Leakage of Sodium Coolant from Secondary Cooling Loop in Prototype Fast Breeder Reactor MONJU

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KOBAYASHI, Hideo (Tokyo Institute of Technology)

(Summary)

On December 8th, 1995, a leakage of sodium coolant occurred at the terminal of the thermometer sensor on the secondary sodium cooling loop in the prototype fast breeder reactor MONJU, of Power Reactor and Nuclear Fuel Development Corporation (PNC) in Tsuruga city. The leakage resulted from the break of the thermometer well caused by fatigue due to the fluid vibration. The reactor was stopped manually in response to the alarm of sodium leakage, and the sodium in the loop pipe was fed back to the sodium tank.

The fatigue fracture was attributed to a defective design standard of the thermometer well that had specified that the vibration by cyclic vortex should be evaluated only in the direction perpendicular to the flow.

1. Component

Terminal of the thermometer sensor on the outlet piping of the secondary main cooling loop in the intermediate heat exchanger. The schematic diagram of the equipment, the appearance of the site, and the broken thermometer well together with the route of the leakage are shown in Figures 1, 2 and 3, respectively.

2. Event

Results of fault-tree analysis are as follows;

○ Figure 4 - Fault-tree diagram based on morphology, mechanism, and process of fracture.

Leakage of sodium occurred as a result of a break in the thermometer well. The break point corresponded to a part of the thermometer well where its diameter had been changed sharply. Investigation and observation of the fracture surface confirmed the cause of the break to be a high frequency fatigue due to fluid vibration in the direction parallel to the flow. The direction of the fatigue crack propagation coincided to that of the sodium flow, which had caused the well to vibrate in a direction parallel to the flow. The flow-induced vibration was clarified afterwards as being due to a symmetrical vortex.

○ Figure 5 - Fault-tree diagram based on defective design standard and fabrication of equipments.

Because of a mistake in the design standard, the designer had evaluated only the vibration in the direction perpendicular to the flow that is caused by an alternative vortex. In addition, the shape of the well had been designed to have a part where the direction changed sharply, and a stress concentration was induced at the region of diameter change that caused the fatigue crack.

Results of event-tree analysis are as follows;

○ Figure 6 - Event-tree diagram on the break of the thermometer-well caused by a flow-induced vibration due to a symmetrical vortex.

There are two kinds of flow-induced vibrations that are induced by Karman's vortex row, a vibration in the direction perpendicular to the flow caused by an alternative vortex, and a vibration in the direction parallel to the flow caused by a symmetrical vortex. The relation between the amplitude and flow rate in vibration of the thermometer well is shown in Figure 7. Based on the defective design standard, the designer had evaluated only the former perpendicular vibration in the design of the thermometer well, not the later parallel vibration. However, the vibration in the direction parallel to the flow that was caused by the symmetrical vortex resulted in a high frequency fatigue fracture in the well due to the resonance and the stress concentration. The resulting break in the well caused the leakage of sodium.

3. Course

On December 8, 1995, the nuclear reactor Monju was operated in raising power for the plant trip test, as a part of the 40% output test. At 18:47, an alarm was triggered that indicated a higher than normal temperature of the sodium at the outlet of the intermediate heat exchanger in the secondary loop C. At the same time, the fire alarm was also sounded. After one minute, an alarm indicating a leak of sodium in the secondary main loop C was also triggered. In response to the alarm, operators opened the door of the secondary main loop C pipe work room, where they observed a smoke, in the expansion of the fire alarm. They decided that the smoke and alarms were caused by a leak of sodium, so they tripped the reactor manually at 21:20, and drained the sodium that was in the pipe to the stock tank. An investigation in the pipe work room C confirmed the leak of sodium from the terminal of the thermometer in the outlet piping of the secondary main cooling system for the intermediate heat exchanger.

4. Cause

(1) Defective design standard

The recommended practice for preventing vibration due to Karman's vortex row was introduced into the design standards for decades ago. In 1974, the ASME(American Society of Mechanical Engineers) Standard, which is widely used on all over the world, provided the following regulation about the vibration in the direction perpendicular to the flow caused by an alternative vortex; ASME Performance Test Code, Supplement on Instruments and Apparatus Part 3, Temperature Measurements, 1974.

$$(\text{Frequency of vortex row}) < 0.8 \times (\text{Frequency of proper vibration for cylinder})$$

In addition, ASME added a supplementary regulation about the vibration parallel to the flow caused by the symmetrical vortex; ASME Boiler and Pressure Vessel Code, Section Ⅲ, Division 1, Appendix N-1300, Flow-induced vibration of tubes and tube-banks, 1995.

$$(\text{Velocity of flow}) / (\text{Diameter of cylinder}) < (\text{Frequency of proper vibration for cylinder})$$

In the Japanese version of the standards, the additional regulation about the vibration parallel to the flow failed to be noticed.

(2) Thermometer well with a sharply changing step-wise diameter

Stress concentration at the point where the diameter of the well changed sharply in a step-wise caused the fatigue crack fracture. In order to reduce the stress concentration, it is necessary to take a large radius of curvature at the changing point of the well's diameter. Inspection for the design with the step-wise shaped thermometer well was insufficient.

5. Immediate Action

The following actions were conducted to counter the causes mentioned above.

(1) It was confirmed that the technical information system would be kept up-to-dated, and the newest design standards were consolidated.

(2) The method for examination of the design was improved in order to strengthen the design management, and the outline of the design process was rechecked.

6. Countermeasure

The design standards should be periodically reexamined and updated with the newest technical information. In 1997, the PNC established a design guideline for preventing the flow-induced vibration of the thermometer (PNC TN94 10-97-042). Based on this guideline, the Japan Society of Mechanical Engineers established the guideline for evaluating the flow-induced vibration of a cylindrical structure on piping (JSME S 012-1998) in 1998.

7. Knowledge

○ Lack of collaboration among specialist fields;

The technical specialists designing the structure of a plant such as the Monju belong to three fields of expertise, that is, materials and strength, thermal fluid flow, and vibration. Each specialist restricts his or her job and area of responsibility ito that specialist's own field of expertise. In particular, the specialist fails to make the effort to develop a mutual understanding and exchange of information with specialists from other fields. The mismatching between the specialists fields is an important cause of accidents such as the one described here. A typical example of the importance of collaboration between different specialist field is the evaluation of fatigue fractures due to flow-induced vibration versus those due to thermal stress.

8. Discussion

A vortex is defined as the motion of a fluid to rotate. There are various kinds of vortices. When a spoon stirs water in a cup, vortices are formed behind the spoon. In the case of airplanes and motor vehicles, vortices of air are formed behind their bodies in the same way. Smoke from a chimney or cigarette smoke from a human mouth forms a ring-shaped vortex. The rotation of the screw of a ship forms a spiral vortex. The source of the fluid vibration is the row of vortices

If a physical solid, for example a cylindrical rod exists in a flowing fluid, vortices are formed behind the solid. The same phenomenon occurs when the solid moves in a static fluid. A row of the vortices is most easily formed if the solid has a shape that is symmetric to the flowing direction, and that does not have any sharp point at the rear, such as that of a cylindrical rod (a cylindrical pole).

Behind a cylindrical rod, if the first vortex is formed on the right hand side, the second one will be formed on the left, and the next one on the right, and so on, alternating between left and right (Figure 8). The direction of the vortices in the row on the right hand side is the opposite of that on the left. The vortices of the two rows occur at even intervals, but rather than being aligned, the vortices on the left and right are arranged in a zigzag fashion. The reason for why this phenomenon occurs was first elucidated theoretically by Th. von Karman, so that this phenomenon is called Karman's vortex row.

If velocity of the fluid is V (m/sec) and the diameter of the cylindrical rod is D (m), the number of vortices f (sec-1=Hz) generated per second can be roughly estimated by the following equation;

$$f = 0.2\ V/D$$

The vortices generated on the left and right are unsymmetrical, so the distribution in the velocity of flow is different on the left and on the right. The different distributions of velocity cause different distributions of the hydraulic pressure (Bernoulli's theorem), so that a composite force is generated by hydraulic pressure in the direction perpendicular to the flow. Alternative vortices on the left and right cause the alternative composed forces by hydraulic pressure, so that a vibrating force having the same frequency f (Hz) acts on the solid. The solid vibrates in the direction perpendicular to the flow (left and right), that vibration called the fluid vibration. Because there is also a difference in the distribution in flow velocity in front of the solid and behind the solid, the solid also vibrates in the direction parallel to the flow. The trembling of reeds in a river is caused not always by the wind but also by the fluid vibration, especially in the case of the shaking of the heads of the reeds. Fluid vibration causes damage in the form of noise and fatigue. A vibrating bamboo rod makes a sound. High tension wires make sound as a result of vibration induced by the wind. The boughs and twigs of trees wail violently in a typhoon. A twig with a diameter D=5 mm vibrates at f=400Hz in response to a strong wind of V=10m/sec, causing a wave of air (an acoustic wave, sound) to vibrates the human eardrum making a gentle sound. A typhoon wind of V=30m/sec makes a shrieking sound of f= 1200Hz. The frequency given by a row of vortices coincides with the proper frequency of the solid to produce the resonance and to generate a strong sound. This is the same principle that causes the strings of a kite to moan. A solid experiencing sympathetic vibration suffers from fatigue and failure easily.

Damage from fluid vibration occurs in high tension wires, chimney stacks, the supports of a bridge, hydraulic turbines, pumps, screw of a ship, and the periscope of a submarine. The fundamental countermeasure is to avoid the sympathetic vibration that gives rise to resonance, by raising the frequency of the proper vibration of the solid over the frequency of the row of vortices. A large diameter raises the former, and lowers the latter, so increasing the diameter of the solid is a simple solution. Another solution is to break the row of vortices by changing the shape of the solid, such as winding a rope around a cylindrical pole, attaching a fin at the rear of the solid, to streamlining the cross sectional shape, and so on.

On December 8, 1995, a leakage of sodium coolant occurred in the secondary main cooling loop of the prototype fast breeder reactor MONJU. The leakage was caused by a break in the thermometer well that had been inserted into the pipe. The break was caused by fluid vibration (Figure 3).

The flow of sodium makes two rows of vortices behind the well, causing the well to vibrate in the direction perpendicular to the flow. This vibration is called fluid vibration. The frequency of the vortices row is very high. For example if flow's velocity is 5 m/sec and the diameter of well is 10mm, then the frequency is 0.20×5／0.01=100Hz. The total number of cycles is, therefore, 8.64×106=107 per day. If the amplitude of the vibration, i.e. the amplitude of the stress on the well is small, fatigue failure can occur easily. Of course, if the frequency of the vortices row coincides with the proper frequency of the well, the amplitude of the stress on the well will increase by resonance causing rapid breakdown in an extremely short period of time.

There are two difficulties in evaluating fluid vibration fatigue. One is the existence of the two directions in the vibration, that is, the well vibrates not only in the direction perpendicular to the flow but also in the direction parallel to the flow. The condition below can stop resonance from occurring with vibrations perpendicular to the flow.

(Frequency of vortex row) ＜ 0.8(Frequency of proper vibration for the well)

However, even with a frequency of vortex row that is enough to avoid resonance with vibrations perpendicular to the flow, resonance can occur with the vibration in the direction parallel to the flow. In order to avoid this resonance, the additional condition below is necessary.

(Velocity of flow)／(Diameter of the well)＜(Frequency of proper vibration for the well)

Furthermore, the vibration under a low frequency of the vortex row continues to vibrate the well in the same direction to the flow, so that it causes the fatigue failure sooner or later. The fracture surface shown in Figure 9 shows that the vibration in the direction parallel to the flow caused the well to break by the fatigue failure.

Another problem is the material of the well. The relation between the stress amplitude of the well materials and the number of cycles to failure for the well (S-N curves) is shown in Figure 10. The well material was an austenitic stainless steel, which has a lower strength against high frequency fatigue than carbon steel or low alloy steels, and shows a monotonic decreases in strength without any fatigue limit. Therefore, fatigue failure will always occur no matter how small the stress amplitude is. The problem is that we do not currently have data for S-N curves where the number of cycle to failure is 10^{7}～10^{11}, which is the range that corresponds to objects subjected to fluid vibration fatigue.

Could we not have predicted the fluid vibration fatigue on the well? If the diameter of the well is increased, the frequency of the row of vortices row will decrease so that the proper frequency of the well should increase resulting in avoiding the resonance, and the stress amplitude of the well decreases so that the number of cycles to failure should increase. Furthermore, if the radius of the curvature at the part of the well that has a sharply stepwise changed diameter is increased, the factor of the stress concentration will decrease and the number of frequency to failure will increase. The shape and dimensions of the well for the JOYO, an experimental type fast breeder reactor, which had not caused any problems, had been changed in many bad ways in the design for MONJU. It can't be helped that insufficient measures against the fluid vibration fatigue were called to account.

Some accidents caused by the fluid vibration fatigue have occurred previously in the nuclear power field. In 1983, a similar accident in a thermometer well for a re-circulation pump was experienced in a nuclear reactor overseas. In 1991, the fracture of the heat exchanger tubes in the steam generator of Mihama No.2 reactor of Kansai Electric Co. was also attributed to the fretting fatigue caused by the fluid vibration. The Kashiwazaki-Kariwa nuclear reactor No.6 and 7 generators, which are improved type boiling water reactors, constructed by Tokyo Electric Co. have re-circulation pumps inside the pressure vessel of the nuclear reactor (internal pump type). Because of concerns regarding fluid vibration fatigue from unpredicted flows of fluids, experiments were conducted for a long period in order to assess the reliability. The knowledge and experience gained from those results, however, were not reflected in the design of MONJU.

There are not a few accidents by the fluid vibration fatigue in other field except the nuclear reactor. In Europe, there are many accidents caused by fluid vibration fatigue in stacks. There are fewer accidents involving stacks in Japan, because the strict regulations for the earthquake-proof designs result in stacks that are built with strong structures. However, there are no regulations regarding earthquake-proof design of the thermometer wells. But overlooking and miscalculations for events to be supposed as a matter of course are attributed to the fault of the engineers.

9. Information Source

(1) Materials in Research committee to utilize fault knowledge (No.4), Leak of sodium from secondary loop in prototype fast breeder reactor MONJU, Power Reactor and Nuclear Fuel Cycle Development Corporation, December 12, 2000.

(2) Hideo Kobayashi: Fluid Vibration, High Pressure Gas, 33-9(1996), 755.

(3) Hideo Kobayashi: Fluid Vibration Fatigue, High Pressure Gas, 33-11(1996), 950-951.

10. Primary Scenario

01. Misjudgment
02. Narrow Outlook
03. Lacked Standard
04. Planning and Design
05. Poor Planning
06. Bad Design
07. Thermometer Well
08. Bad Event
09. Thermo-Fluid Event
10. Fluid Event
11. Fluid Vibration
12. Karman's Vortex
13. Vibration Parallel to Flow
14. Failure

15. Fracture/Damage
    16. Fatigue
        17. Crack
            18. Penetrate through Wall Thickness
                19. Leak of Sodium

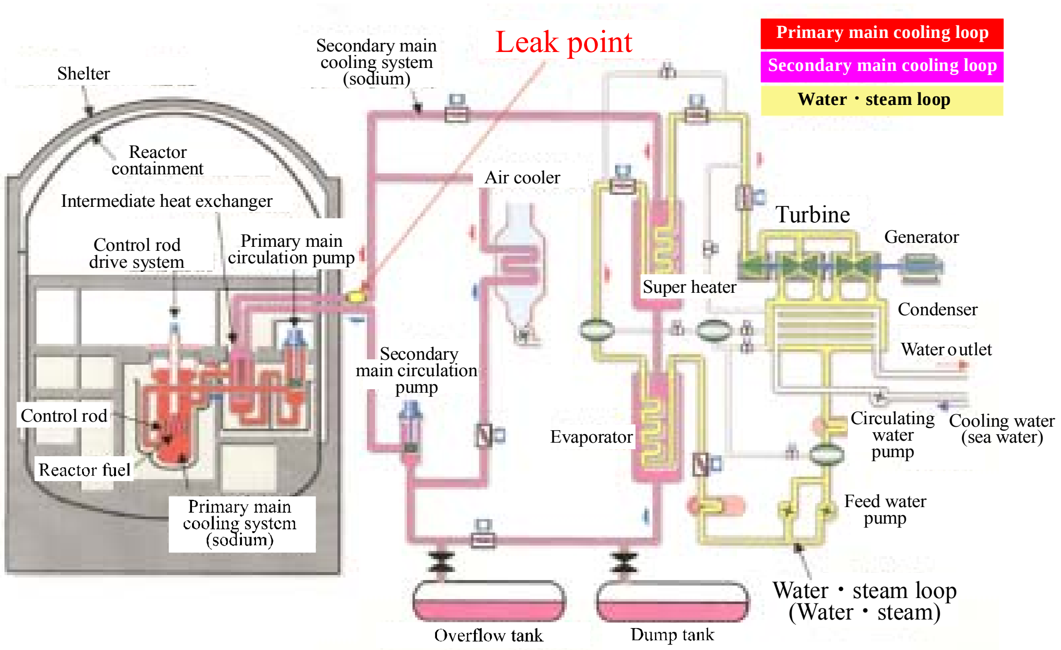

Fig. 1　Schematic diagram of reactor.

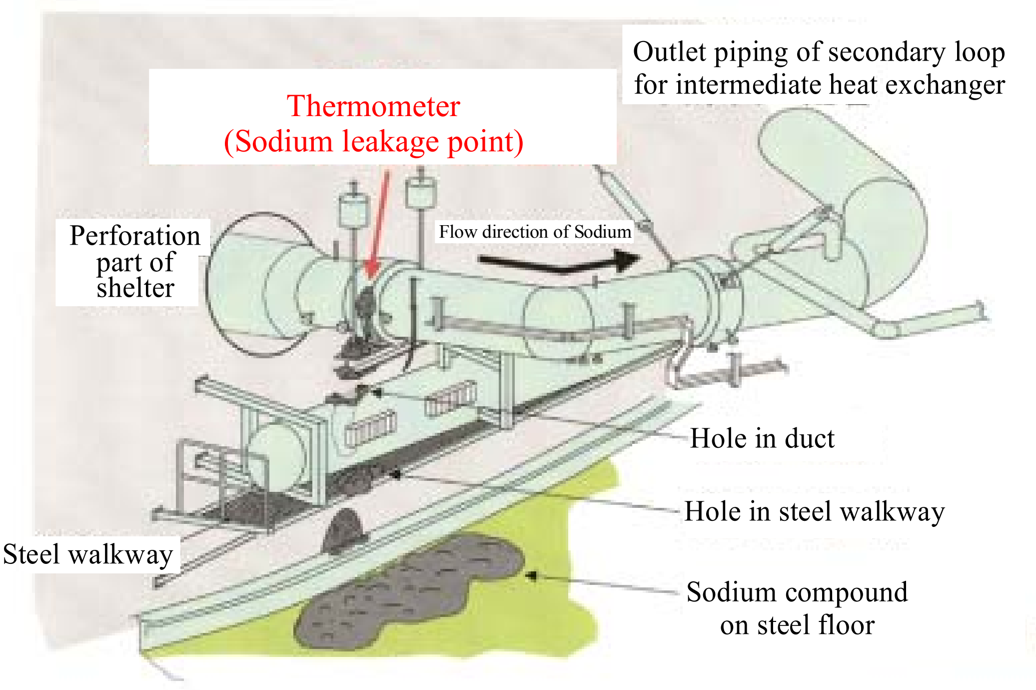

Fig. 2　Appearance of leakage point of sodium.

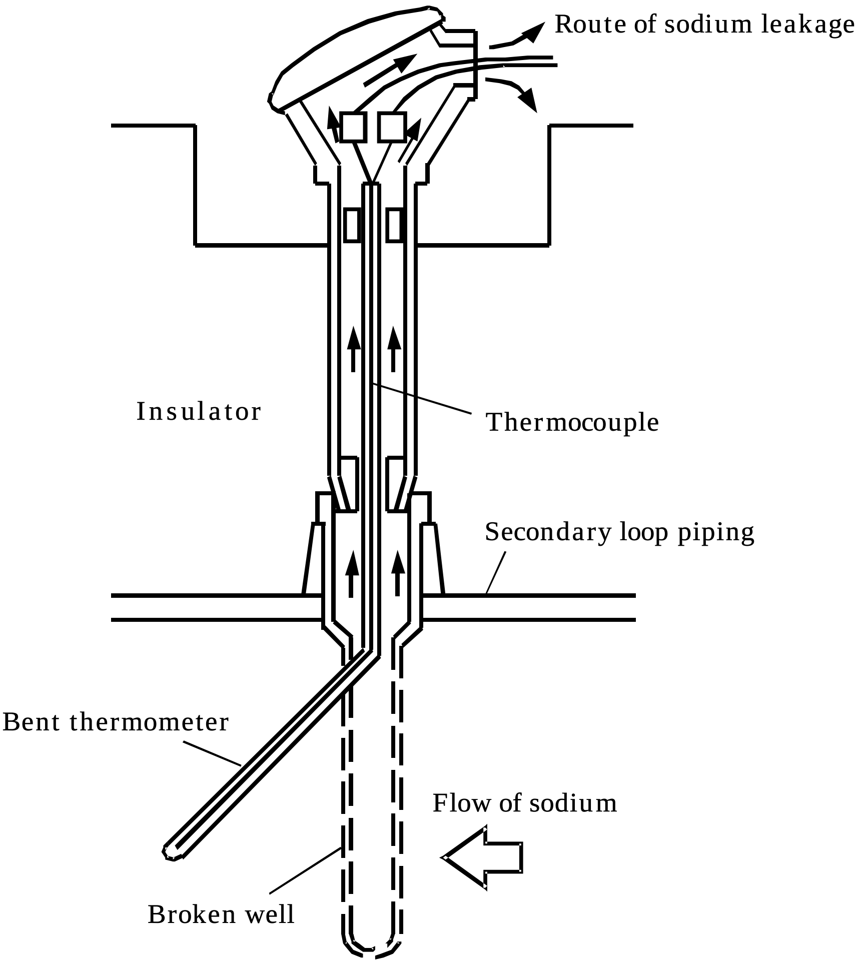

Fig. 3 Broken thermometer well and leakage route of sodium.

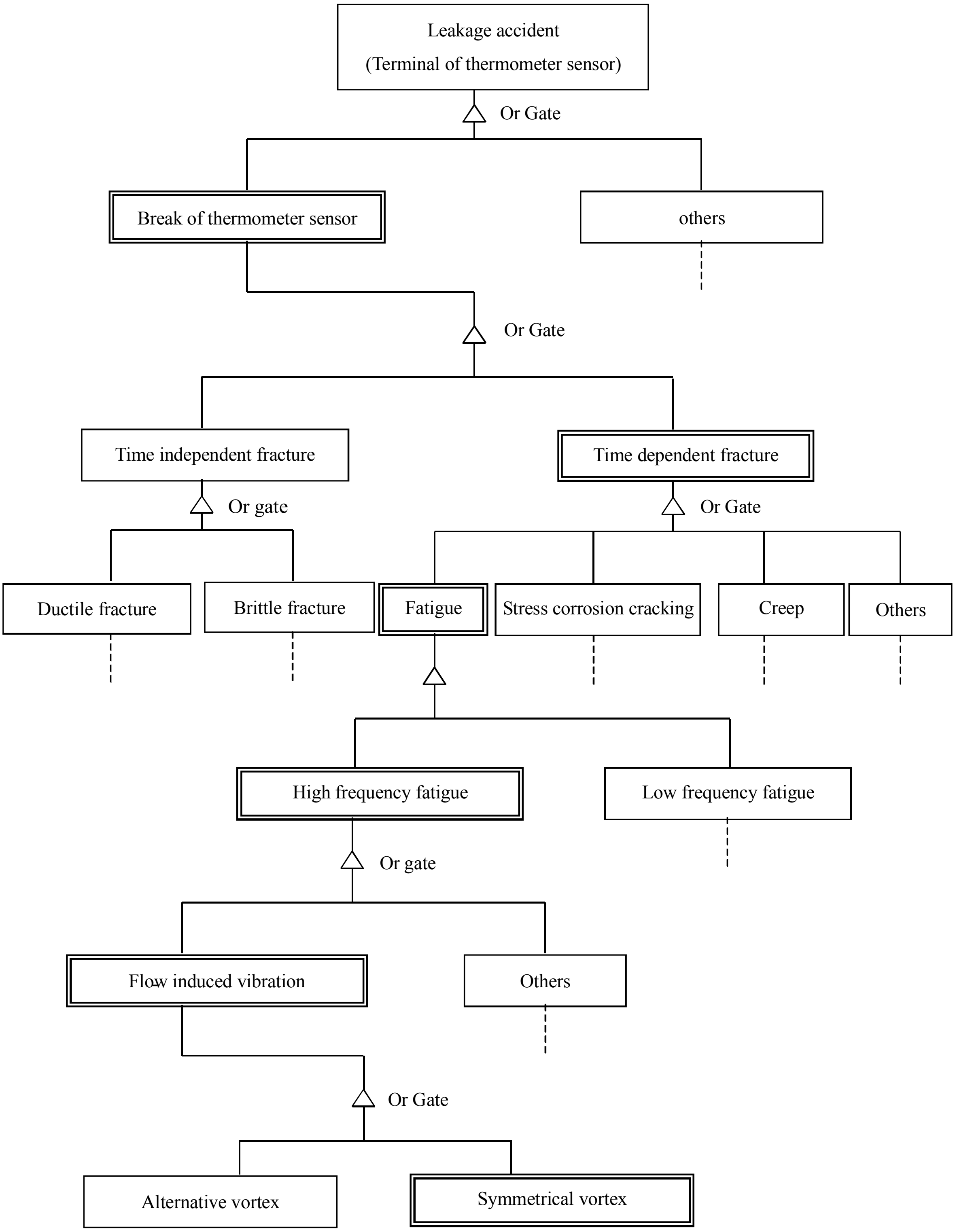

Fig.4 Fault-tree diagram based on morphology, mechanism, and process of fracture.

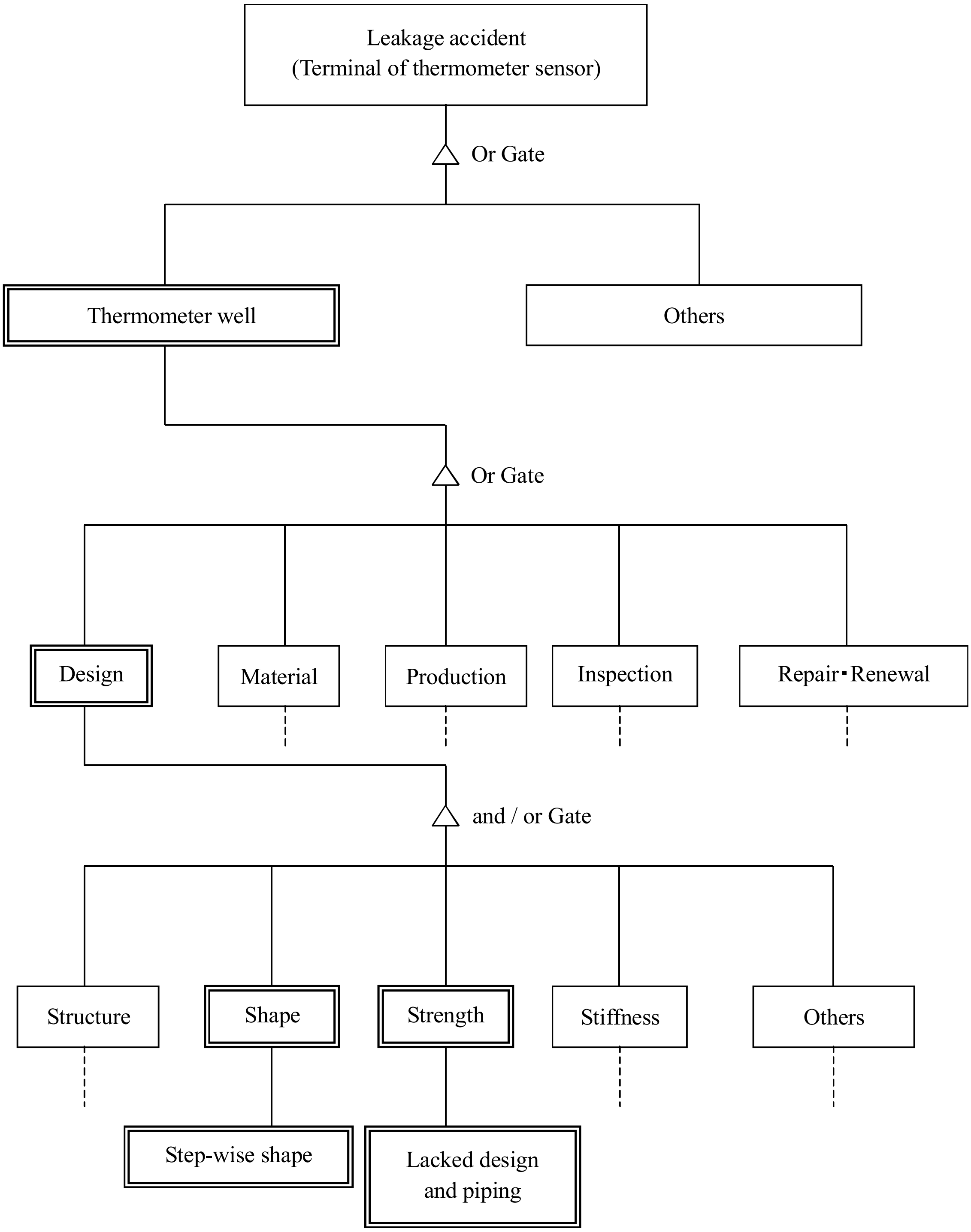

Fig. 5 Fault-tree diagram based on wrong design and fabrication of equipments.

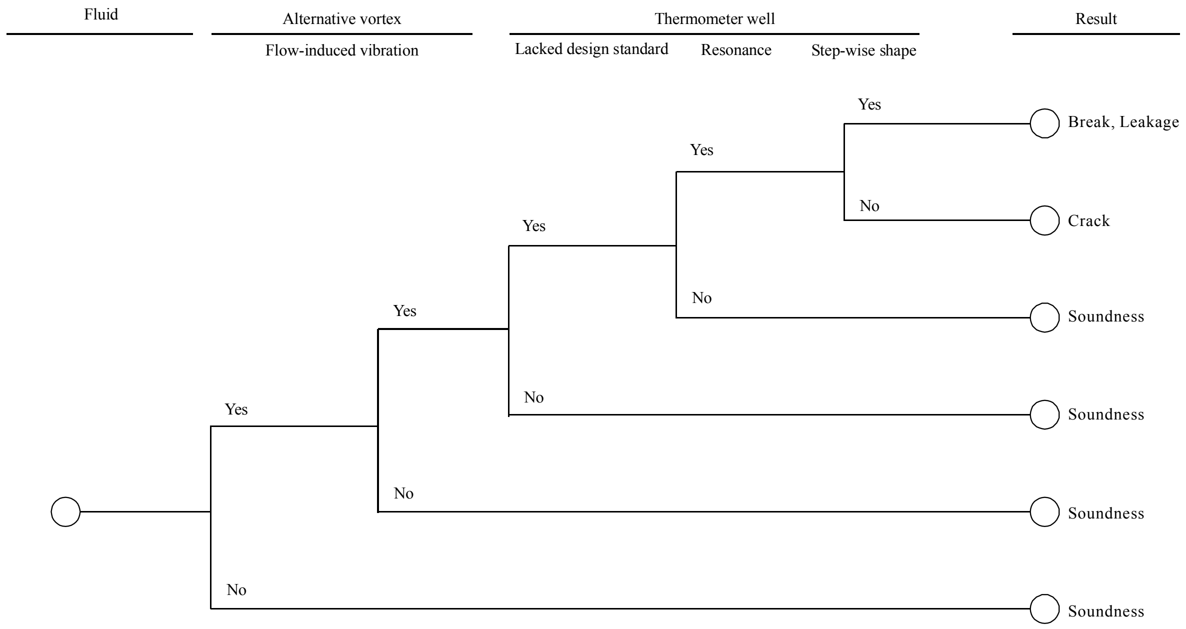

Fig. 6 Event-tree diagram on the break of thermometer-well caused by a flow-induced vibration due to a symmetrical vortex

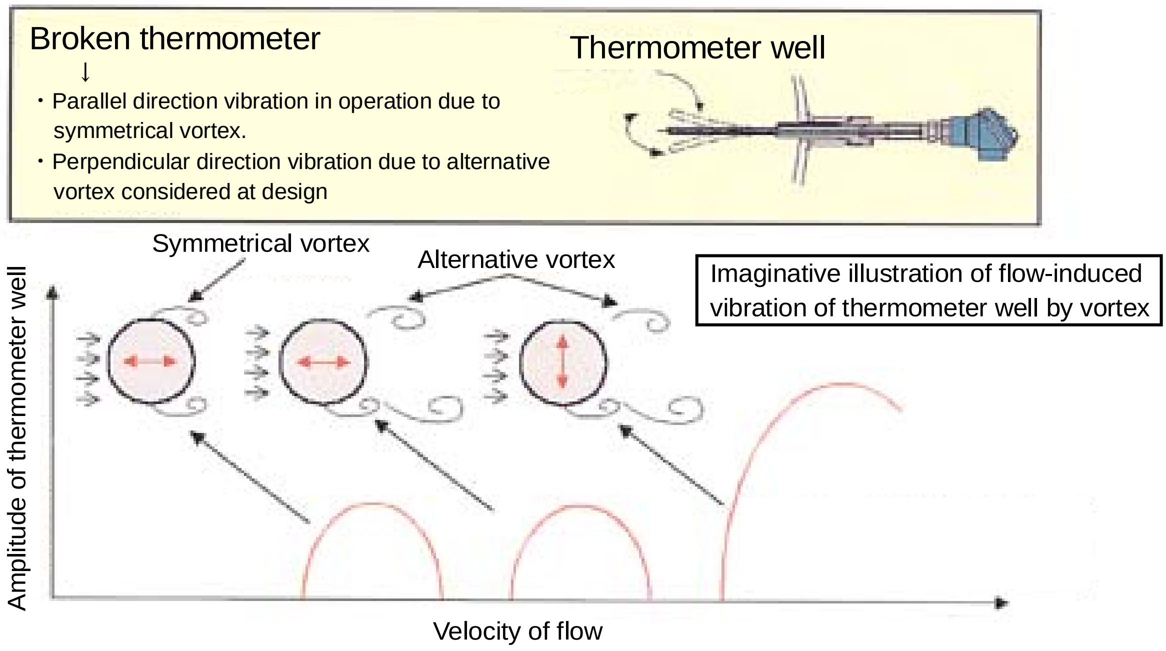

Fig. 7 Relation between amplitude and flow rate in vibration of thermometer.

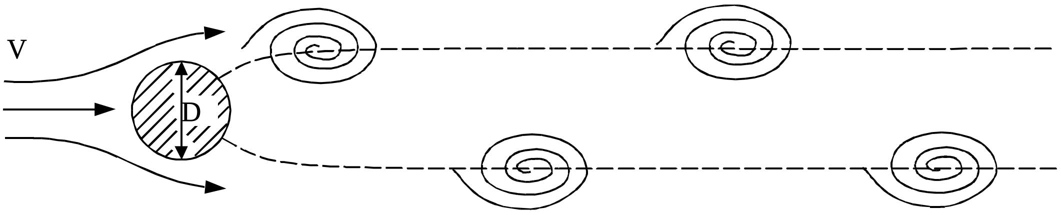

Fig. 8 Karman’s vortex row

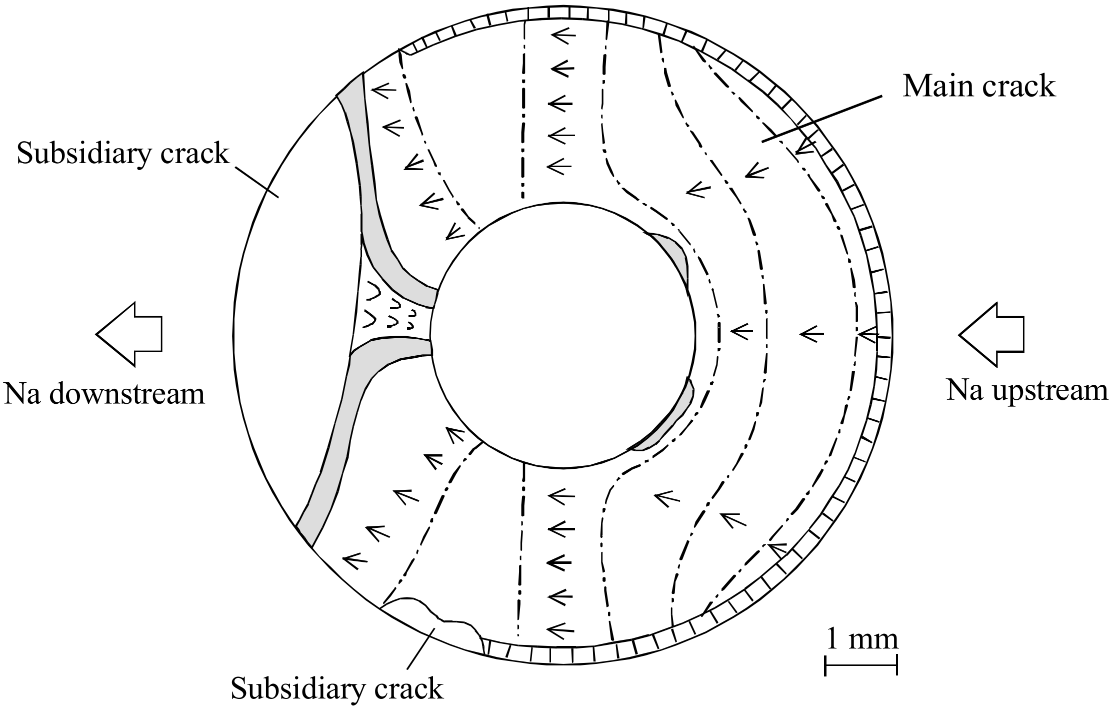

Fig. 9 Fracture surface of well and direction of crack .

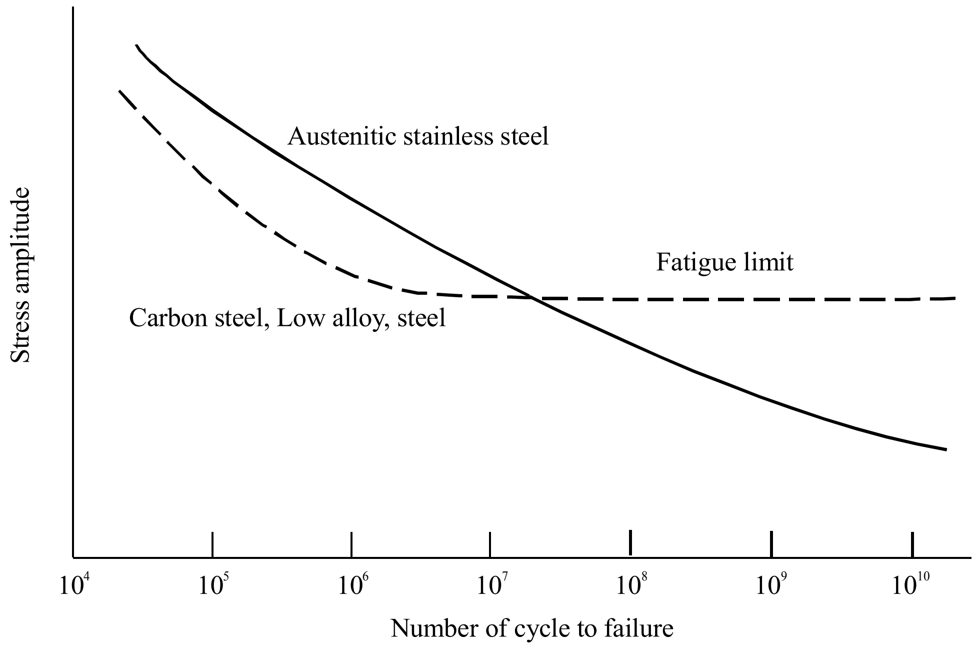

Fig. 10 S-N curve of material (log-log plot)