Sodium Leak at Monju (I)
- Cause and Consequences -

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Abstract

On December 8, 1995, a sodium leak from the Secondary Heat Transport System (SHTS) occurred in a piping room of the reactor auxiliary building at Monju. The sodium leaked through a thermocouple temperature sensor due to the breakage of the well tube of the sensor installed near the outlet of the Intermediate Heat Exchanger (IHX) in SHTS Loop C. There were no adverse effects for operating personnel or the surrounding environment. The reactor core remained cooled and thus, from the viewpoint of radiological hazards, the safety of the reactor was secured. On the basis of the investigations, it was concluded that the breakage of the thermocouple well was caused by high cycle fatigue due to flow induced vibration in the direction of sodium flow.

1. INTRODUCTION

Monju is a prototype fast breeder reactor designed to have an output of 280 MWe (714MWt). Monju is fueled with mixed oxides of plutonium and uranium and cooled by liquid sodium. The principal data on plant design and performance are shown in TABLE I.

The construction of Monju is a major milestone in the Japanese national FBR development plan, based on the Atomic Energy Commission's long-term program for development of nuclear energy. The Power Reactor and Nuclear Fuel Development Corporation (PNC) is responsible for the management of the project and began construction in October 1985 at the Tsuruga site. Loading of the fuel assemblies into the core started in October 1993 and the reactor attained initial criticality in April 1994. The first test generation of electricity was in August 1995. After this, the program of power raising tests was being carried out, with the rated power test planned for June 1996; in the course of this program, a sodium leak occurred in SHTS Loop C at 19:47, on December 8, 1995.

This paper describes details of the sodium leak accident and the present situation of the cause investigation.

TABLE I Principal Design and Performance Data of MONJU

Reactor type	Sodium-cooled / loop-type	Reactor vessel	
Number of loops	3	height / diameter	18 / 7 m
Thermal output	714 MWt	Primary coolant systems	
Electrical output	280 MWe	Coolant sodium mass	760 ton
Fuel material	PuO_2-UO_2	Inlet / outlet reactor temperature	397 / 529 ℃
Core dimensions		Coolant flow rate	5.1×10^6 kg /h / loop×3loops
Equivalent diameter	1,790 mm	Coolant flow velocity	6m/s(inlet), 4m/s(outlet)
Height	930 mm	Secondary coolant systems	
Plutonium enrichment (inner core / outer core)		Coolant sodium mass	760 ton
	(Pu fissile %)	Inlet / outlet IHX temperature	325 / 505 ℃
Initial core	15 / 20	Coolant flow rate	3.7×10^6 kg /h / loop×3loops
Equilibrium core	16 / 21	Coolant flow velocity	5 m/s
Fuel inventory		Water - steam systems	
Core (U+Pu metal)	5.9 t	Feed water flow rate	113.7×10^4 kg/h
Blanket (U metal)	17.5 t	Steam temperature (turbine inlet)	483 ℃
Maximum burnup(F/A)	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
Blanket thickness			with fixed arm FHM
Upper / lower / radial	30 / 35 / 30 cm	Refueling interval	6 months
Breeding ratio	1.2		

2. SUMMARY OF THE ACCIDENT AND POST-ACCIDENT RESPONSE

Following a programmed shutdown, Monju restarted operation on December 6, 1995. On December 8, while power was being raised for a plant trip test as part of the 40% electric power test (thermal power 43%), a high sodium temperature alarm at the outlet of the IHX in SHTS Loop C sounded at 19:47 and at approximately the same time the fire alarms (smoke detector) sounded in the same area. A sodium leak detection alarm followed, indicating that there was a sodium leak in the piping room of SHTS Loop C. The plant conditions at the time of the sodium leak occurrence are shown in Fig.1.

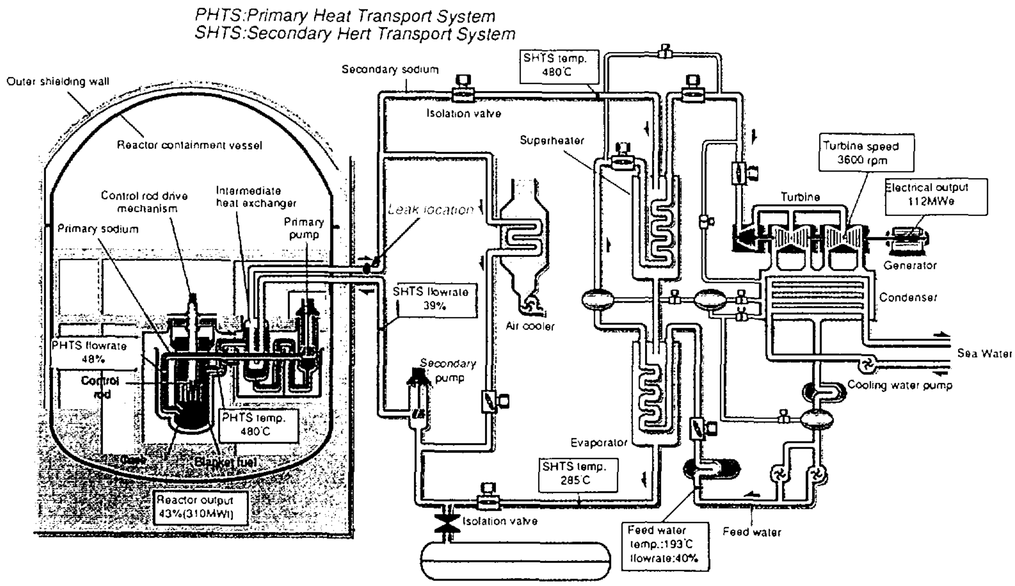


Fig.1 Monju Plant Condition (just before the Sodium Leak)

The presence of smoke was confirmed when the door of the SHTS Loop C piping room was opened. The plant operators determined that a sodium leak had occurred and decided to begin a normal plant shut-down operation, the correct Operating Procedure for what they judged to be a small-sized sodium leak. Reactor power-down operations began at 20:00. The state inside the piping room was checked again at 20:50 by partially opening its door and an increase in white fume was observed. Accordingly, electric power generation was stopped at 21:15, and the reactor was manually tripped at 21:20. Immediately after the trip, the reactor was cooled by the Auxiliary Cooling System (ACS) of all three secondary loops. In order to stop the leak, the draining of sodium from the affected loop was started at around 22:40. The blowers of the air ventilation system for Loop C were turned off automatically at 23:13 by the low sodium level interlock on the evaporator. The loop draining operations were completed at 00:15, December 9. Later, the sodium in the Primary Heat Transport System (PHTS) Loop C was also drained. Subsequent decay heat removal from the core was therefore by the PHTS, SHTS and ACS of Loop A and Loop B operated at minimum flow rate.

As it was a secondary cooling system leak, there was no radiation effect from the leak for either the general public or the plant personnel.

An inspection of the SHTS Loop C piping room on December 9 confirmed the presence of solidified sodium residue materials in the vicinity of the thermocouple well at the secondary-side outlet of the IHX. It was concluded that the thermocouple well was the probable origin of the leak. The state of the piping room after the sodium leak is shown in Fig.2. On the 6mm thick steel floor liner approximately $1m^3$ of sodium compounds formed a semicircular mound, nearly 3m in diameter and 30cm high. Other sodium compounds resulting from the leak were lightly spread over the floor and walls of the room. The only damage observed was to a ventilattion duct and an access walkway. The ventilation duct, running directly under the SHTS piping, had a hole extending over half the perimeter facing the wall with lumps of deposits around the opening. On the steel walkway grating under the piping, an opening was formed and globules of deposits stuck around the edges. Sodium compounds from the leak were found over the entire floor of the Steam Generator room of SHTS Loop C connecting to the piping room and in the passages.

From December 14, work began to remove and recover sodium compounds from the floor near the leak site. About 3m length of the ventilation duct which obstructed access to the suspect temperature sensor was removed during January 4~8, in order to make a closer inspection and establish the cause of the leak.

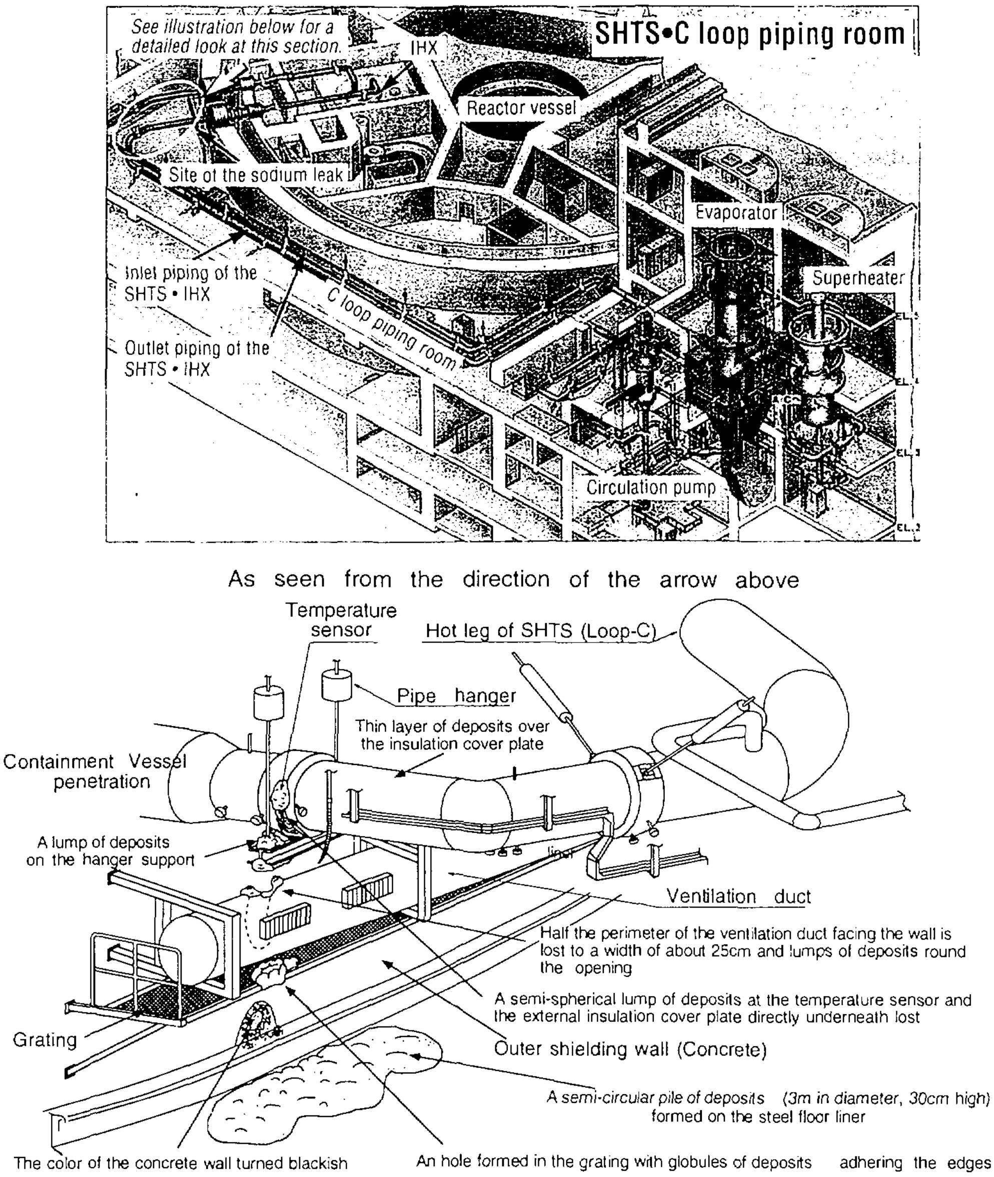


Fig.2 The State of the Piping Room (C) after the Sodium Leak

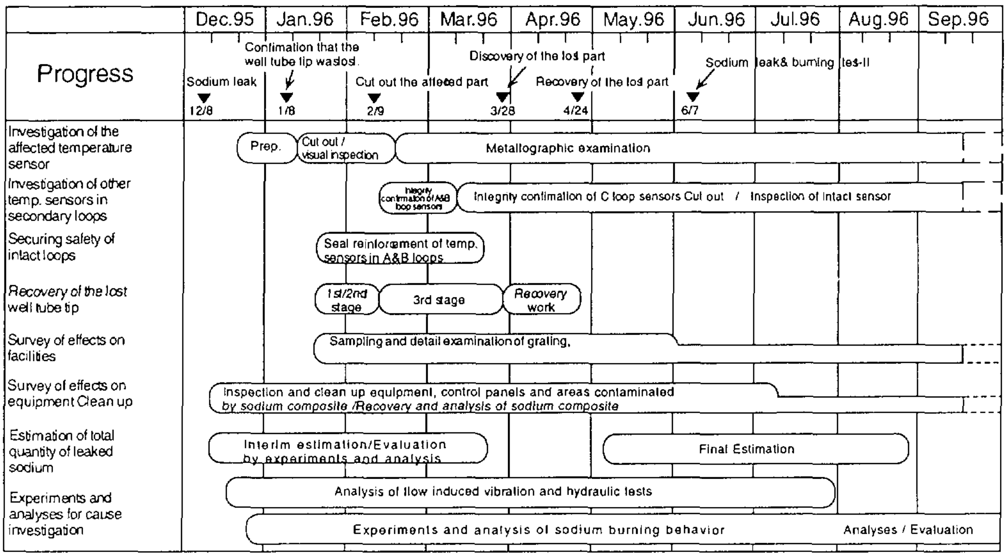
3. INVESTIGATION OF THE CAUSE

3.1. Organization of the investigation

After the accident investigations were started by PNC and independent nuclear safety organizations. The Nuclear Safety Bureau (NSB) of the Science and Technology Agency (STA) set up a task force to investigate the cause of the accident and consider effective measures for preventing another sodium leak in Monju. Another independent investigation was launched by the Nuclear Safety Commission (NSC) whose working group was assigned to work under the direction of the Research & Development Reactor Subcommittee of the Reactor Safety Review Committee. The scope of this investigation covered not only technical matters but all aspects of software, such as operation manuals and information management systems.

PNC's investigations have been carried out under the supervision of STA's "Investigation Task Force on the Sodium Leak Accident in Monju"; the task force members consisted of STA's Nuclear Safety Technology Panel experts. The schedule of the technical investigation is shown in Fig.3.

Fig.3 The Schedule of the Cause Investigation



3.2. The affected temperature sensor

The thermocouple wires are enclosed in a sheath that is itself housed within the well tube. This well tube extends horizontally toward the center of the pipe. The tip of the well tube (some 15 cm in length) is thinner in diameter than at its root. (Fig.4)

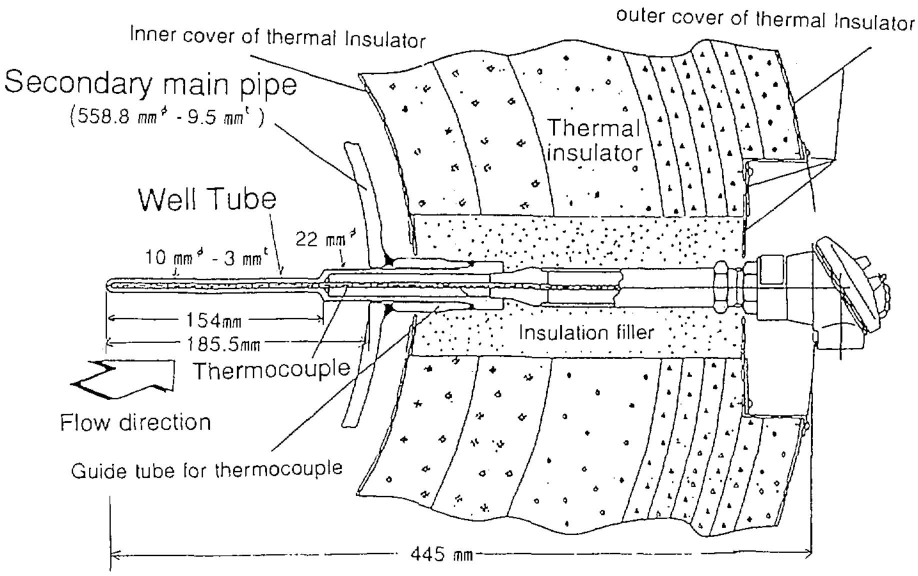


Fig.4 The Thermocouple Well of the Secondary Loop

On January 7 & 8, radiographs were taken of areas close to the temperature sensor to investigate the cause of the sodium leak, specifically to estimate the extent of remaining sodium compounds around the temperature sensor and to assess its structural condition. It was found that the tip of the well tube had been lost and the thermocouple (3 mm diameter) was bent at an angle of 45 degrees toward the downstream flow direction (Fig.5). The protective body of the thermocouple unit was found to be filled with sodium compounds; but the thermal insulating materials around the thermocouple did not exibit density shadows typical of the compounds. No other anomalies were observed on the radiographs. These findings confirmed that the failure of the thermocouple well was the direct cause of the sodium leak.

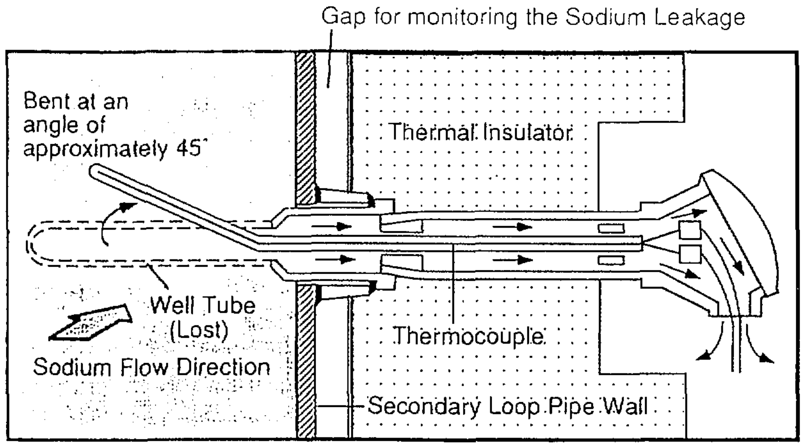


Fig.5 The Sodium Leak Flow Path

From February 7~9 the entire temperature sensor, thermocouple and well, 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) .

3.3. The other temperature sensors in the SHTS

Visual, ultrasonic and radiographic examinations were used to confirm the integrity of all the other temperature sensors in the SHTS. As an interim solution to prevent any further leaks, the temperature sensors of the same design in the intact secondary loops, Loops A & B, were reinforced with additional seals. Three intact temperature sensors were cut out for Loop C for the detailed investigation.

3.4. Location and recovery of the lost well tube tip

The search for the lost well tube tip of the thermocouple well began on January 26. Firstly, radiography was carried out along the horizontal pipes downstream of the affected temperature sensor on the secondary main cooling system (hot leg) and the secondary sodium filling-draining system, a total of about 185 m in length,but the well tube tip was not found. On March 28, a CCD camera inserted into the sodium-inlet header of the superheater, showed the lost well tube to be in the distributor at the top of the superheater (Fig.6). The lost well tube tip was recovered using a specially developed gripper on April 24.

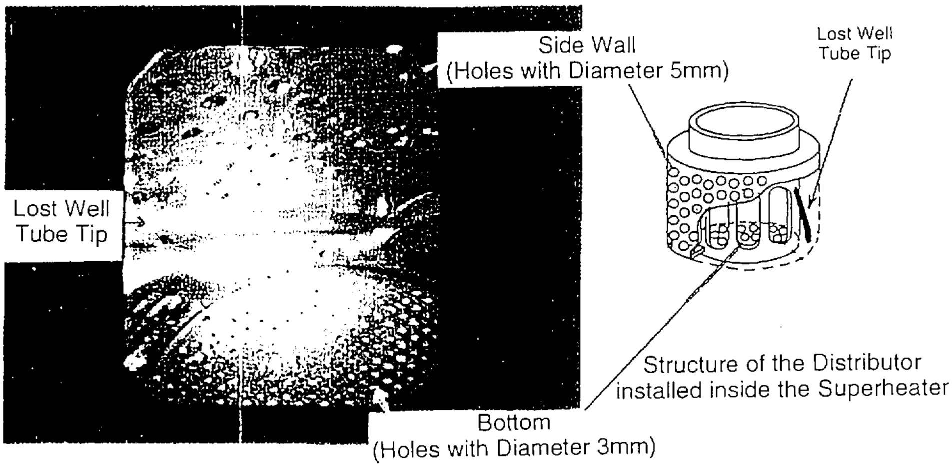


Fig.6 The Lost Well Tube Tip found by CCD Camera in the Distributor inside the Superheater

3.5. The cause of the well tube breakage

Detailed microscopic and metallographical examinations of the well tube and the fractured surface, examination of welded parts of the well, and the thermocouple sheath were carried out at JAERI (from February 13) and the National Research Institute of Metals (NRIM) (from February 16). The results of the microscopic inspection of the fractured surface of the thermocouple well are shown in Fig.7.

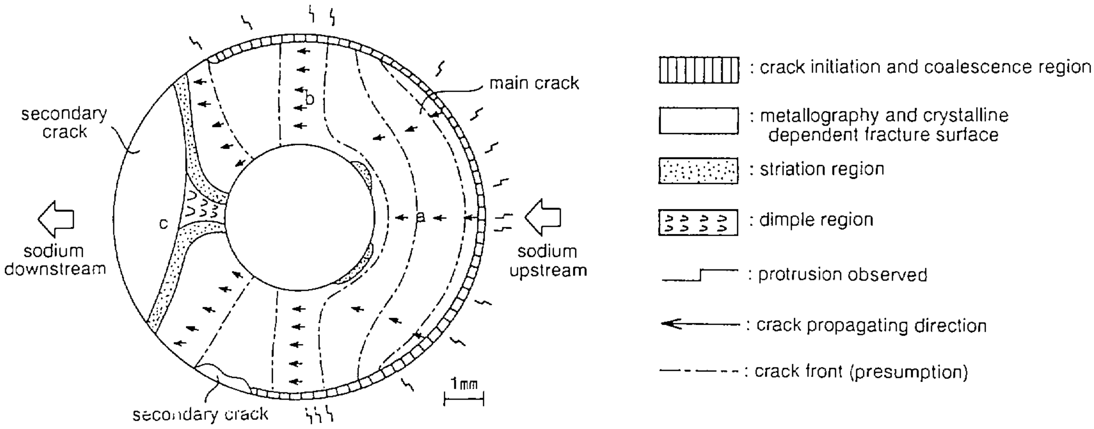


Fig.7 Microscopic Inspection of the Fracture Surface of the Thermocouple Well

Flow induced vibration analysis and mock-up tests have been conducted to identify the direct cause of the failure. On the basis of these investigations, it was concluded that the breakage of the thermocouple well was caused by high cycle fatigue due to flow induced vibration in the direction of sodium flow. The results of the analysis of flow induced vibration are shown in Fig.8, where the stream line oscillations of the well tube were observed with symmetric vortex shedding from both sides of the tube.

According to fatigue crack analysis, on the basis of the operational history, it was deduced that the cracks initiated at an early stage of the 100% flow operation, propagated in the subsequent operation, and finally led to the failure of the well tube in the last period of 40% flow operation. This failure mode agreed with the results of the examination of the rupture surface and a full scale in-water hydraulic vibration experiment.

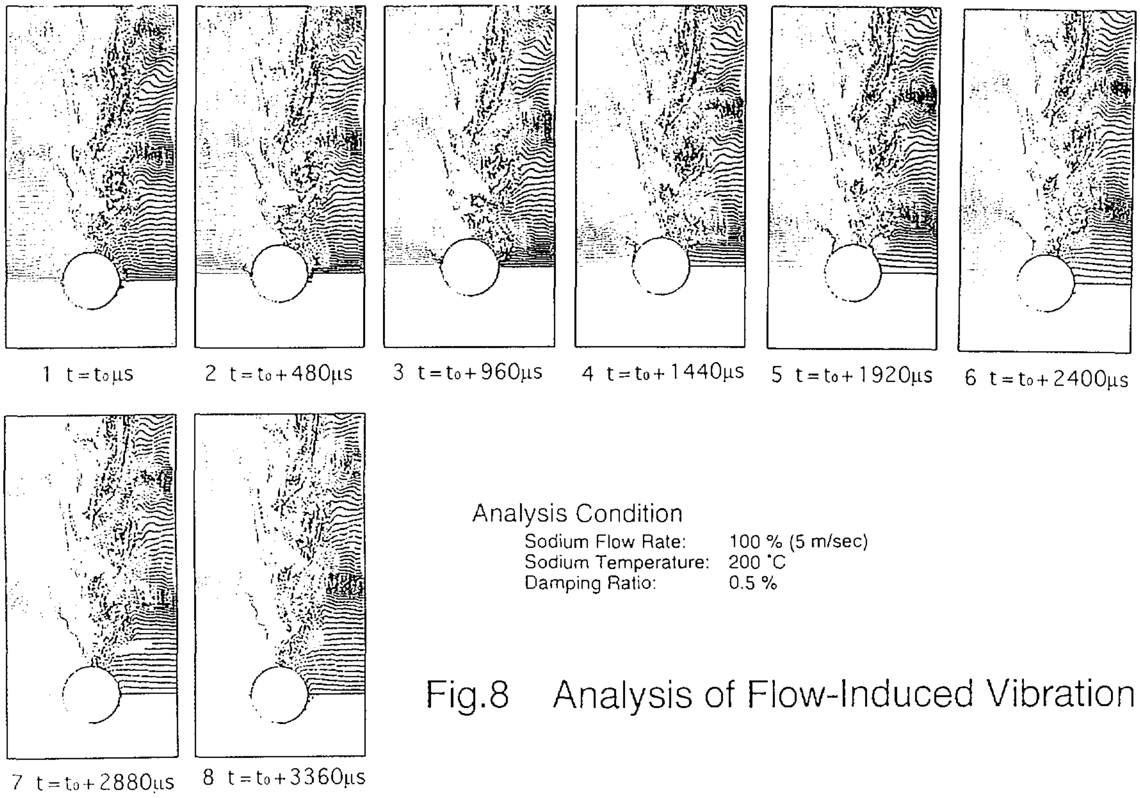


Fig.8 Analysis of Flow-Induced Vibration

The problems were in the design of thermocouple well tube. The designers applied the ASME (American Society of Mechanical Engineers) Performance Test Code, PTC 19.3, where the design rules are provided only for the recommendedtapered well tube to prevent resonant vibrations of the well tube due to vortex shedding. These were inappropriate for the Monju well tube having a local sharp taper (at an angle of 120 degrees). As a result, the vortex induced vibration in the drag direction could not be prevented. Another point was that PNC and fabricators involved did not take account of the issue of the 1991 addenda to the ASME Boiler and Pressure Vessel Code, Section III, Appendix N, the newly published non-mandatory design rules, which includes the prevention of vortex-induced vibrations in both lift and drag direction. An opportunity to make a re-evaluation of the design of thermocouple well tube in the light of this code revision was.

3.6. Operational procedure problems

There were deficiencies in the Operating Manual for the handling of abnormal events and the actions of the operators were not deemed appropriate. Specifically, the problems are as follows ;

(1) The size of the leak should have been recognized early on, and the reactor shut down immediately by a manual trip.

(2) Monitoring of the plant and visual inspections of the leak site were not carried out appropriately.

(3) After the second inspection, an emergency shut down was decided but the action was delayed.

(4) A procedure for the draining of sodium at high temperature (i.e. that does not require a cooling period) should have been prepared.

(5) The ventilation system should have been stopped at an early stage.

(6) All of the operators should have been made proficient in sodium technology with sufficient training.

4. MEASURES AND SOLUTIONS (Fig.9)

On February 9, 1996, the NSB of the STA issued a report[1], which pointed out 14 items problem areas and called for the implementation of safety review on nuclear facilities. PNC carefully reviewed the report and urgently submitted its reply on February 27. On May 23, 1996, the STA issued a consective report[2] on the accident.

4.1. Plant Improvement

All similarly designed temperature sensors in the SHTS will be replaced.

Considering the extensive effects of the sodium fire, all aspects of the emergency operation and leak related equipment will be re-assessed and any required improvements carried out. Specifically, the reactor will be shut down immediately if a sodium leak is confirmed. Improvements will be made to enable quick draining of sodium from the SHTS in the event of a leak. The Operating Manual will also be revised to clarify definitions of leak size, and operator responsibilites and actions. Equipment such as the sodium leak detection system, the fire detection system, the ventilation system, will be reviewed and, if neccessary, improved. New remote monitoring systems such as closed circuit television cameras will also be installed in SHTS areas.

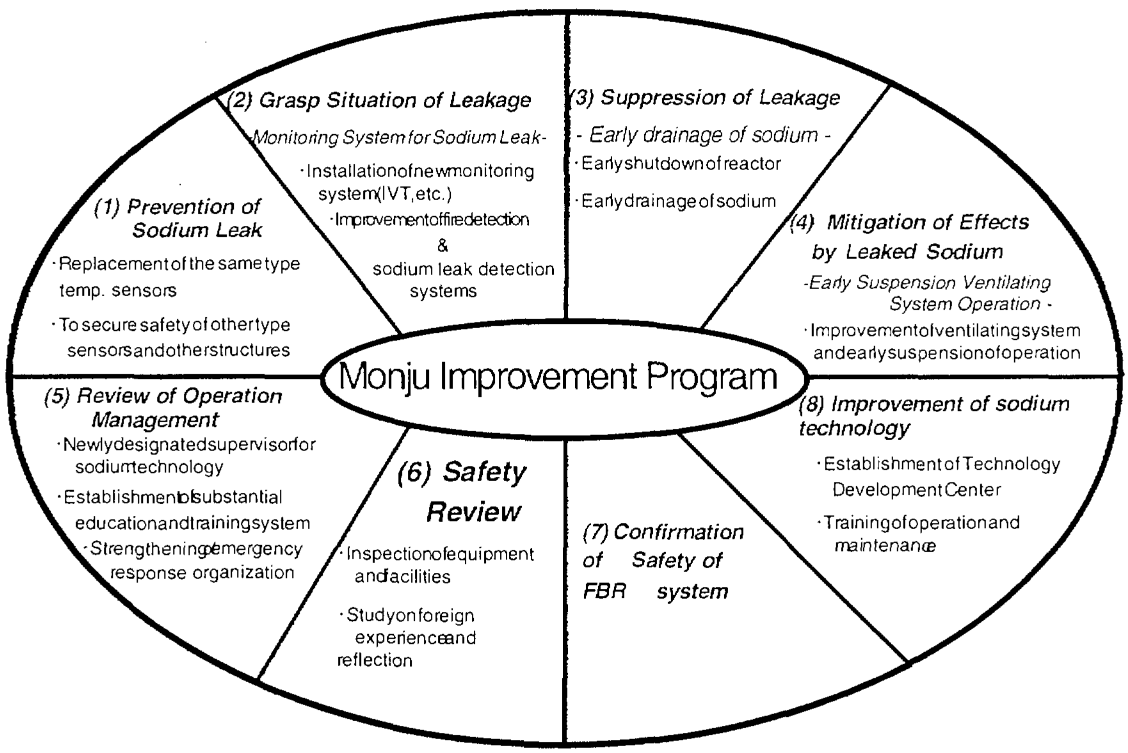


Fig.9 The Monju Improvement Program

4.2. External response at the time of the accident

Considering the delay in initially reporting the accident occurrence, operational procedures have been revised. Under the new procedure, the responsible person at the site should immediately make an initial report.

Thorough practical training will be undertaken, short and effective information routes established, to supply accurate information at the right time.

4.3. Review of Emergency Response Organization

A review of the Emergency Response Organization was carried out. The number of facilities reviewed was 46, including Monju, Fugen, and Joyo. Regulations were revised to speed up the reporting and supply of information.

4.4. Establishment of "technical trust" and "social trust"

The accident poses two sorts of problems: the technical problems associated with a sodium leak and the public confidence issues resulting from PNC concealment of some of the videotape records in the immediate aftermath of the accident. These are two very different problems which must be considered separately. Nevertheless, the concealment of information has detracted from the credibility that had been built up and has been used to ferment misgivings about the development of FBRs.

From the experience of this accident, it is clear that regaining the establishment of "technical trust" and "social trust" are of paramount importance. To tackle the problem of technical trust, specifically in PNC's safe application of sodium technology, the following actions will be taken ;

(1) Establishment and practice of countermeasures
(2) Examination of other facilities
(3) Review of regulations and Emergency Operating Manuals
(4) Review of emergency response organization of each nuclear facility
(5) Newly designated supervisor for sodium technology
(6) Inspection of equipment and facilities
(7) Study of foreign experience

PNC will also carry out complete safety review of Monju. Crisis management information release to the public, and strengthening of communication with local communities will all be addressed. Specifically, PNC actions to regain social trust are as follows ;

(1) Reinforcement of crisis management organization
- Rearrangement and reinforcement of emergency response organization
- Improved training system for operation shifts teams, etc.

(2) Sufficient information release to the public
- Establishment of "Public Information Section" in PNC head office, etc.

(3) Strengthening of communication with local communities
- Start of local round-table meetings
- Investigation of the opinions of general people, etc.

On April 1, PNC set up a Public Information section in PNC's Headquarters. This will further promote the understanding and distribution of information on PNC as a whole and make plans to deal with information distribution. For each plant, a supervisor of information distribution was designated whose aim is to promote the thoroughness, correctness, and promptness of information distribution at each plant.

5. CONCLUSION

With regard to the sodium leak and consequential sodium fire, it was recognized that breakage of relatively small parts attached to sodium pipes, such as the thermocouple well tube, may cause large effects on social acceptance of FBR.

The sodium leak accident revealed that there were problems with the precautions for secondary heat transport liquid sodium systems and that more importance has to be attached to be supply of accurate information. In addition to the investigation and analysis of technical causes for the accident, exhaustive study will be given to the way information should be supplied and responses offered in the event of an accident. It is very much to be hoped that the lessons of this accident will be put to effective use in the progress toward commercial utilization of plutonium under appropriate safeguards.

6. REFERENCES

1. STA / NSB, "Report on the Investigation into the Sodium Leakage Accident at the Prototype FBR Monju of the PNC", February 9, 1996
2. STA, "Report on the Sodium Leakage Accident at the Prototype FBR Monju of the PNC (Interim Investigation Report)", May 23, 1996

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