crack initiation, very slow propagation, and final ductile rupture, as shown in Fig.5. In parallel, flow-induced vibration analysis and mockup tests were conducted to identify the direct cause of the failure. These investigations confirmed that the breakage of the thermocouple well was caused by high cycle fatigue of the well tube tip due to flow-induced vibration. This vibration was not caused by well-known Von Karman vortex shedding, but a symmetric vortex shedding (Fig.6). According to fatigue crack analysis on the basis of the flow rate history, it was estimated that the cracks initiated at the early stage of the 100% flow operation, propagated in the subsequent operation, finally leading to the well tube failure in the last 40% flow operation. It was confirmed that the estimated breakage process agreed with the investigation results of the fractured surface and the full scale in-water experiment .

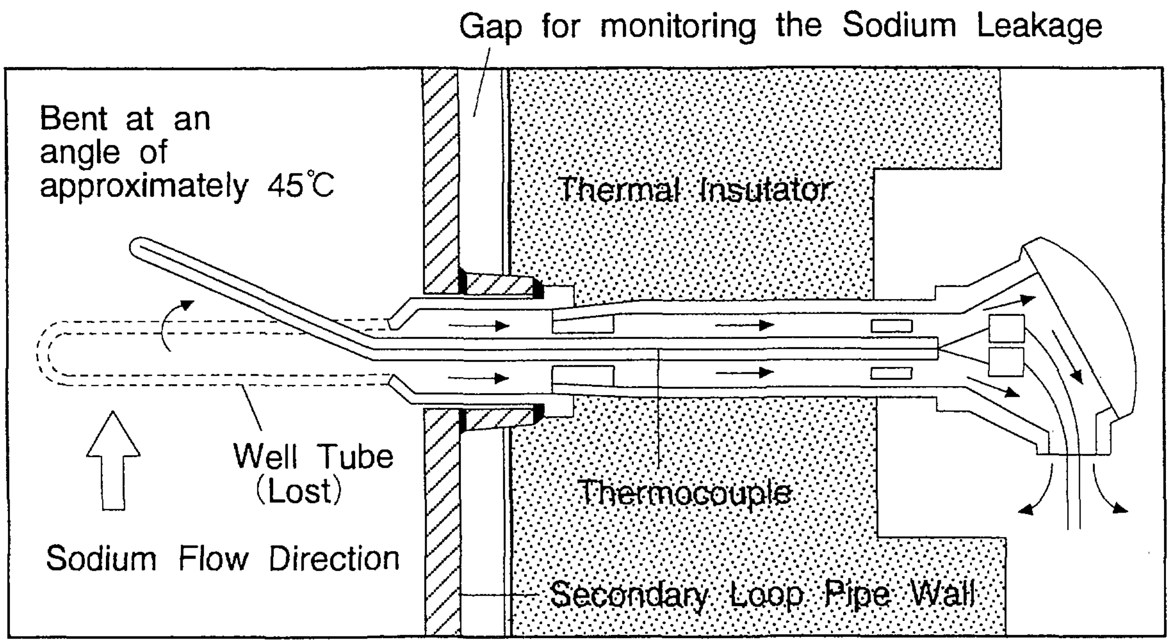

Fig. 4. The sodium leak flow path.

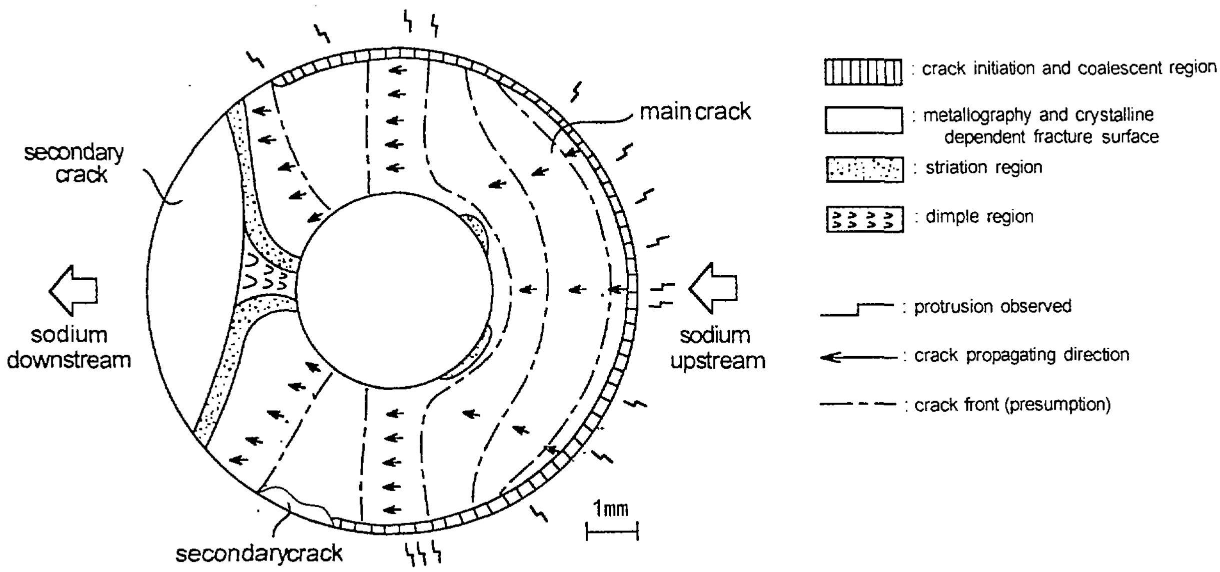

Fig. 5. Microscopic inspection of the fracture surface of the thermocouple wall.

4. MEASURES AND SOLUTIONS

A. Prevention of sodium leakage

It was decided to replace all the thermocouple wells susceptible to vibration in the secondary circuit with modified designs. A new design guide against the flow-induced vibration was prepared by JNC. It is more comprehensive and definitive than the existing design guide "ASME N-1300".

Using this design guide, three new thermocouple well designs were developed, according to their functional requirements and locations. All the designs use a tapered well, instead of steep diameter change. A leak suppression mechanism is also incorporated into the new design. The three thermocouple designs, Type A, B, and C are shown in Fig. 7, along with the existing design. The "Type A" thermocouple well is directly welded to the pipe wall, while the "Type B" and "Type C" thermocouple wells are mounted on the existing nozzles. The three design types have different penetration designs and different insertion length into the flowing stream.

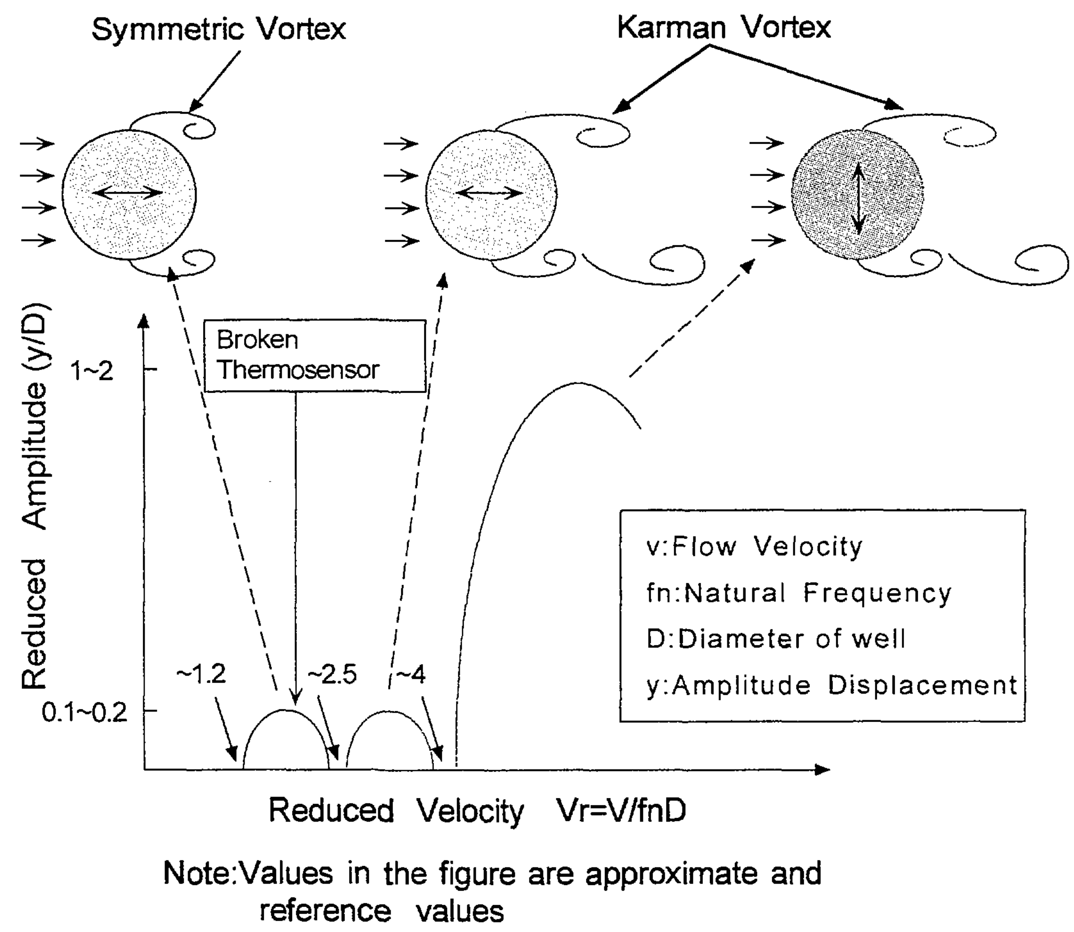

Fig. 6. Explanation of vortex shedding.

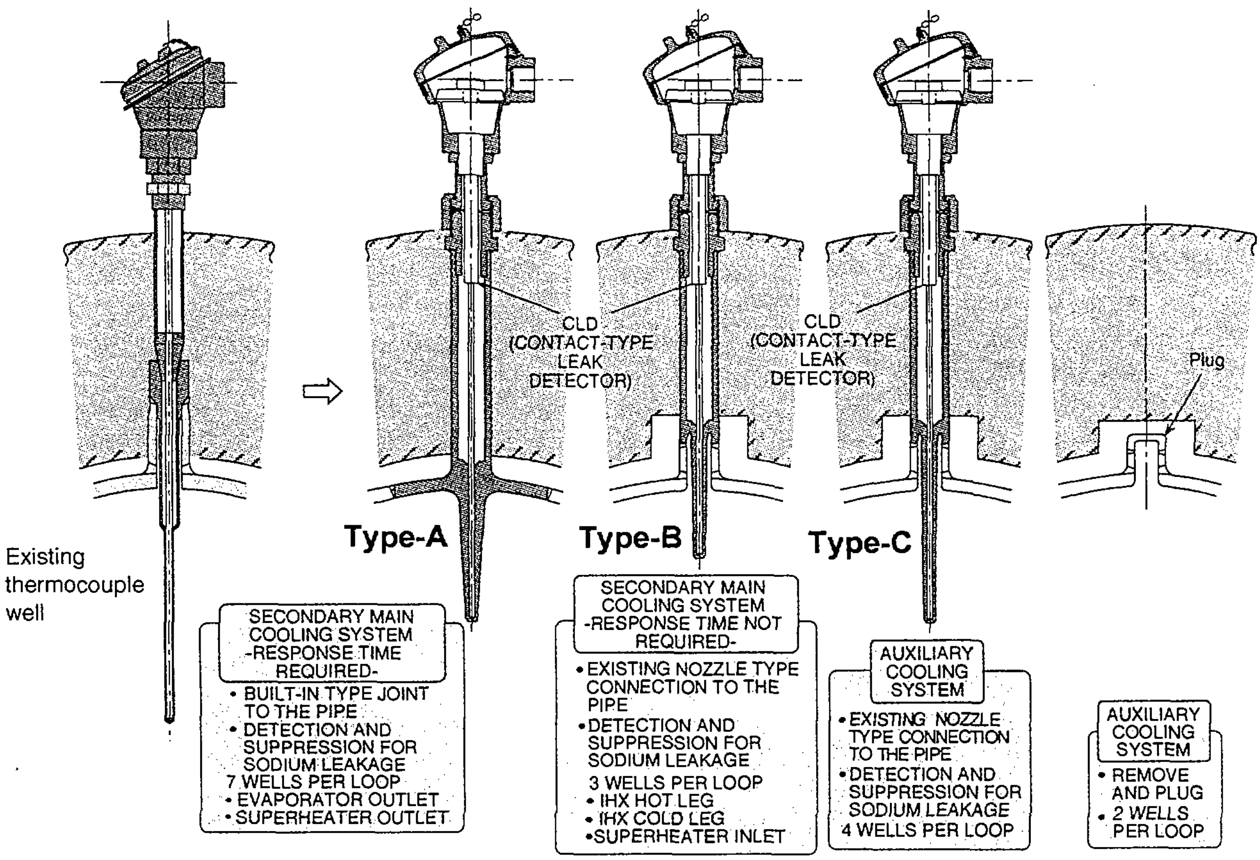

Fig. 7. Modified design concepts for the thermocouple wells on the secondary cooling system.

B. Mitigation of sodium leakage influence

A comprehensive review was performed concerning sodium leakage. The review concentrated on the following three points:

- Detection of sodium leakage at an early stage
- Reduction of the quantity of sodium leakage
- Limiting the diffusion of sodium aerosol and the combustion of spilt sodium

These were chosen in order to investigate if systems and components with regard to the sodium leakage could be improved or not.

The design of the systems and components was also reexamined considering the experience and knowledge accumulated at other fast reactors, research and development results and new findings. As a result of the review, some additional aspects were appeared. Some existing systems and components related to sodium leakage were found to require modification, and it was recommend that new systems and components should be introduced. Typical systems and components are ;

- Sodium leakage detection system (to be modified)
- Ventilation system (to be modified)
- Drain system (to be modified)
- Partition of the secondary circuit room (to be introduced)
- Nitrogen injection system (to be introduced)
- Thermal insulation structures (to be introduced)

Each of these is described in greater detail below :

(1) Sodium leakage detection system

It was possible to detect the sodium leakage because Monju already had sodium leak detectors and fire detectors in the secondary circuit. However it was found that these were insufficient for the operators to grasp accurately the conditions in the room at an early stage. To help the operators confirm sodium leakage more quickly and easily, the detectors will be increased in number and diversified method and an integral leakage monitoring system will be installed.

The fire sensors are able to detect sodium leakage by two different methods. One is smoke (aerosol) detection and the other is by temperature increase in the room where a sodium fire occurs. Monju already used the former method and this type of sensor will be increased to detect the sodium leakage more quickly and more certainly. The latter method type fire sensors will be introduced for greater diversity in the detection of the sodium fires. Visual information was found to be useful for operators to know the condition of the room, and so, TV cameras will be installed in the secondary circuit.

The integral leakage monitoring system will be composed of three parts : detection, data processing and monitoring display. Detection will consist of the signals from fire sensors, sodium leak detectors, plant process sensors (sodium flow rate, sodium level in the overflow tank, etc.) and visual information from the TV cameras.

A monitoring display panel will be installed in the main control room and information from the various sensors and TV cameras will be displayed. The new leakage monitoring system should enable the plant operators to take the necessary actions - such as a plant trip and loop drain - earlier, since they will be able better to understand the condition at the leak site without leaving in the main control room. A schematic of this system is shown in Fig.8.

(2) Ventilation system

To control the spread of aerosol and the combustion of sodium, the ventilation system will be shut down more quickly by signals from the newly installed integrated leakage monitoring system. At present, in the case of small and medium-scale leaks, the shut down of the ventilation system is carried out manually by the operators. Only in the case of a large sodium leak, the ventilation is shut down automatically by an interlock signal from an abnormally low level in the steam generator. At present, if a small or medium-scale leak occurs, the sodium aerosol spreads from the leak site room to all areas that are connected by the ventilation ducts until the ventilation system is shut down.

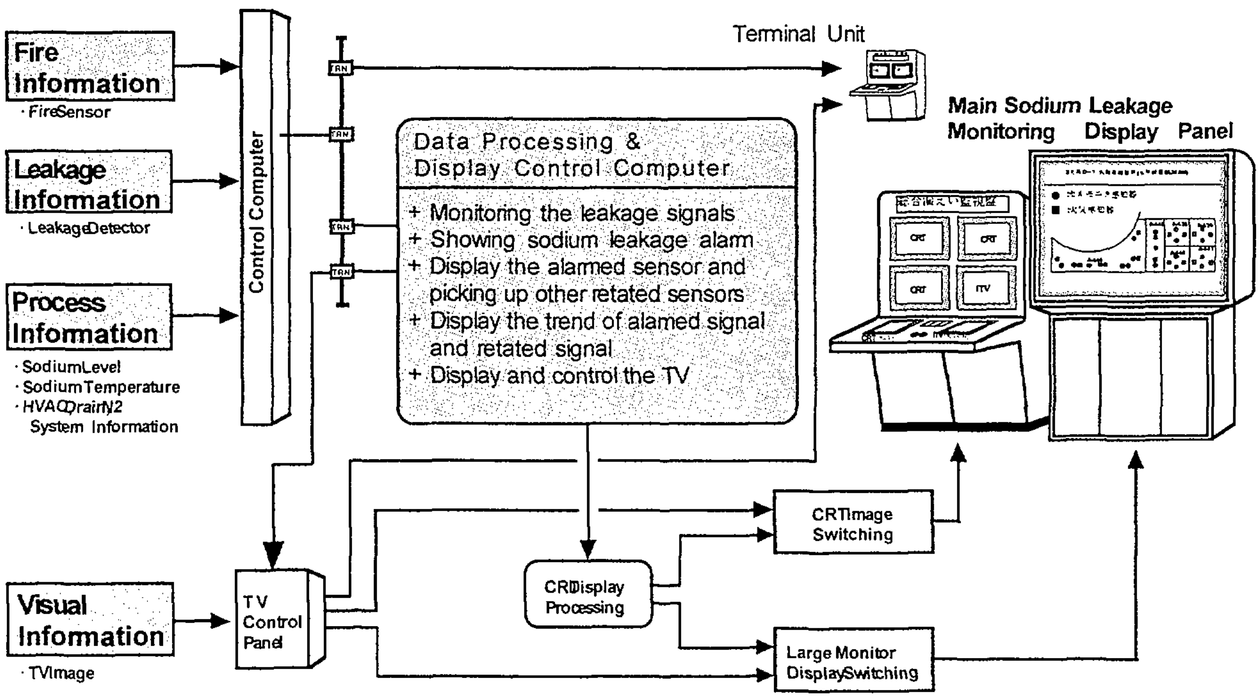

Fig. 8. Organization of integral leakage monitoring system.

By connecting the leakage monitoring system signals to the ventilation system via an interlock sequence, the shutdown of ventilation system can be achieved within two minutes after detection even for small or medium scale leakage.

(3) Drain system

To reduce the quantity of sodium leakage, the drain system was found to require two improvements. One is the addition of a new drain line pipe at the inlet of the secondary pump. The other is the replacement of all drain lines by pipes of larger diameter. In the existing system, each drain line has two drain valves in series to prevent accidental draining by single valve action error. In future so as to assure the draining, each drain line will have double drain valves in parallel. After these improvements, the drain time will be shortened from approximately 50 minutes to 20 minutes. It is estimated that it takes 40 minutes from the occurrence of sodium leakage to finish the drain for the secondary circuit. The modified drain system is shown in Fig.9.

(4) Partition of the secondary circuit room

To limit the diffusion of aerosol and the combustion of sodium more quickly, the area associated with each secondary circuit will be divided into four smaller zones. At first, more than four smaller zones were considered because partition is effective in controlling the diffusion of aerosol. However, it was found to be difficult to provide a dust-tight structure for some of the large openings between the proposed zones which allow air transfer. It was also difficult to prevent pressure in smaller zones from increasing and it is almost impossible to replace the existing ventilation ducts. Hence, four zones were adopted as the optimal solution. The openings for the cables or pipe penetrations through the wall between each zone will be improved to be almost airtight and additional isolation dampers will be fitted in the ventilation ducts between each zone. Pressure release lines will be installed to prevent an increase in internal pressure resulting from the smaller zones. The partition of the secondary circuit area is shown in Fig.10.

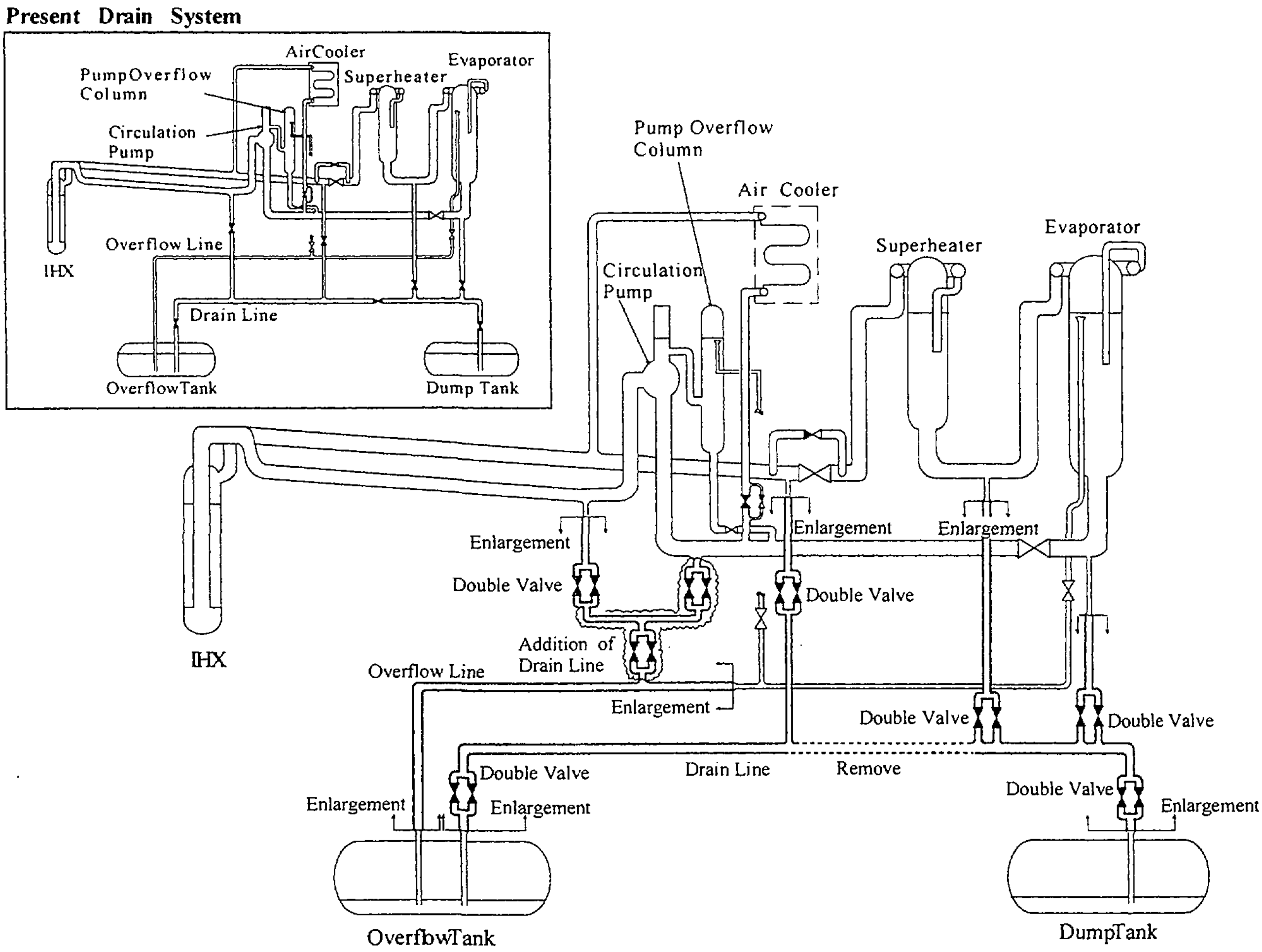

Fig. 9. Modified drain system.

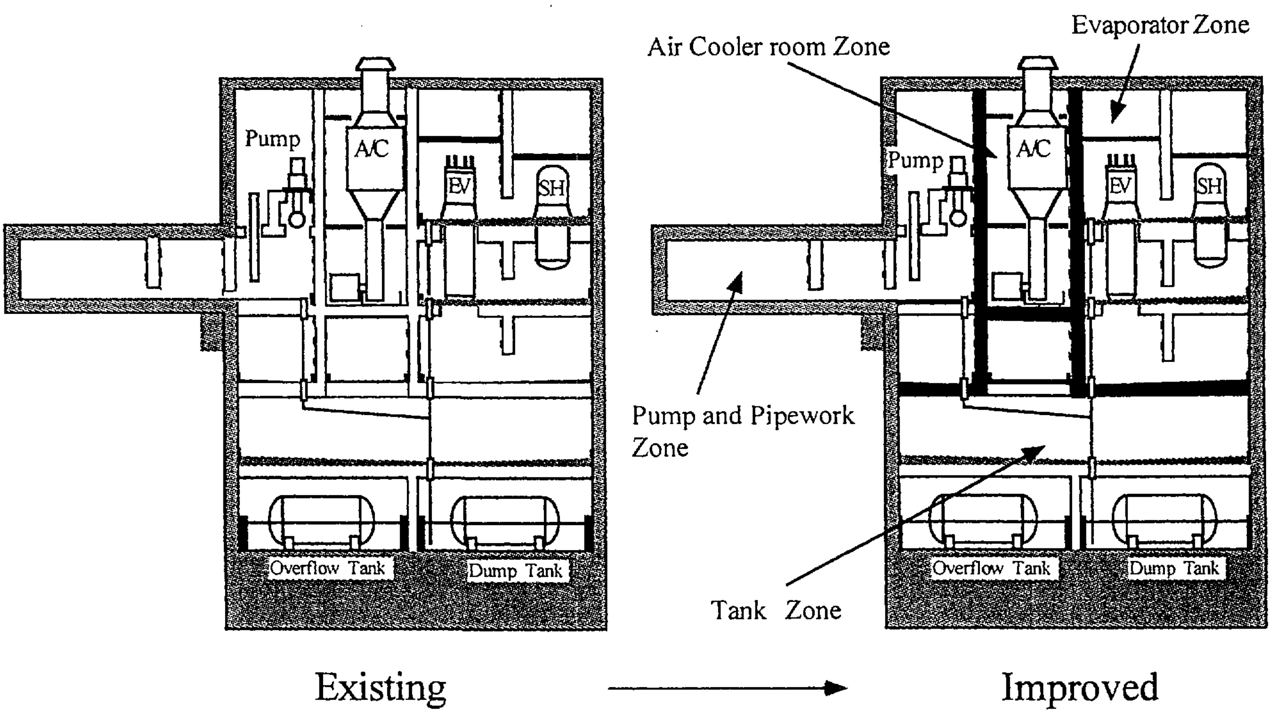

Fig. 10. Partition of the secondary circuit area.

(5) Nitrogen injection system

To extinguish the sodium fire more quickly and to prevent it from re-igniting in contact with oxygen, a nitrogen gas injection system will be installed to cut off the supply of oxygen. The nitrogen injection system is shown in Fig.11. The tanks are common to the entire system and the piping is connected to the each zone. After the personnel evacuation of the secondary circuit is confirmed, the operator will release nitrogen gas into the affected zone. According to an assessment of the relationship between nitrogen flow rate and extinguishing time, if more than 10,000 Nm^3/h of nitrogen gas is injected, a sodium fire can be extinguished within 15 minutes for any sodium leak rate.

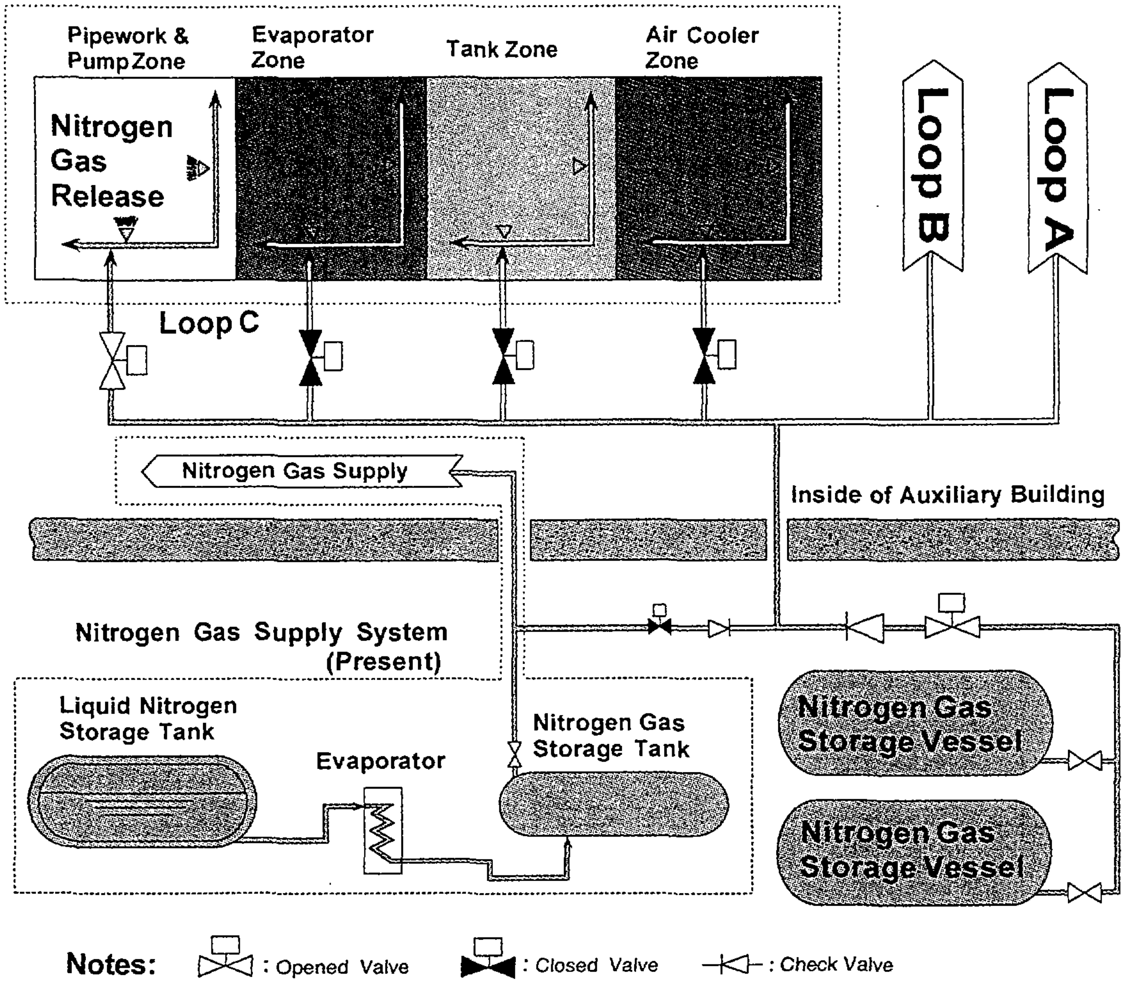

Fig. 11. Nitrogen injection system.

(6) Thermal insulation structure

To reduce the water release from the structural concrete, thermal insulation will be fitted to the walls and ceilings. This is important because if a large amount of water vapor is released from the concrete during a sodium leaks, there is an increased probability of generation of hydrogen and corrosive hydroxide in the chemical composition of the sodium debris. By using insulation, the temperature rise of the wall can be brought down to under approx. 100℃. The structure of thermal insulation is shown in Fig.12.

5. ASSEESSMENT OF COUNTERMEASURES AGAINST SODIUM LEAK INCIDENT

The effectiveness of the plant improvements described above have been assessed by the latest sodium combustion analysis code, called ASSCOPS. Typical results of analysis are as follows:

(1) Since the duration of the leakage is shortened approximately 40 minutes by the modified drain system, the total amount of leakage will be reduced to approximately 50%. The period of exposure to high temperature decreases (See Fig.13).

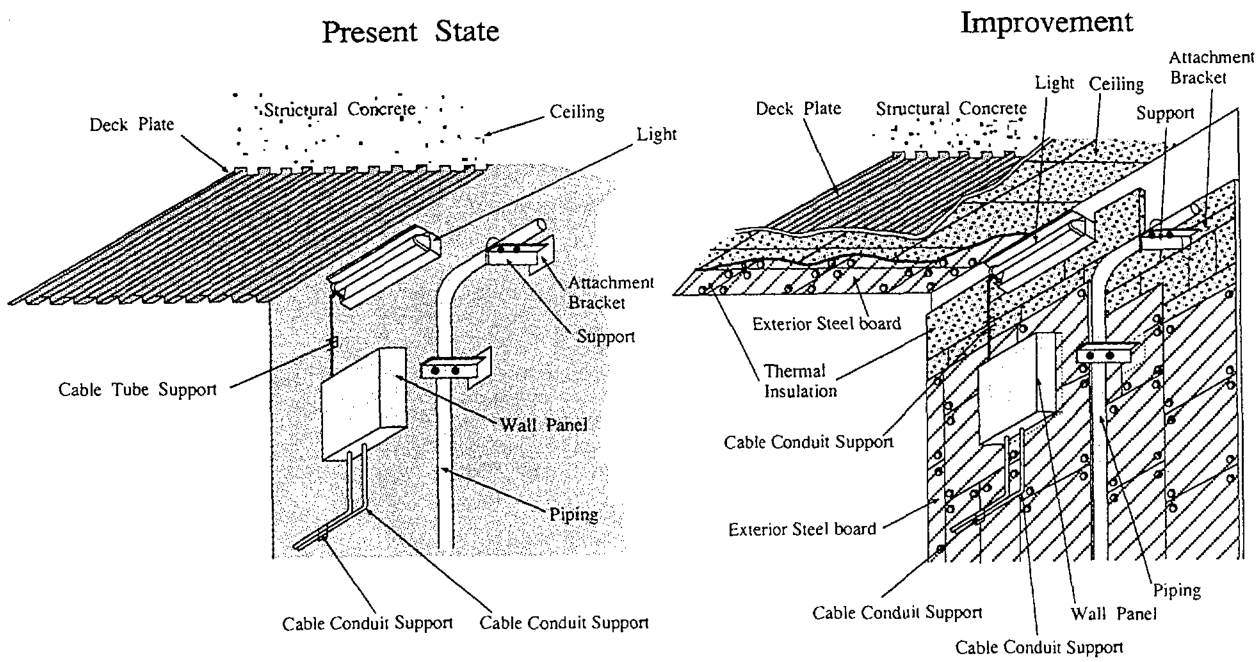

Fig. 12. Thermal insulation for walls and ceiling.

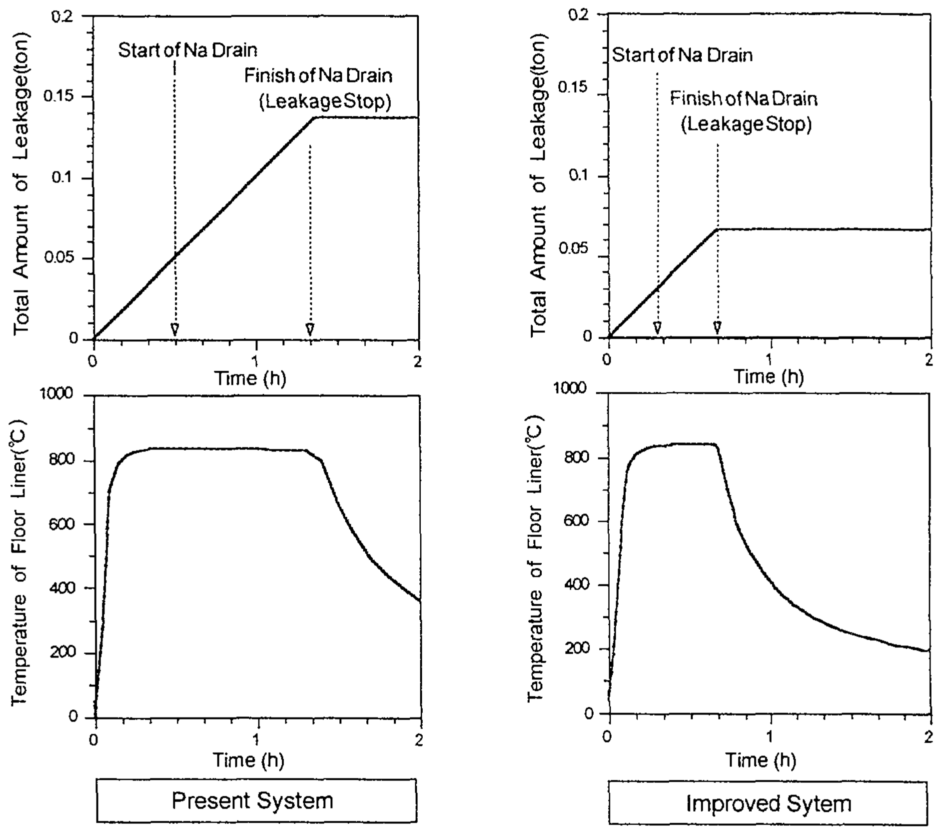

Fig. 13. Effectiveness of improvements (pipework room, leakage rate: 0.1t/h) (without nitrogen release).

(2) Since the temperature rise of the concrete is reduced from over 200 centigrade to approximately 100 centigrade by the thermal insulation on the walls and ceilings. At this temperature, the water release is considerably reduced. (See Fig.14).

(3) Since the ventilation system is shutdown automatically and the air inventory in the room is reduced by the division into four smaller zones, oxygen concentration in the combustion room and neighboring room is reduced. (See Fig.15).

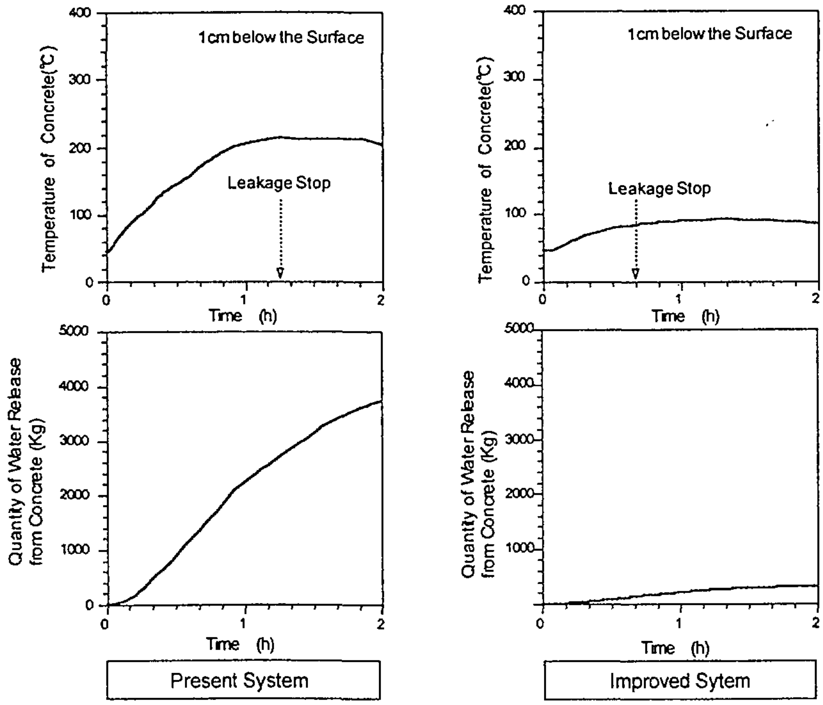

Fig. 14. Effectiveness of improvements (pipework room, leakage rate: 10t/h) (without nitrogen release).

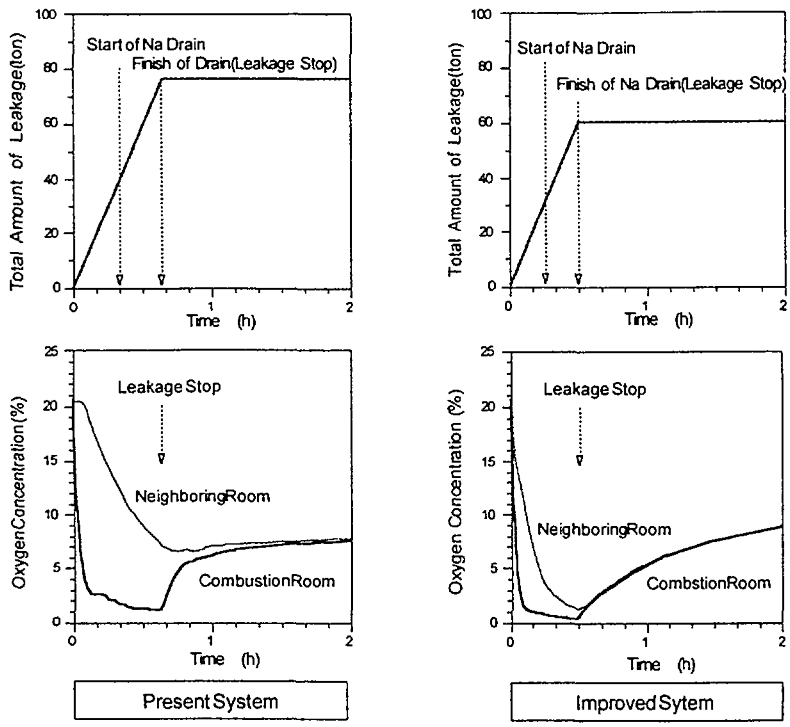

Fig. 15. Effectiveness of improvements (pipework room, leakage rate: 119 t/h) (without nitrogen release).

6. CONCLUSION

On December 8 1995, the sodium leakage from the secondary circuit occurred at Monju. The secondary sodium leaked through a temperature sensor, due to the breakaway of the tip of the thermocouple well. The reactor remained cooled and the safety of the reactor was secured. There were no adverse effects for operating personnel or the surrounding environment. The cause of the thermocouple well tube failure resulted from high cycle fatigue due to flow induced vibrations. It was found that this flow induced vibrations were not caused by well-known Von Karman vortex shedding, but a symmetric vortex shedding. The original design of the thermocouple well was reviewed. A new design guide against the flow-induced vibration was prepared by JNC. According to this design guide, the modified thermocouple wells were proposed.

The comprehensive safety review was completed in March 1998. It has been demonstrated that the following improvements are effective against the sodium leakage incidents and enhance the safety and reliability of the plant.

(1) As prevention of sodium leakage,
- A new design guide against the flow-induced vibration was prepared
- secondary circuit thermocouple wells will be replaced.

(2) As detection of sodium leakage at an early stage,
- Sodium fire sensors will be increased in number and diversified method,
- Integrated sodium leakage monitoring system will be introduced.

(3) As reduction of the quantity of sodium leakage,
- The drain system will be remolded.

(4) As limiting the diffusion of sodium aerosol and the combustion of spilt sodium,
- Ventilation system will be shut down automatically,
- Secondary circuit area will be divided into four smaller zones,
- Nitrogen gas injection system will be introduced,
- Thermal insulation for walls and ceilings will be introduced.

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