Leak Detection and Location in MONJU Steam Generators

T. SAITO*
T. KOSUGI*

Abstract

Leak detection system of MONJU steam generator depends mostly on in-sodium hydrogen detectors. The requirements on leak detector performance is determined from the point of view of protecting tube leak propagation due to wastage, and the process of determining the performance is shown briefly.

Research and development activities on in-sodium hydrogen detectors are described and the specifications of leak detectors for MONJU are also presented.

In-cover-gas hydrogen detector and acoustic detector are under development.

Research and development activities on the leak location after steam generator shutdown by such methods as an electromagnetic method and ultrasonic method are described. The results of the research and development work on inserting the test probes into tubes are described also.

An idea for finding the condition of tubes in the neighbourhood of the leak is also presented.

---

* Power Reactor and Nuclear Fuel Development Corp.

Introduction

Considerations on water leakage from heat transfer tubes are important in improving the plant availability of LMFBR steam generators. When a leak occurs, it must be detected as soon as possible and measures have to be taken to protect leak propagation. Later it is necessary to find the leak location as well as to examine the damage of surrounding tubes in order to take appropriate measures to bring the plant back in operation. In case of a small leak the location of leakage can not be easily identified, because the self plug is likely to occur depending on the shutdown sequences.

So, careful shutdown sequence has to be selected for smooth reoperation.

On the other hand, small leak may grow up to middle leak or large leak due to self wastage if protective actions are not taken. If any protective actions are not taken for a long time, damage will be extended.

In this paper, leak detection and location method on MONJU steam generator system are presented including their research and development activities.

1. Leak detection during operation

Water/steam leak from a heat transfer tube has a significant probability of damaging adjacent tubes by wastage. Failure time of adjacent tubes would be predicted based upon the equations of wastage rate which were established by many leak simulation experiments.[1)]

As a heat transfer tube failure affects the plant operatability and economy, it is necessary to limit the damage as small as possible. Extent of the influence depends on the size of initial leak hole. At present, leak phenomena can be classified for MONJU steam generators as Table 1-1.

For each of these leak rates, it is necessary to select proper detectors to prevent the damage of steam generator or propagation of leaks to adjacent tubes.

An example of the performance curve of MONJU leak detector is shown in Fig. 1-1.

In general, in-sodium and in-cover-gas hydrogen detector are effective in the range of micro leak or small leak, cover gas pressure detector is effective in the range of intermediate leak, and rupture disc bursting detector or pressure detector in pressure relief system is effective in the range of large leak.

During the startup operation of steam generators, there are high hydrogen background in sodium. Hydrogen gas is initially generated in the water side of tubes by tube wall corrosion, and is permeated through tube walls. At this stage, oxygen meter is effective, though it is not always necessary for MONJU steam generators.

In case of tube leak occured at upper part of steam generators, in-cover-gas hydrogen detectors will be effective owing to short transport time of hydrogen to detectors.

1.1 Leak detector performance

Leak detector performance is evaluated from the point of view of protecting tube failure propagation due to wastage.

Basic flow of the analytical evaluation is shown in Fig. 1-2.

The time taken before appropriate action to protect tube failure propagation by wastage due to initial small leak in steam generators, is the sum of the following items:

a) Time for the reaction products by small leak to increase up to the detectable concentration at the leak location.

b) Time for the reaction products to transport to the detector location from the leak location.

c) Response time of the detector itself.

d) Time to the initiation of shutdown action of steam generators after judging the detector signal.

e) Time for the steam generator pressure to decrease by steam dumping down to almost no wastage pressure.

Detector locations in the secondary circuit of MONJU are shown in Fig. 1-3.

Effects of the major parameters on leak detector performance are schematically shown in Fig. 1-4.

1) Comparison between initial operating condition and normal operating condition

As hydrogen permeation rate through tubes at the initial operating condition is much higher than that of the normal operating condition, back-ground hydrogen concentration is higher at the former condition. So, the curve of the leak detection time tends to shift to right hand side.

2) Comparison by power level

High power level means large sodium flow rate. So, the hydrogen gas transport time to detector is shortened at the high power level. Leak detection time tends to shift lower at higher power level.

On the other hand, hydrogen concentration decreases with increasing power at the same leak rate, and the curve of the leak detection time tends to shift to the right.

The curve of the leak detection time tends to move away from the tube failure propagation region on the combination of large leak rate and high power level and also of small leak rate and low power level.

3) Comparison by leak position

Hydrogen transport time to detector becomes shorter with the leak position becomes lower in steam generators, the curve of the lead detection time tends to move lower.

Hydrogen concentration in sodium increases more rapidly at the lower leak position than upper position, because the hydrogen gas dissolves easily into sodium at the lower sodium temperature.

So, the curve of the leak detection time tends to move to the left and tends to move away from the tube failure propagation region.

On the other hand, as the wastage time increases as the sodium temperature decreases, the curve of the allowable wastage time tends to move to upward at the lower leak position in steam generators.

4) Comparison by sensitivity

Lower limit of the detectable leak rate extends to smaller leak rate if the detector sensitivity is improved.

So, the curve of the leak detection time tends to move to left hand side as the improved detectors are used.

5) Comparison by steam generator type

Vertical movement of the curve of the leak detection time depends on the time for the sodium to pass the steam generators. So its horizontal movement depends on the sodium flow rate. The curve of the allowable wastage time depends on tube materials and sodium temperature at the leak position.

	EV	SH
tube material	2 1/4 Cr-1Mo	SUS-316
sodium temperature	low	high

1.2 Hydrogen detector

1.2.1 Research and development targets of PNC in-sodium hydrogen detectors

The in-sodium hydrogen detector was designed by PNC to have the functions as follows:

a) To have a capability of water/steam leak detection

b) To have a capability of hydrogen concentration detection

c) To be made compact

d) To provide the built-in calibration method with high accuracy

e) To make it handling easily.

Another purpose of developing the in-sodium type hydrogen detector is to establish the suitable design method of the detector for operating conditions of all ranges.

1.2.2 R&D history on hydrogen detectors in PNC

a. Basic R&D

In order to determine the most suitable sensor, the PNC-MAPI type in-sodium hydrogen detector was designed and installed in SWAT-2 test rig to obtain the sensitivity and response charactristics at the small leak sodium-water reaction test.

This detector is equipped with a mass spectrometer and an ionization gauge (Bayard-Alpert gauge) and a sputter ion pump as the sensors.

By the water injection into sodium in the rig, the response characteristics of the sensors were found as follows.[2)]

(1) The mass spectrometer showed very good sensitivity but the worst stability.

In addition, the device itself is somewhat large and complicated.

(2) The ion pump can be used as evacuating device as well as sensor. When used as the sensor, it is more stable but considerably less sensible than the mass spectrometer.

However, it was indicated that the sensitivity of ion pump would be much improved when it was used under a suitable design condition.

(3) The ionization gauge showed the best stability among them and was as sensible as the mass spectrometer.

From these results, it was determined to adopt an ion pump and an ionization gauge and to abandon a mass spectrometer as sensors for the in-sodium hydrogen detectors to be developed in future.

b. Establishment of design method

PNC in-sodium hydrogen detectors are required to have the high reliability, stability, sensitivity, durability, operability and capability of measurement of the wide range concentration.

To satisfy these requirements, many items were investigated as shown in Fig. 1-5.3)

Two different types of PNC in-sodium hydrogen detector were developed, and the total of 8 units were so far manufactured.

Table 1-2 shows the specifications for type I hydrogen detector. Two different vacuum systems, called Mark I and Mark II, were fabricated. They have the same specifications except the nickel membrane area and the bakeout conditions of the vacuum system.

Table 1-3 shows the specifications for type II hydrogen detector.

The type II hydrogen detectors were improved from the type I detector to some extent.7)

The statically and dynamically measuring chambers are separated from each other in the vacuum system, so that the static and dynamic modes of measuring operation can be made in the same time and independently. So the function of leak detection is not lost also during the static equilibrium pressure measurements for hydrogen detector calibration.

c. Experimental investigation of design method

Each type of detectors was installed at SWAT-2 rig, and response characteristics for sodium-water reaction were tested.

Evaluation tests of leak detection system were scheduled and conducted also at 50 MW steam generator test facility.

d. Long term performance test

Five detectors were installed in some sodium loops at PNC OEC, and long term effects are being investigated.

e. Time dependent characteristic test of ion pump

Tests for the next objects are under way at present.

(1) To establish time dependent characteristics of an ion pump exhausting speed.

(2) To establish time dependent characteristics of an ion pump noise.

(3) To confirm the effects of a recovery process on exhausting speed and noise.

1.2.3 Features of PNC designed in-sodium hydrogen detector

PNC type-II in-sodium hydrogen detector has been selected for MONJU steam generators at present.

A special feature is that the vacuum system have two separated chambers. (See Fig. 1-6)

Left side chamber is called "dynamic chamber", and is composed of Ni membrane, ion pump, ultra high vacuum gauge and their connecting vacuum piping. Right side chamber is called "static chamber", and is composed of Ni membrane same as that of dynamic chamber and Schultz gauge for measuring static equilibrium pressure.

To conduct the evacuation of static chamber, both chambers are connected with each other by opening two vacuum stop valves.

Sodium is heated up to 500°C through an economizer which have an electric heater immersed in the sodium. Sodium is pumped out by an electro-magnetic pump through half-inch piping. Sodium flow is separated by a distributor, changes the direction at the inlet of Ni membrane, cooled down by an economizer and back to the main loop through electro-magnetic flowmeter. Outer diameter at the location of the economizer is 34 mm, total length is 1.5 m.

Installations of PNC designed in-sodium hydrogen detector is shown in Photo 1-1.

1.2.4 In-cover-gas hydrogen detector

The detector itself is same nickel membrane type as in-sodium detector, and the additional elements which are needed in order to use as the in-cover-gas detector are connecting pipes of inlet and outlet of the detector with the cover gas area of steam generator vessel.4)

Specifications of cover gas hydrogen detector are shown in Table 1-4.

Schematic diagram of Ni membrane type cover gas hydrogen detector is shown in Fig. 1-7.

1.3 Acoustic detector

Acoustic detectors which measure the sound generated by the leak of water into sodium, has the advantage over the concentration monitor type detector because of its essentially zero response time.

In-sodium hydrogen detectors have a weak point in response time because of the transport time of hydrogen from a leak point to the sensor.

Research and development of acoustic detectors are being proceeded for the target as follows.

(1) Attain high reliability of leak detection system using acoustic detector together with Ni membrane type leak detectors.

(2) By locating the leak point using the acoustic detector during operation, maintenance of leaked tube will be conducted easily after plant shutdown.

From several basic R&D activities, a little knowledge on acoustic detection methods were obtained.5)

Sound of sodium-water reaction have same kind of generation mechanism and frequency spectrum as the water boiling sound in tubes which is the major element of background noise in steam generators. Based on this fact, high grade signal analyzing techniques will be required for judging the water leakage.

Magnitude of acceleration was about 0.2 m/s^2 at the leak rate of 0.1 g/s by using the wave guide installed at the shell.

This is expressed in next relation.

$$\mathrm{Acc} \propto \mathrm{LR}^n$$

where Acc = acceleration of wave guide

LR = leak rate

n = constant (1/3 or 1/2)

Though, there is no inherent peak frequency, there is random frequency of wide range or narrow range.

Shape of the spectrum does not change so much by leak rate or sodium temperature.

Shape of the spectrum of sodium-water reaction sound is similar to that of the gas injection sound into sodium or water.

Example of simulation experiment on location of sound in steam generators is as follows.[6)]

Block diagram of the experimental apparatus are shown in Fig. 1-8.

Simulated tube assembly is installed in a stainless steel vessel which is 130 cm dia. and 120 cm depth.

Assembly is composed of 12 layers (inner dia. = 20 cm, outer dia. = 108 cm, height = 65 cm, pitch = 4 cm, tube dia = 25 mm).

Four wave guides are installed in the vessel.

At the top of each wave guides, acoustic transducers are mounted, and detect the acoustic signal. Wave guides is 103 cm length, 12.5 mm dia.

Experimental result shows that the error of the location is 7.6 ± 4.7 cm.

1.4 Operating procedure after leak detection

When a hydrogen detector alarms the increase of hydrogen concentration in sodium, operator must try to find the cause of it. At the present status, it is not so easy to decide as the water leakage from a steam generator tube by only a hydrogen detector signal. Because, hydrogen concentration increases by cold trap malfunction or plant operating condition changes without any water leakage from steam generator tubes. Therefore, it is important to present operators the increasing rate of hydrogen, oxygen concentration, flow rate, temperature of sodium and sodium level changes.

After confirmation of water leakage, operator stops the water supply and blowdown the steam from affected steam generators.

If steam pressure decreased to near the sodium side pressure, nitorgen gas has to be supplied into steam generator tubes so as to protect the sodium entering into tubes.

Then, it is helpful to find the location after shutdown.

It is considered that the sodium temperature must be kept constant for a while to avoid the self-plugging under the sequence of shutdown. And, holding time of sodium temperature has to be selected carefully on the basis of research activities in future.

1.5 Determining the condition of tubes in the neighbourhood of the leak

In-sodium or in-cover-gas hydrogen detector can serve the information for assessing the time history of leak rate in case of small leak in a steam generator.

Number of failed tubes, however, can not be judged directly from the signal.

If the conditions of tubes in the neighbourhood of the small leaks are obtained previously based on many simulated wastage experiments, it is considered that the time history of the hydrogen concentration gives us the information for judging the effect to the surrounding tubes.

Effects of small leak to the surrounding tubes depend on the following items.

- wastage rate (target wastage, self wastage)
- sodium temperature
- sodium flowrate
- leak size
- tube-to-tube distance
- leak direction
- tube layout
- tube material, outer dia. and thickness
- shutdown time

Considering these items, it is considered that we can estimate the time sequence of leak propagation theoretically.

Finaly, the condition of tubes in the neighbourhood of the leak can be defined after inspection.

Fig. 1-9 shows the flow diagram for the determining the condition of tubes in the neighbourhood of the leak.

2. Inspection and location of damaged tubes

2.1 Volumetric examination

Application of visual examination for heat transfer tubes of "Monju" steam generator has to be limited to specific portions such as downcomer tubes by its structural limitation. So volumetric examination is one of the most important ways for in-service inspection of heat transfer tubes and inspection of damaged tubes.

Eddy current and ultrasonic methods had been applied and now are under investigation. The insertion of test probes into tubes is necessary due to the obstruction of access from outer surface by tube supports and is substantial problem to be solved because of the difficulty due to the complicated configuration of helical coil tubes.

The methods of volumetric examination and insertion of the probes into tubes are described in the following.

2.1.1 Eddy current method

Eddy current method is effective for the detection of flaw and leak location of heat transfer tubes in steam generators by the reasons shown as follows:

a) Good detection performance for austenitic stainless steel tubes used for "Monju" superheater.

b) Not require so strict accuracy for probe position in tubes as ultrasonic method.

c) Not take long time for inspection because of the permission of high speed movement of probe in tubes.

But there is one problem with eddy current method. Detection performance for tube wall thinning on the outer surface is low, because the tube material to be used for "Monju" evaporator is 2 1/4Cr - 1Mo steel. The results of performance tests for the feasibility of eddy current method for magnetic material are described.

(1) Theory

For the detection of flaws at tubes from the inner surface with eddy current method detection performance should be equal on the outer and inner surface of tubes.

In general eddy current attenuates sharply as it passes through the tube wall in the direction of wall thickness because of the surface effects. The degree of attenuation depends on the resistivity, permeability of the material and the frequency of magnetic field to be applied to induce eddy current.

2 1/4Cr - 1Mo steel has relative permeability of $\mu s = 200$ and resistivity of $\rho = 40\ \mu\Omega\cdot cm$. Fig. 2-1 shows the attenuation of eddy current through the wall for 2 1/4Cr - 1Mo steel.

Fig. 2-2 shows the effect of permeability and frequency of eddy current on the penetrating depth, at which attenuation of eddy current becomes 37% of that on the surface.

It is recognized from this figure that the frequency of alternating magnetic field should be less than 500 Hz when tubes of 3.2 or 3.8 mm thickness are to be inspected by this method.

(2) Methods and test results

The configuration of test probe is shown in Fig. 2-3. The structure and dimensions of the candidate probe was selected by the evaluation of measured probe coil impedance of various types. A lot of test pieces with many kinds of simulated flaw and tube conditions shown in Fig. 2-4 were examined.

Fig. 2-5 shows the patterns of the signals induced by the tube flaws. The signals, as shown in the charts, have "8" shaped slopes in amplitude. Test results show the tendency that the amplitude varies mainly according to the volume of the flaw and the slope changes with the flaw depth. Fig. 2-6 and Fig. 2-7 show the relationship between flaw depth and signal phase whose variation is induced by circumferential thinning on the inner and outer surface of the tube. Fig. 2-8 shows the test result of the relationship between the flaw volume per the unit length and signal amplitude. The test frequency is 100 Hz, and the length of the probe coil is 10 mm; at this condition the amplitude of signals for outer surface flaw is the largest. From this result, it can be concluded that an outer surface flaw having a volume rate of 1500 mm^3/cm cannot be detected, but as for the inner surface flaws, the detection limit can be estimated to be about 60 mm^3/cm.

Summarized results of those tests showed that the detectability by this method is very low: only 40% depth of wall thinning on the outer tube surface was detected. Compared with non-magnetic materials, in which case wall thinning of a few percent can be detected, detectability by this method for magnetic materials is extremely low.

(3) Future works

More experiments for the eddy current method to examine more wide parameters such as probe coil dimensions and frequency are now under way. The detectability for the outer surface flaw seems to be improved with higher frequency and the magnetic method. Magnetizing the materials, not so strongly as to saturation, was found to be effective.

2.1.2 Ultrasonic method

Ultrasonic method is available for detection of flaws, cracks, leak pinholes and wastages in heat transfer tubes of steam generators. The probes for ultrasonic examination was designed to be inserted into helical coil tubes easily and inspect the tube wall.

For first step, the following fundamental investigations were conducted.

(1) Constitution of probe

Various scanning methods for ultrasonic beam were studied and the studies of each probe unit were conducted. The conceptual depictions are shown in Fig. 2-9. Each probe has the following characteristics:

a) Slip-ring type probe

The probe itself and the slip-ring device are integrated. The electric signals are transmitted by the contact between the rotor and the stator in the slip-ring device.

b) Separated slip-ring type probe

The probe and the slip-ring device are separated in order to insert the probe at tube bends easily.

c) Rotating mirror type probe

The ultrasonic beam can be scanned in the tube circumferentially by means of rotating acoustic mirror despite a fixed transducer. Therefore the reflector with the acoustic mirror is provided to have the ultrasonic beam project into the inner surface of the tube at a proper angle.

d) Multi-array type probe

Scanning the ultrasonic beam can be done in a few seconds by means of switching the transducers electrically which are arranged circumferantially.

To make the total diameter of the cable thin, the probe interface circuit which is multiplexed is involved in the circuit unit.

The probes which are made for trial are shown in Photo 2-1.

(2) Study of signal transmission

In an inspection of the tube by ultrasonic examination, it is necessary to transmit the signals over the whole length of the tube (about 60 - 90 m) while keeping the fidelity of the signals. These signals are high frequency signals and the pulses of high voltage and fast rise and fall time.

In this transmission, attenuation and deformation of the shape of the signal are the significant problems to be solved.

On the other hand, it is necessary that the diameter of the cable is less than 3 or 4 mm in order to insert the cable into the tube easily.

Therefore, the attenuation of pulse was measured quantitatively and the frequency characteristics, effects of reflection, effects of cable length and pulse characteristics were studied by using various cables which seemed to be proper for this inspection system.

Consequently, in consideration of the total diameter of the cable and the various electrical characteristics of the cable, a thin coaxial cable (SA-7/0.12) with a 1.02 mm diameter was selected for this inspection system.

The relations between frequency and attenuation are shown in Fig. 2-10. In this results, the difference of attenuation between BW (Burst Wave) and CW (Continuous Wave) was not significant.

When the length of the cable was 100 m, the attenuation was about 16 dB at 5 MHz and about 28 dB at 10 MHz. As a result of transmitting the practical ultrasonic signal on condition that the impedance was matched, the deformation of signal shape was not significant, and then it was confirmed that this coaxial cable could be applied to this inspection system.

(3) Future works

The study of the detecting performance tests was just started using above mentioned probes. It is expected that ultrasonic method will be applied to inspection of helical coil tubes in steam generators.

2.1.3 Study of probe driving method

In the preliminal study$^{(10)}$, the method using the flexible driving cable was considered as a candidate method, although it seemed to be difficult to insert the probe into the whole length of the helical coil tube using the cable. On the other hand, the method, which is to insert the probe without any signal cables into the tube by air pressure, seemed to be proper on the point of inserting performance of the probe. But there were many problems such as the transmission of signals, the control of the traveling rate of the probe, detection of the probe location in the tube.

In this study, probes were connected to the signal cables and the probe driving methods using fluid pressure were studied. Especially, a number of guide balls were attached on the cable at regular intervals to make inserting performance improve. Model probes which were used in this study were equivalent to probes used for ultrasonic examination. The configurations of these probes are shown in Fig. 2-11.

The specifications of the helical coil tube which were used in this study are shown in Table 2-1. The configuration of the full scale heat transfer tube model of evaporator for "Monju" is shown in Fig. 2-12. It was confirmed after tube to tube welding that an inner-diameter gauge which has a 16 mm diameter could pass through the tube to tube welded joints.

Two kinds of coaxial cables were used in this study. The outer-diameters of these cables were 7.3 mm and 3.2 mm. In the preliminal study, the total diameter of the signal cable to transmit the signals was estimated to be about 7 mm. Therefore the coaxial cable with a 7.3 mm diameter was used in this study. Specifications of these cables are shown in Table 2-2. In order to improve the inserting performance of the cable, a number of guide balls were attached on the cable at regular intervals. The cables with attached guide balls are shown in Photo 2-2.

Main items of the examinations which have been carried out are: (1) to confirm the effect of guide ball on inserting performance of the cables, (2) to insert the probe and cable into the full scale helical coil tube model.

First, to confirm the effect of the guide ball on inserting performance of the cable, the driving force of the cable was measured under the condition of the guide balls being placed on the cable at various intervals and using two kinds of cables. The typical result of these measurements is shown in Fig. 2-13. From this result, following considerations are obtained.

(1) The prove driving force increases with the length of the cable inserted, since the cable winds tightly to the tube increasing the contact area between the cable and the tube.

(2) When the interval of the guide ball is 100 mm or 200 mm, the probe driving force doesn't increase so remarkably with the length of the cable inserted. This is considered the effect of guide balls attached on the cable.

Secondly, attempts to insert the probe and cable into the full scale helical coil tube model were conducted. From these attempts, the following considerations were obtained:

(1) The probe and cable can be inserted by air pressure

through the whole length of the helical coil tube from both sides of the tube, coil side and downcomer side, by using the cable which has a 3.2 mm diameter.

(2) In the case of using the cable with a 7.3 mm diameter. The probe and cable, which are inserted into the tube, can be drawn out by pressurizing the tube at the other end of the tube.

2.2 Other method

Above mentioned volumetric examination method is expected to be effective for the location of the leak and the inspection of the wastage of tubes with some future R&D activities. But as those methods have not been established yet, the alternative way of the location of the leak should be considered. The following procedure is thought to be used as an alternative way to confirm the leak.

1) Measuring the change of the shell side and tube side pressure with pressurizing the tube side by argon gas.

2) Same as above but helium gas is used as pressurizing gas, and helium concentration is measured with helium leak detector together with measuring pressure change.

3) Detecting the helium in the tube side by pressurizing the the shell side.

4) Detecting the acoustic sound of the gas jet to water by filling tube side with water and pressurizing the shell

side with argon gas.

5) Detecting the acoustic sound and measuring the fluctuations of sodium level by pressurizing the tube side with argon gas.

In all cases leak holes must not be self-plugged under the sequence of shutdown. As to the procedure 3) and 4) the possibility of self-plug by the sodium is expected. Procedure 4) and 5) have some unknown factors for measuring acoustic sound and fluctuation of sodium level, so they must have some difficulty to detect the small or micro leaks. By our leak experience11) at 1 MW steam generator with two helical coil tubes, procedure 1) and 2) were effective for the specification of the leak tube and location. The result of leak detection by the way of procedure 2) is shown in Fig. 2-14. The response of helium detector clearly shows the existence of the leak with some delay time due to the volume of shell. Fig. 2-15 shows the result of the helium leak detection for damaged tube in the case of the two tubes were separated each other. As for the normal tube, helium leak detector indication was zero.

Probability of self-plug at this leakage was low because the leak occured at the cover gas region of tube.

From these experiences of 1 MW steam generator it was confirmed that the above mentioned method for leak detection at "Monju" steam generator must be used. It is important to prevent the self-plug, so it is planned to research this problem in future.

3. Design requirements to facilitate the inspection

The following requirements are taken into account at the design of "Monju" steam generator for the sake of effective inspection of the heat transfer tubes.

1) The capability of pulling out the tube bundle from the shell

   The shell has a couple of flange in capable of pulling out the tube bundle. (Fig. 3-1) Visual inspection of outer surface of downcomer tubes and connecting part of downcomer and riser tubes is possible.

2) Good operatability at inlet and outlet steam-water nozzle

   Steam-water nozzles have cap ends at the top of them. With this configuration, the apparatus can be set and operated easily for the insertion of the test probe into tubes, so it saves times for inspection.

3) Wide working space at the top of shell

   The attention is paid at the "Monju" design to provide the enough space for working and setting up the apparatus for inspections, such as the arrangement of nozzles and ring headers.

4) Tube wall thickness of downcomer tubes

   In early design downcomer tube wall was thicker than that of riser portion of helical coil tubes for the purpose of preventing the heat transfer to the downcomer. But now downcomer tubes of same wall thickness as helical coil tubes are used in consideration of the easy insertion of the test probe from water inlet nozzle.

Acknowledgment

The authors gratefully indebted to Messrs. K. Kawashima, M. Hori, M. Sato, N. Kanegae, T. Tsuchiya and K. Sakano.

References

1) N. Kanegae, et al., "Wastage and Self-Wastage Phenomena Resulting from Small Leak Sodium-Water Reaction - Studies of Small Leak Sodium-Water Reaction (7) -", PNC SN941 76-27 (Mar. 1976)

2) H. Nei, et al., "Studies of Small Leak Sodium-Water Reaction (2) - Characteristic Tests of Leak Detectors -", PNC SN941 72-14 (Aug. 1972)

3) N. Kanegae, et al., "How to Design a Nickel Membrane-Ion Pump Type Hydrogen Meter Leak Detector in Sodium - Studies of Small Leak Sodium-Water Reactions (10) -", PNC SN941 76-30 (Mar. 1976)

4) S. Adachi, et al., "Development of Nickel Membrane Type Cover Gas Hydrogen Meter" Fall Mtg. of the Atomic Energy Society of Japan, E14 (1977)

5) H. Nei, et al., "Studies of Small Leak Sodium-Water Reactions (5) - Acoustic Leak Detection -", PNC N941 74-70 (Aug. 1974)

6) MICHIGUCHI, et al., "Preliminary Tests on the Location of Sodium-Water Reaction by Acoustic Method," Fall Mtg. of the Atomic Energy Society of Japan (1975)

7) M. Hori, et al., "Design of PNC In-sodium Hydrogen Meter Type II" Fall Mtg. of the Atomic Energy Society of Japan, E-21 (1977)

8) M. Yamada, et al., "Examination on Sensor of In-Service Inspection for Steam Generator Tubings - Fundamental Examination on Eddy Current Testing -" PNC SJ222 77-06 (May 1977)

9) E. Shibato, et al., "Test Results of Sensors Developed for In-Service Inspection for Steam Generator Tubings - Preliminary Design of Wireless Ultrasonic Examination Method -" PNC SJ202 77-07 (May 1977)

10) E. Shibato, et al., "Examination Design Study on In-Service Inspection Equipments of Heat Transfer Tubes of Intermediate Heat Exchangers and Steam Generators for the Prototype LMFBR 'Monju'" PNC SJ202 75-03 (Mar. 1975)

11) H. Yagisawa, et al., "Leakage Experiences with 1 MW Steam Generator" PNC ZN941 76-54 (June 1976)

Table 1-1 Classification of Leak for MONJU Steam Generators

Classification of leak		Main effect	Leak rate	Leak size (dia.)
Large leak	large leak	pressure	> 2 kg/sec	> 7 mm
	intermediate leak	multi-tube target wastage	10 g/sec ∿ 2 kg/sec	1.0 ∿ 7.0 mm
Small leak	small leak	single-tube target wastage	50 mg/sec ∿ 10 g/sec	0.07 ∿ 1.0 mm
	micro leak	self-wastage	< 50 mg/sec	< 0.07 mm

Table 1-2 Design Specification of PNC Hydrogen Detector-I

Operating Range	45 ppb - 10 ppm Hydrogen in Sodium	
Sensitivity, Responce Time	Detect 10% Change in Hydrogen Concentration within 30 Sec.	
Diffusion Membrane		
Material	Nickel 201	
Area	200 cm^2 (MK-I), 150 cm^2 (MK-II)	
Thickness	0.05 cm	
Shape	Tubular (Sodium Inside)	
Ionization Gauge		
Ultrahigh Vacuum Gauge	10^{-10} - 10^{-3} torr	
Schultz Gauge	10^{-5} - 3 torr	
Sodium System		
Membrane Temperature	500°C	
Sodium Flowrate	2.5 L/min	
Design Pressure	10 kg/cm^2	
Design Temperature	520°C	
Vacuum System		
Volume	976 cm^3	
Inner Surface Area	1012 cm^2	
Ion Pump		
Pumping Speed (Low)	2.7 L/sec	
" " (High)	25 L/sec	
Bakeout Condition		
	Mark I	Mark II
Temperature	550°C	550°C
Hours of Baking	120 hrs	700 hrs
Outgas Rate (torr, L/sec, cm^2)	$5x10^{-10}$	$1x10^{-11}$

Table 1-3 Specification of PNC Hydrogen Detector-II

Operating Range	45 ppb - 15 ppm Hydrogen in Sodium
Sensitivity, Responce Time	Detect 10% Change in Hydrogen Concentration within 30 Sec.
Diffusion Membrane	
Material	Nickel 201
Area	150 cm^2
Thickness	0.05 cm
Shape	Tubular (sodium Inside)
Ionization Gauge	
Ultrahigh Vacuum Gauge	10^{-10} - 10^{-3} torr
Schultz Gauge	10^{-5} - 3 torr
Sodium System	
Membrane Temperature	500°C
Sodium Flowrate	3.2 L/min
Design Pressure	10 kg/cm^2
Design Temperature	520°C
Vacuum System	
Volume	254 cm^3 (Static Chamber)
Inner Surface Area	480 cm^2 (" ")
Ion Pump	
Pumping Speed	23 L/min
Bakeout Condition	
Temperature	600°C
Hours of Baking	350 hrs
Outgas Rate	$<9x10^{-12}$ torr, L/sec, cm^2

Table 1-4 Specification of Cover Gas Hydrogen Detector

Type	Nickel Diffusion Membrane Type
Operating Range	1 - 600 v ppm Hydrogen in Cover Gas
Sensitivity, Responce Time	Detect 10% Change in Hydrogen Concentration within 40 Sec.
Diffusion Membrane	
Material	Nickel
Area	63 cm^2
Thickness	0.025 cm
Shape	Tubular (Vacuum Inside)
Gas System	
Membrane Temperature	500°C
Gas Flowrate	20 L/min max.
Operating Pressure	1.7 kg/cm^2
Design Temperature	600°C
Design Pressure	10 kg/cm^2
Vacuum System	
Volume	168 cm^3
Inner Surface Area	255 cm^2 (Static Chamber)
Ion Pump	
Pumping Speed	22 L/sec
Ionization Gauge	
Range	$1x10^{-5}$ - 1 torr

Table 2-1 Specification of Tube

Item	Unit	Helical coil tube model	Evaporator for "Monju"	Remark
Outer Diameter	mm	25.4	25.4	
Wall Thickness	mm	3.2	3.2	
Material		304ss	$2\frac{1}{4}$Cr.1Mo	
Coil Diameter	mm	1080	1080*	*minimum coil diameter
Axial Pitch	mm	480	480	
Effective Heat Transfer Length	m	-54	-54	
Gradient	degree	8	8	
No. of Turn		-15	-15	
Minimum Bending Radius	mm	100	100	
Tube-to-tube Welding Method		TIG	TIG	

Table 2-2 Specification of Cable for Study of Probe Driving Method

Type of Cable	Outer Diameter (mm)	Weight (g/m)	Volume (cm^3/m)	Specific Gravity
1.5C - 2V	3.2	14.3	7.7	1.9
5D - 2V	7.3	81.7	43.3	1.89

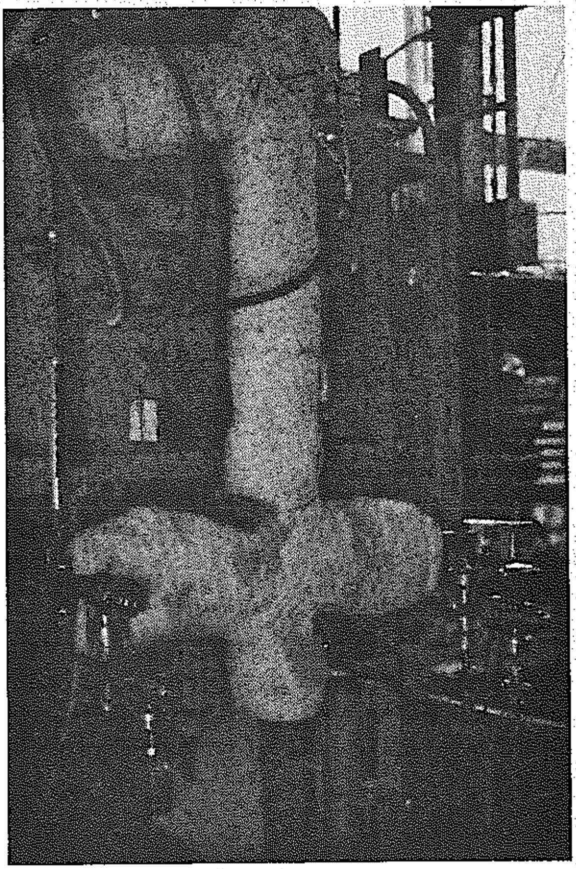


Photo 1-1 Installations of PNC Designed In-Sodium Hydrogen Detector

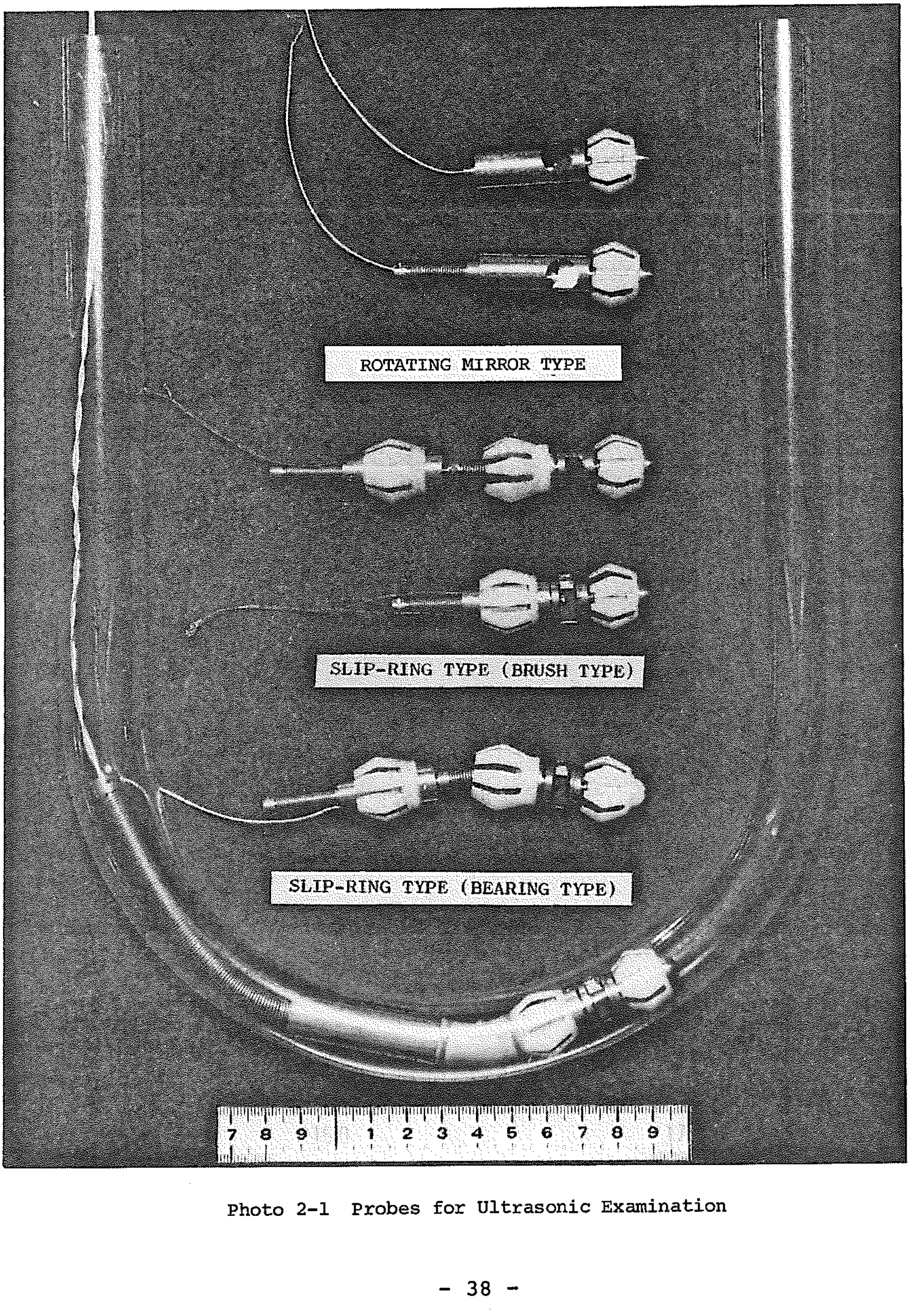
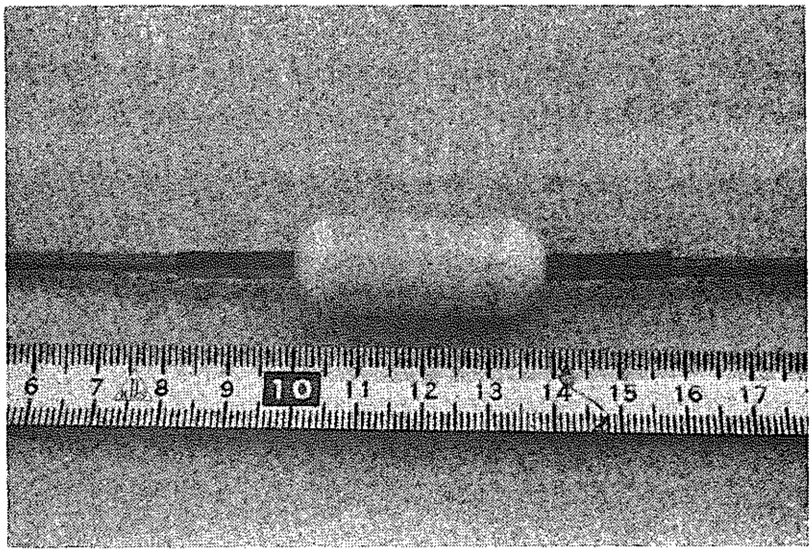
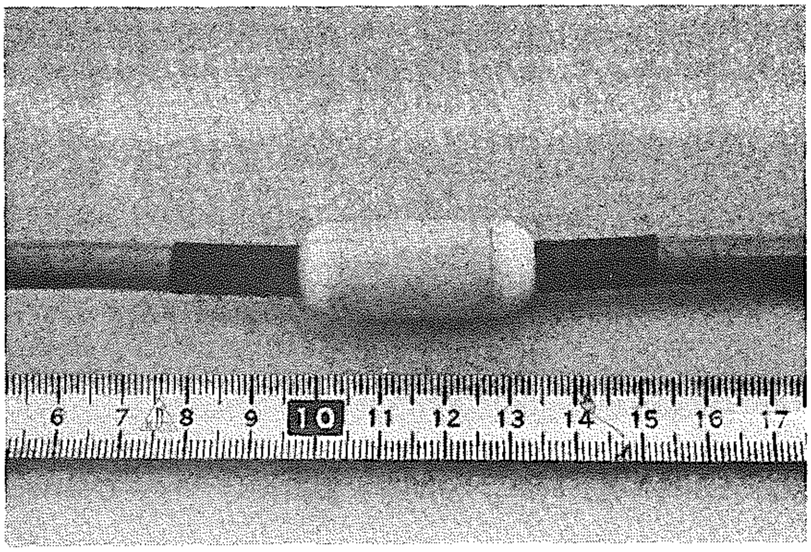


Photo 2-1 Probes for Ultrasonic Examination



a) Outer-Diameter of Cable: 3.2 mm



b) Outer-Diameter of Cable: 7.3 mm

Photo 2-2 Cables Attached Guide Ball

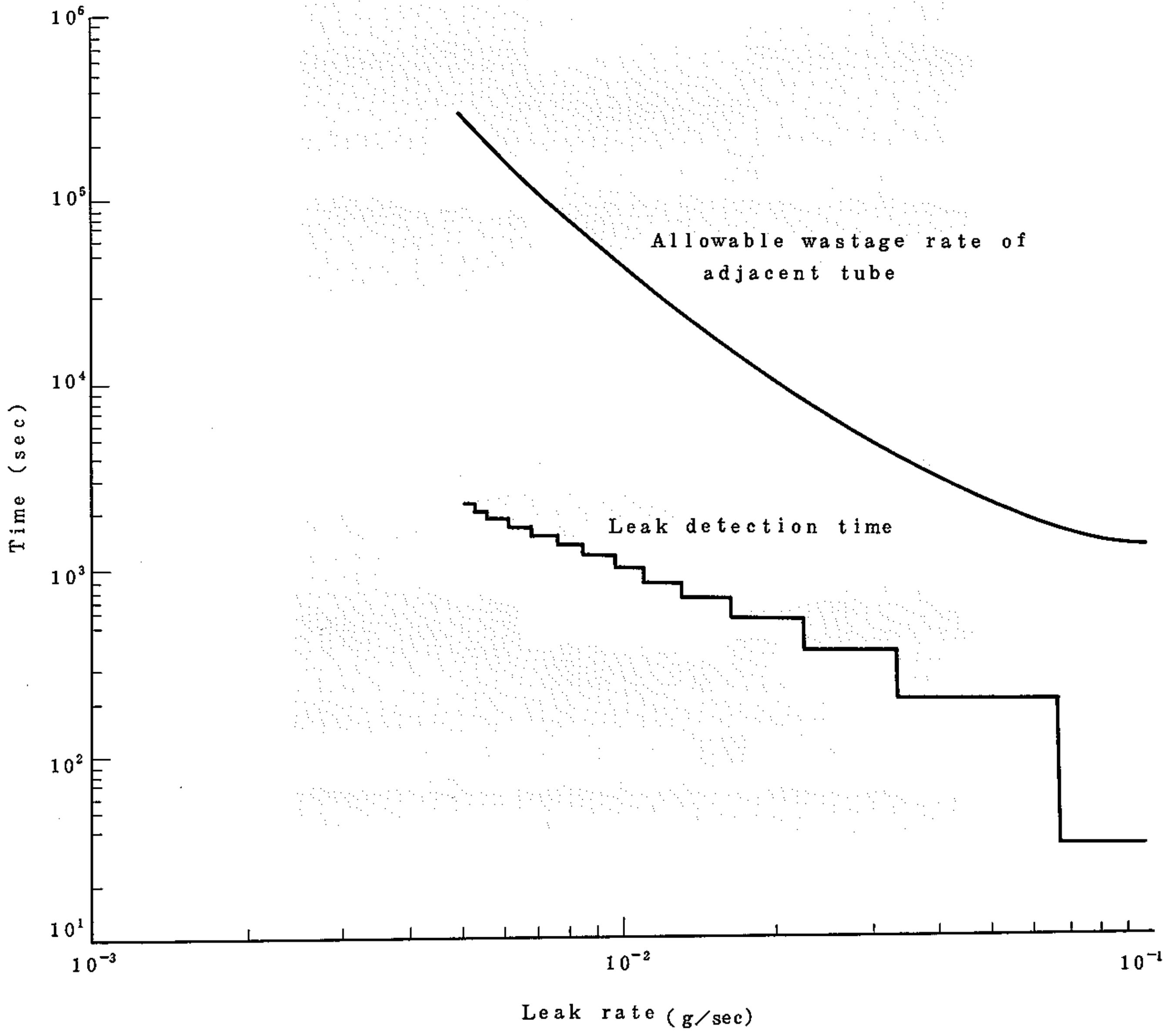


Fig.1－1 Leak Detector Performance

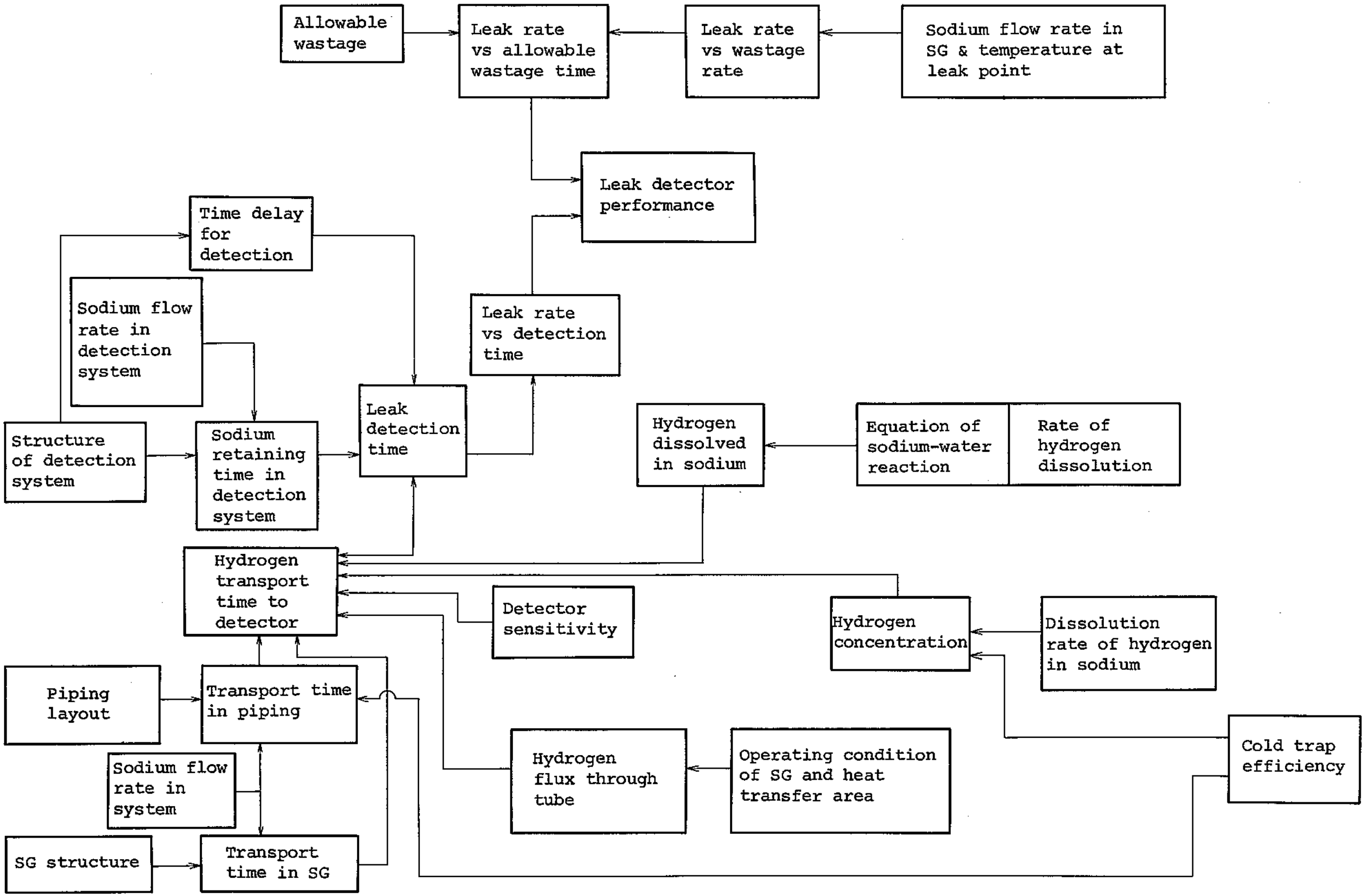


Fig. 1-2 Basic Flow for an Analytical Evaluation of Leak Detector Performance

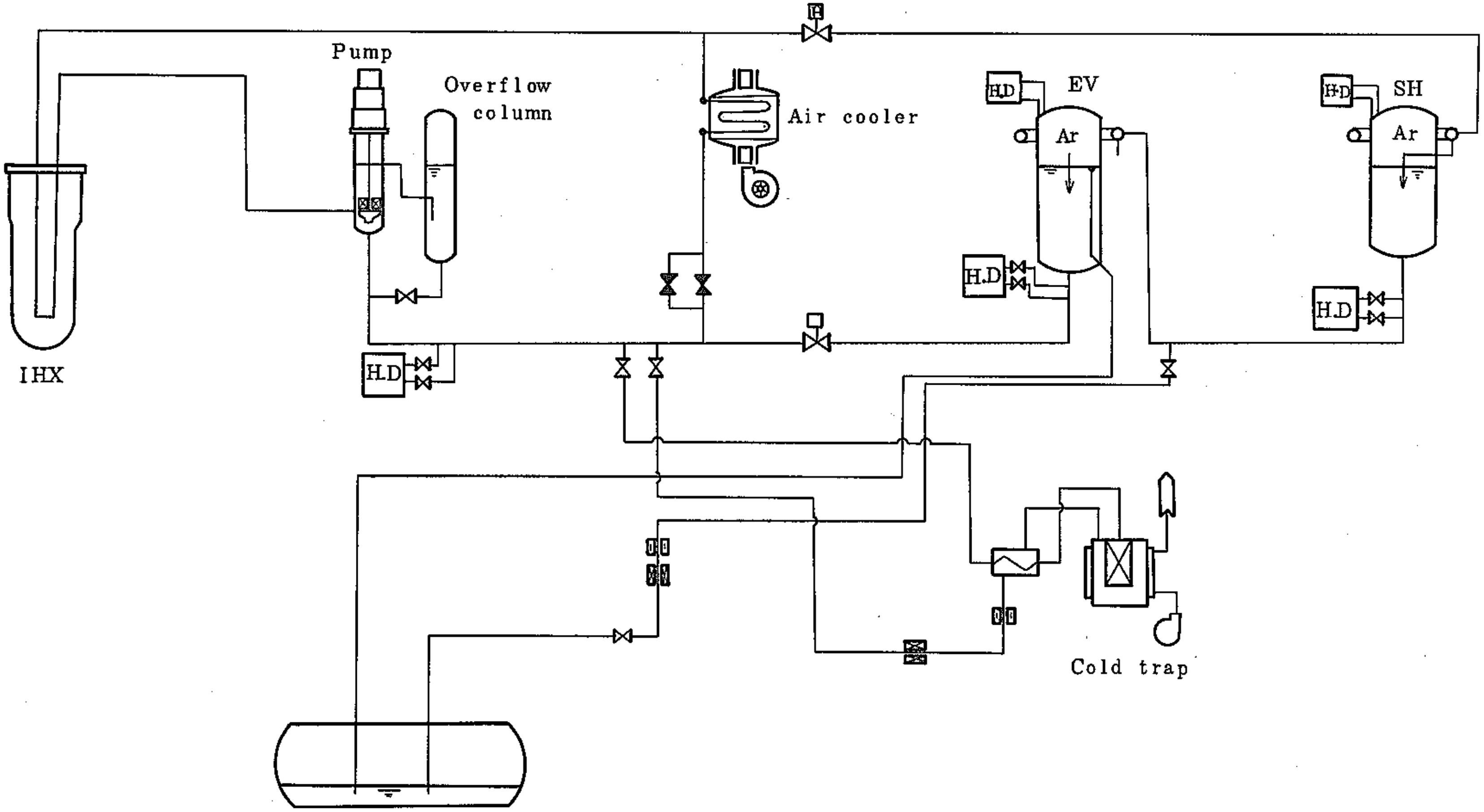


Fig.1−3 Detector Location in Secondary Circuit

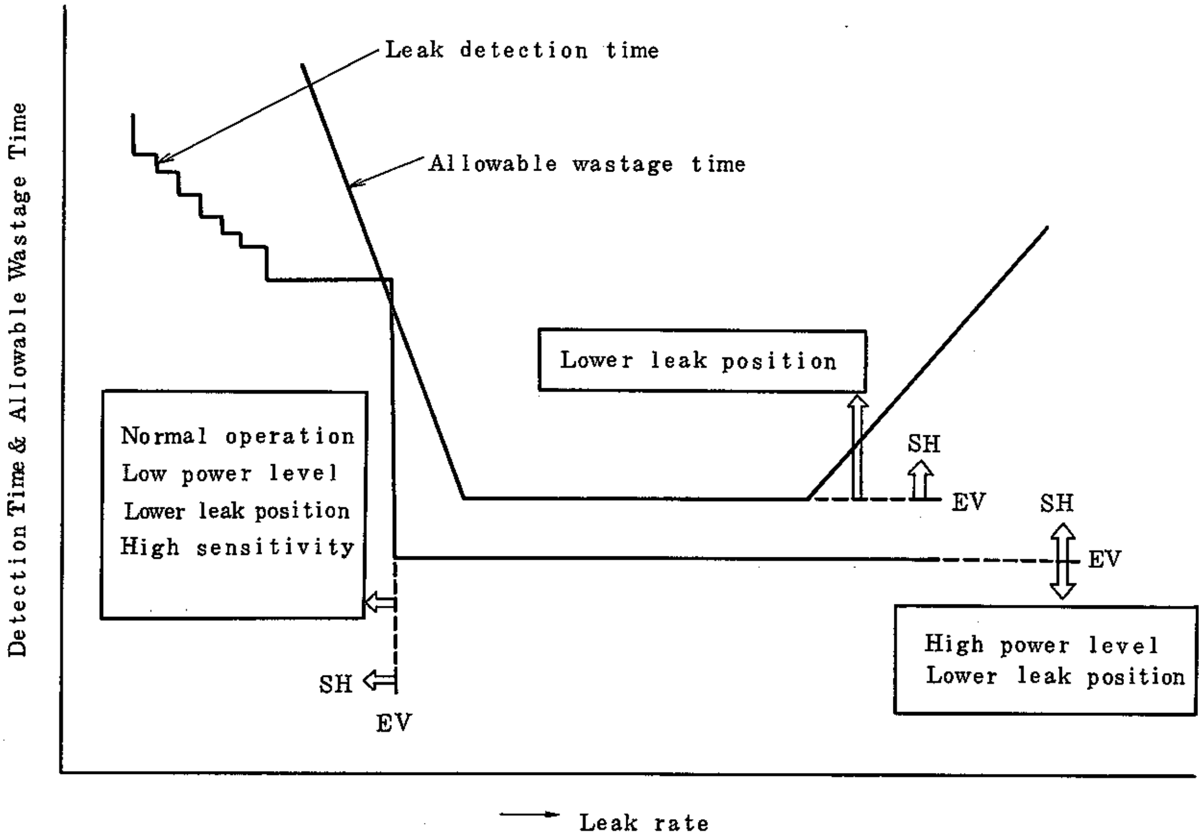


Fig.1－4 Effects of the Major Parameters on Leak Detector Performance

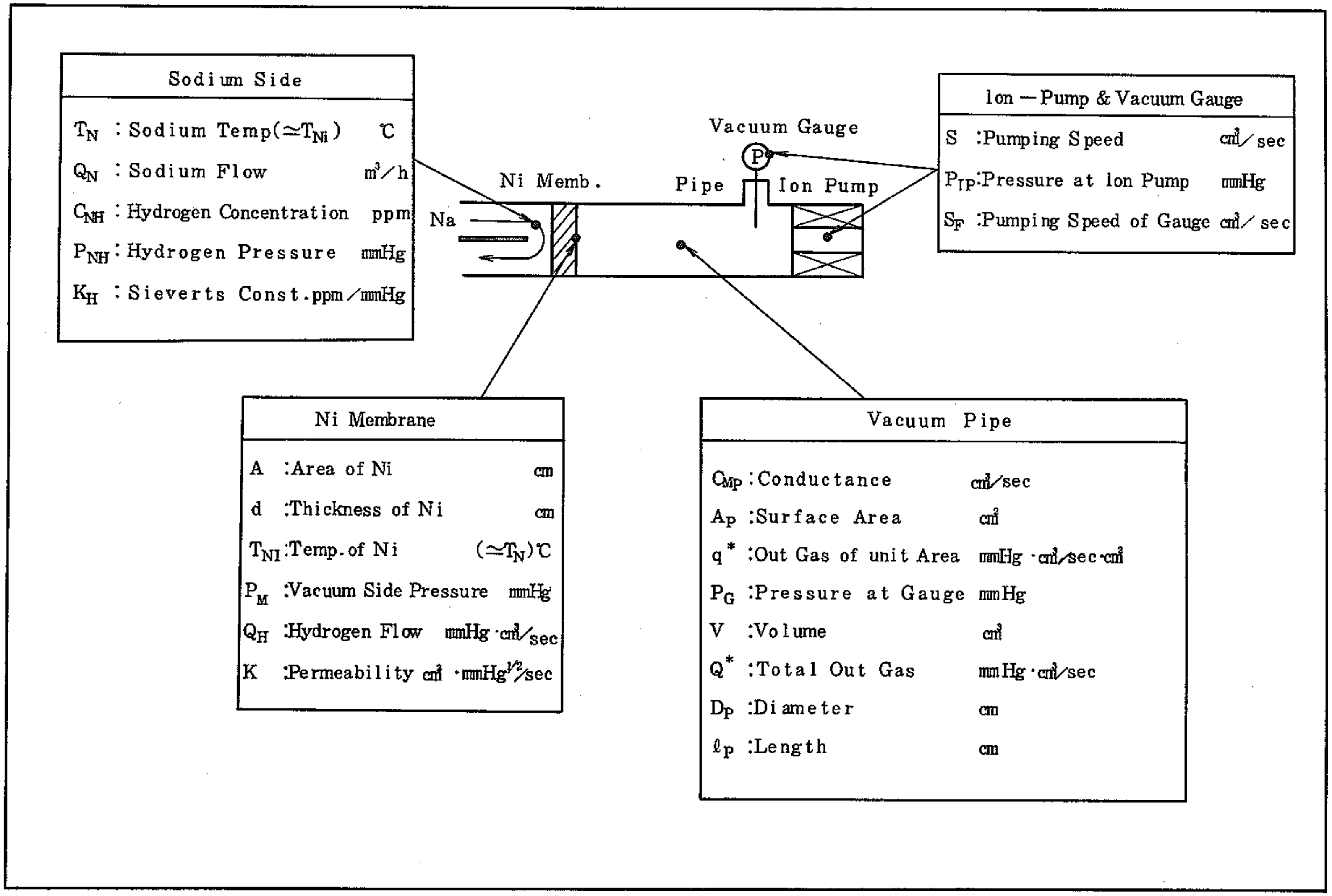
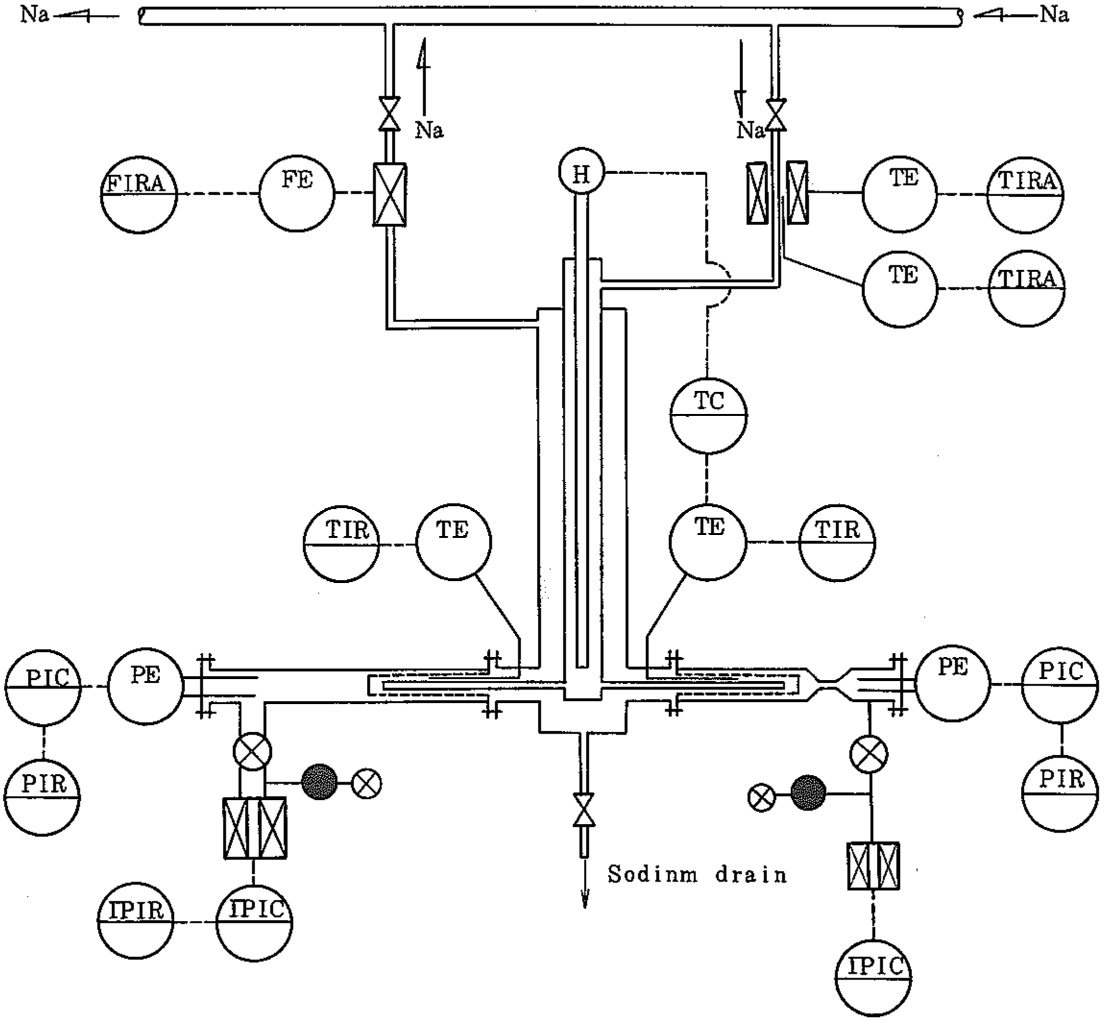


Fig.1—5 Schematic Figure of Ni Membrane — Ion Pump Type Hydrogen Detector



⊠ ⊠	EM Pump	Ⓗ▭	High Flux Heater	⊠ ⊠	Ion Pump
⊠	EM Flowmeter	┌┐	Niekel Membrane		
⊣⊢	Flange	⋈	Sodium Valve	⊗	Vacuum Valve

○	Instrumenta-tion	P	Pressure	F	Flowrate	T	Temperature
⊖		IP	Ion Pump	C	Control	R	Record
E	Sensor End	I	Indication	A	Alarm		

Fig. 1−6 PNC In−Sodium Hydrogen Detector Type Ⅱ

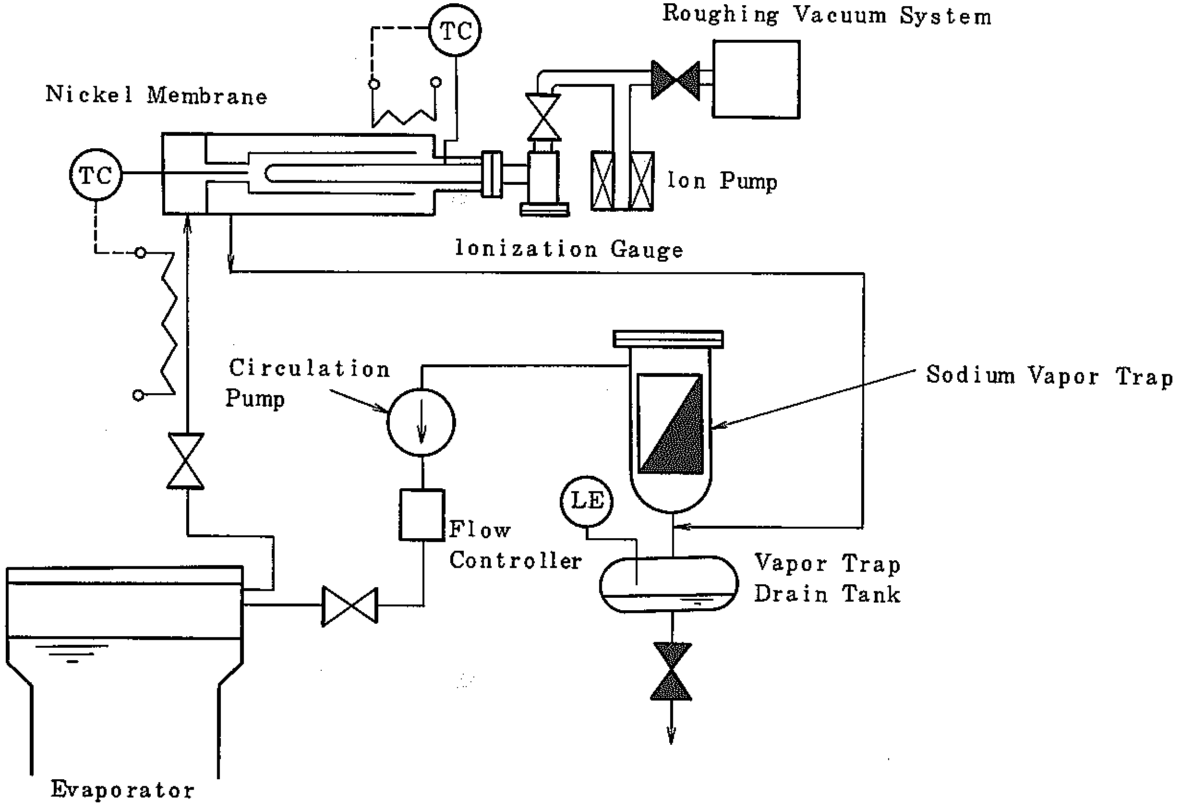


Fig. 1-7 Schematic Diagram of Nickel Membrane Type Cover Gas Hydrogen Detector

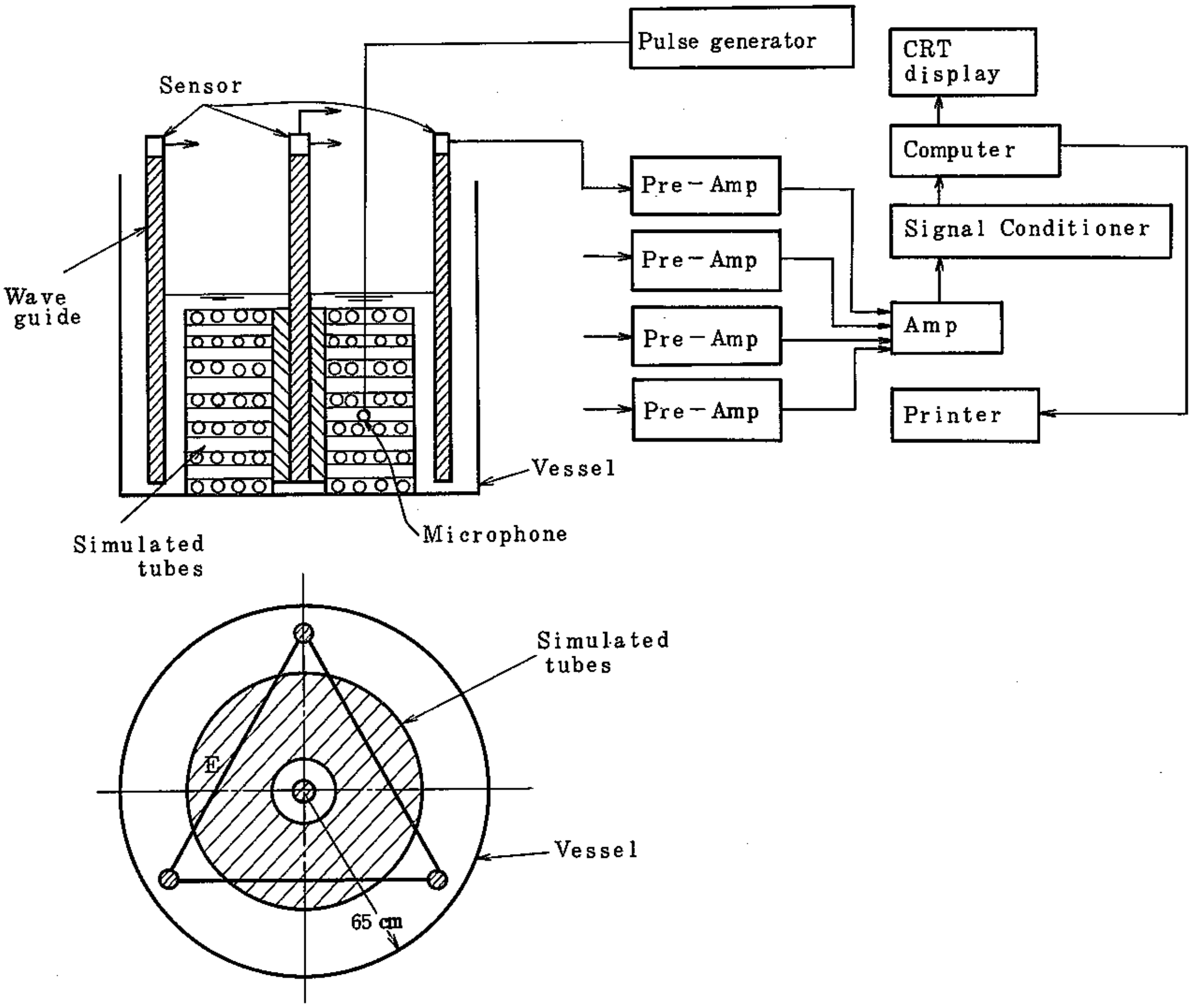


Fig 1－8 Block Diagram of the Instruments for Locating the Sound Source

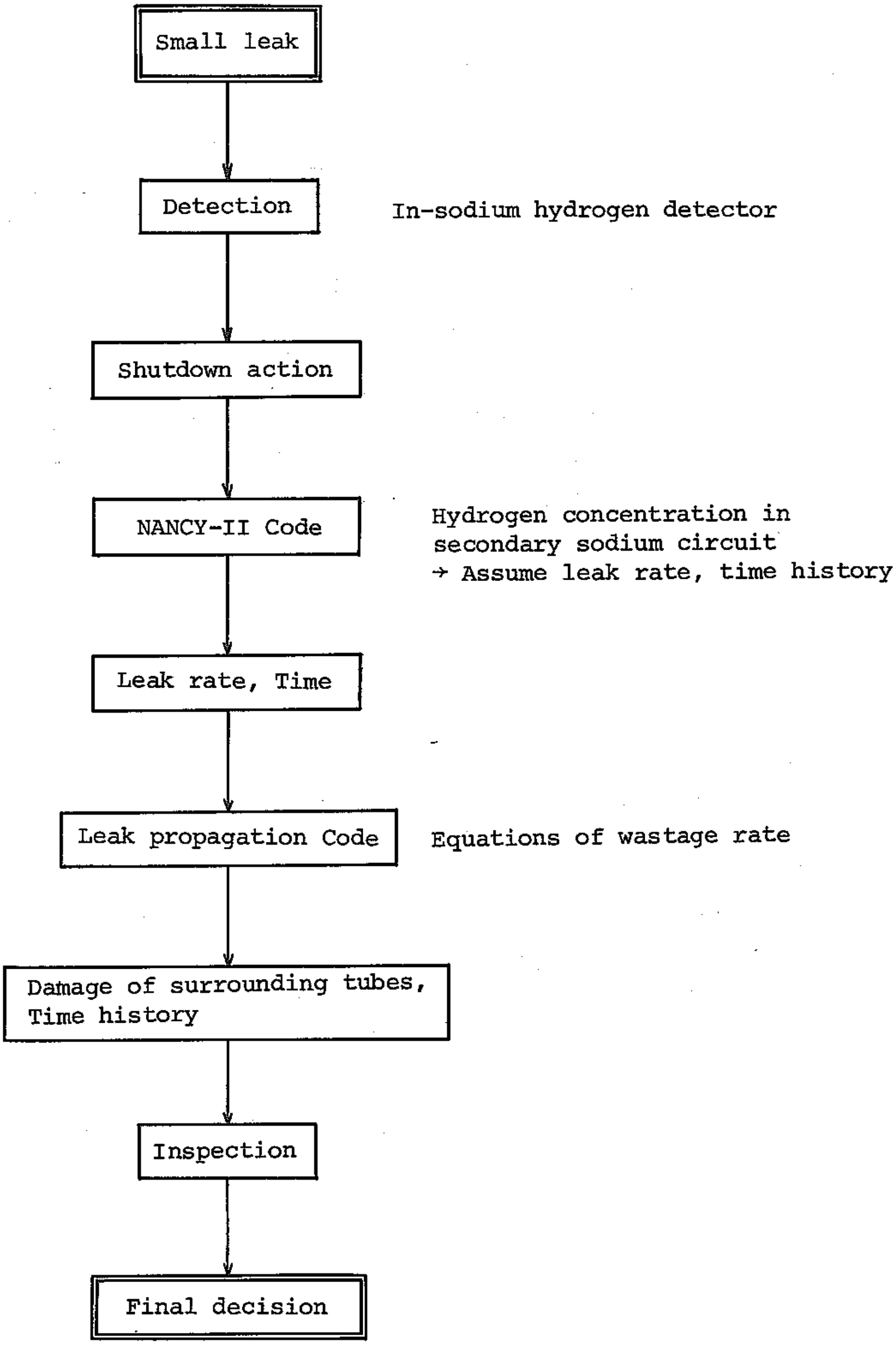


Fig. 1-9 Flow Diagram for the Determining the Condition of Tubes in the Neighbourhood of the Leak

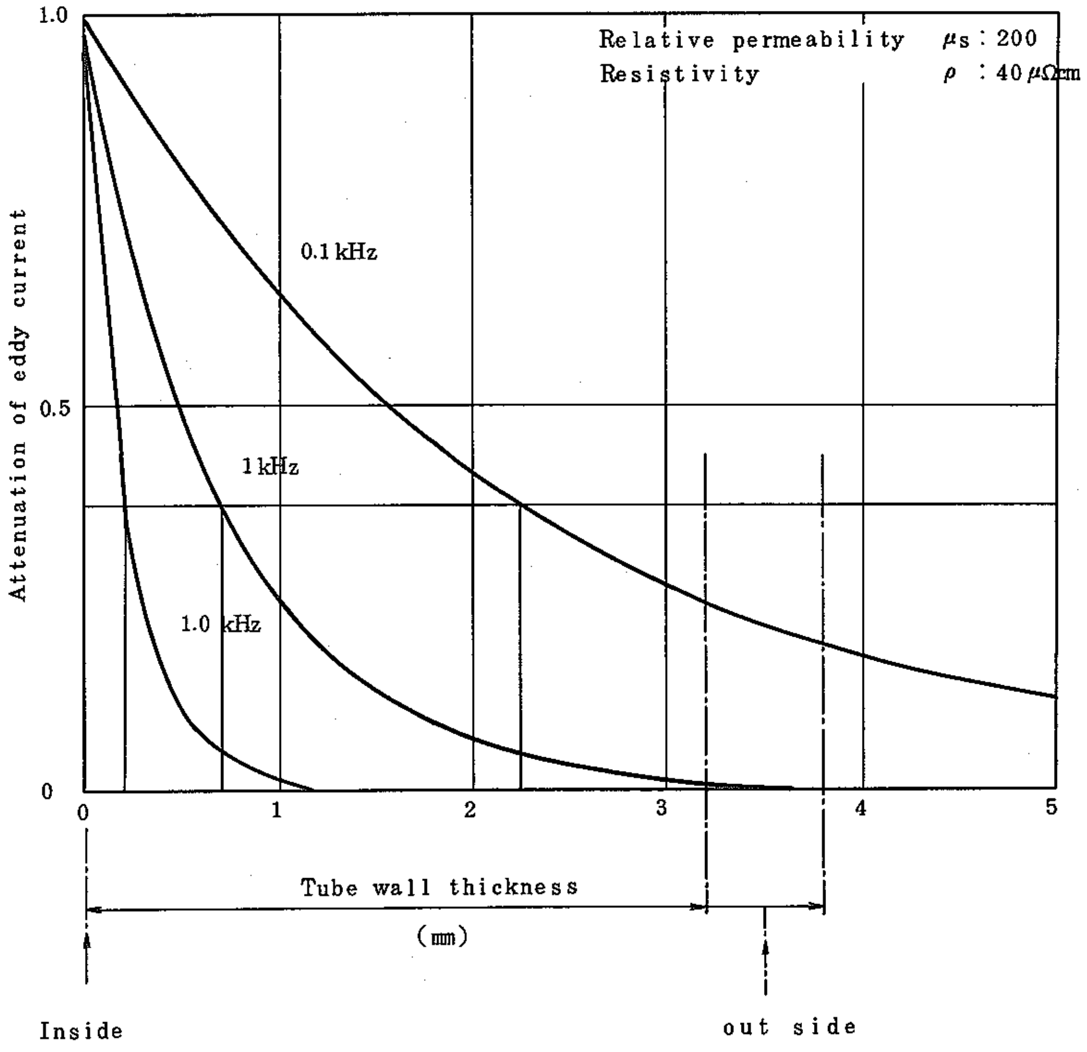


Fig 2－1 Attenuation of Eddy Current

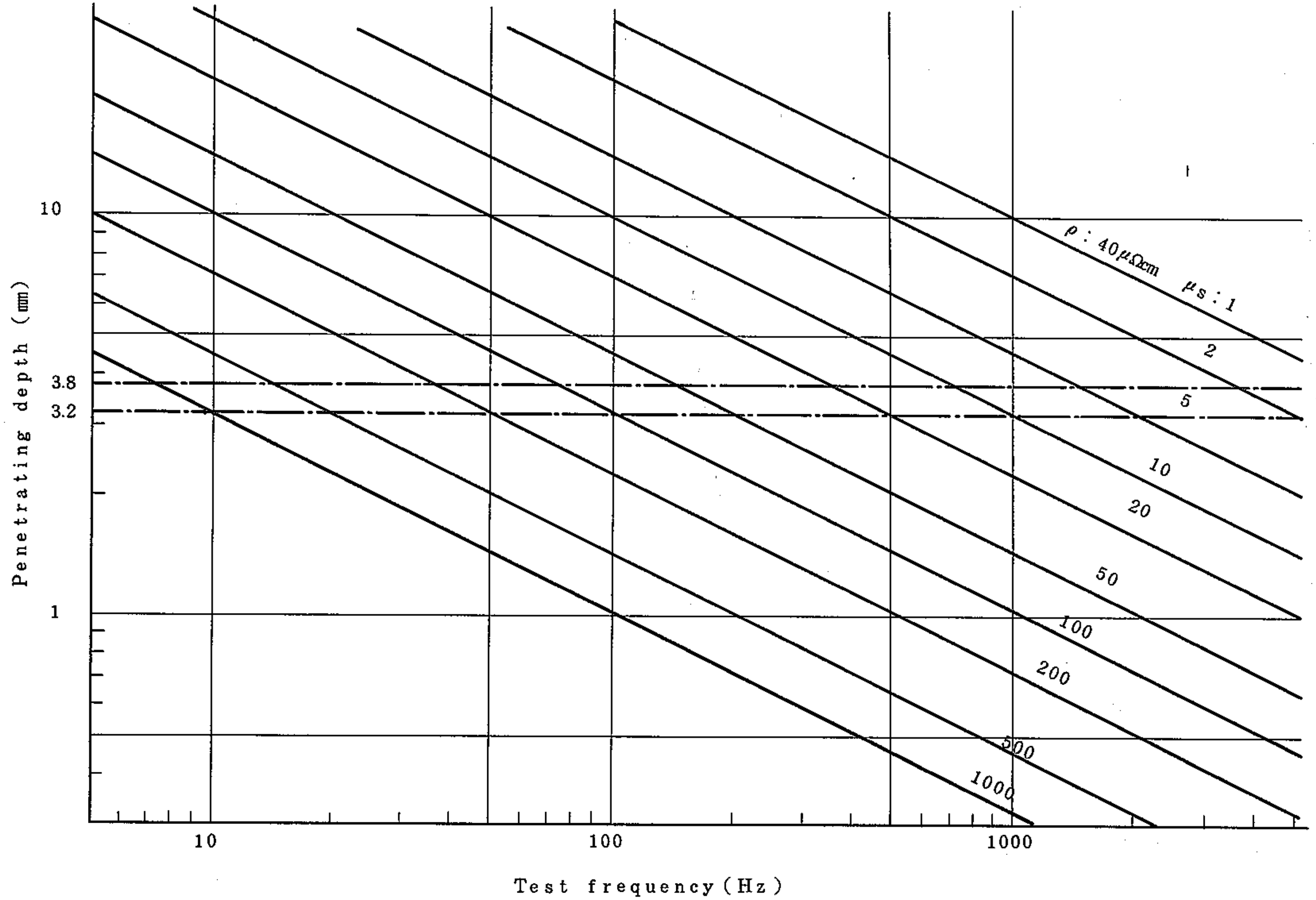
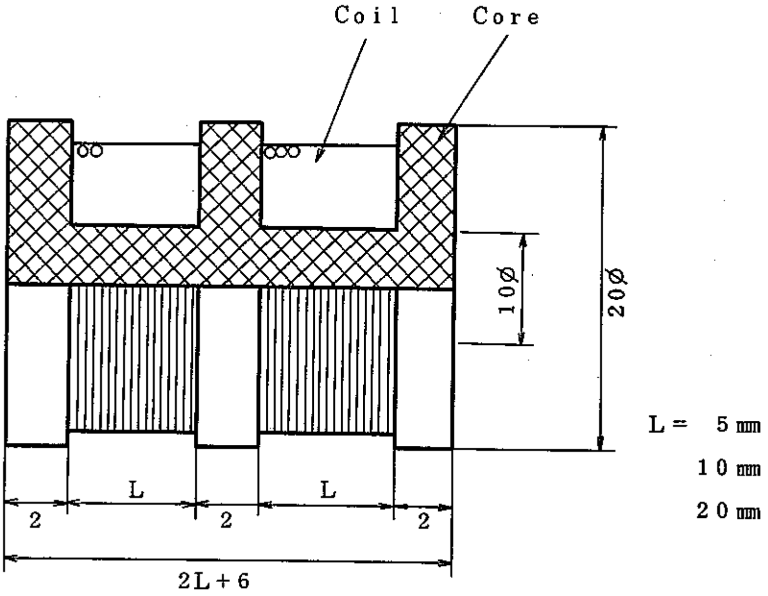


Fig 2 — 2 Penetrating Depth of Eddycurrent



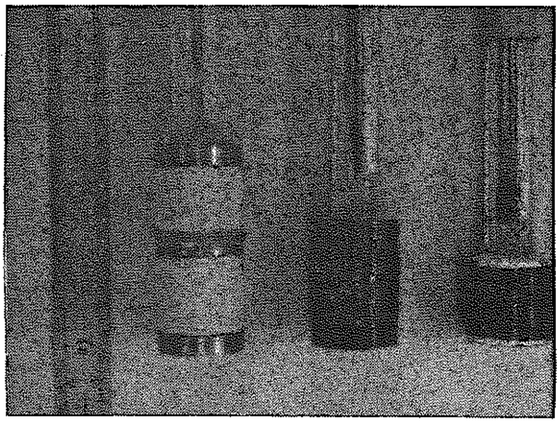
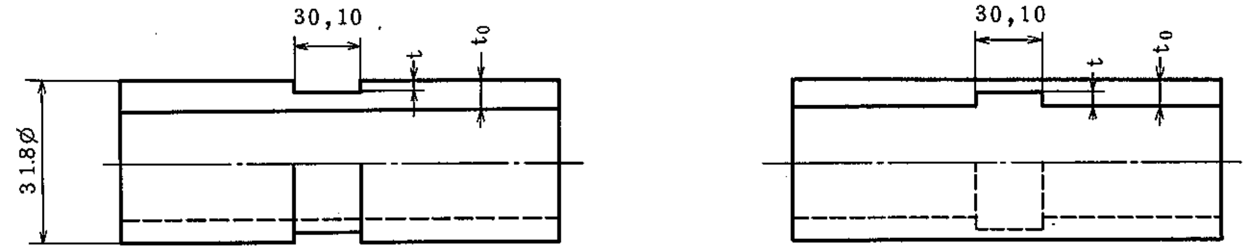


Fig 2 − 3 Structure of Test Probe for Eddy Current Examination

(a) Circumferential groobe (outer surface)

(b) Circumferential groobe (inner surface)

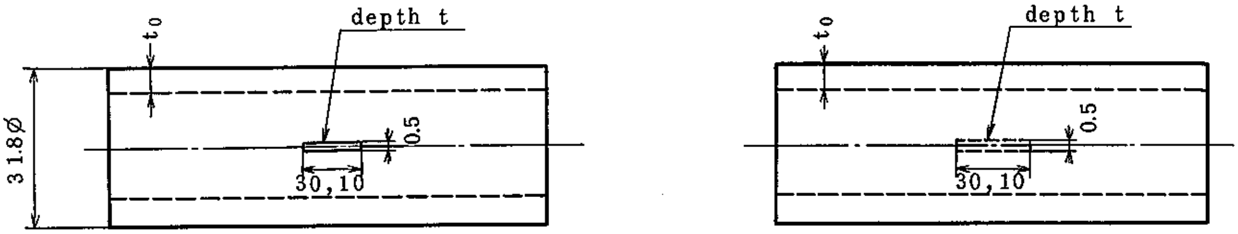


t_0 = 3.8 , t = t_0 × 0.8 , 0.6 , 0.4 , 0.2

t_0 = 3.8 , t = t_0 × 0.8 , 0.6 , 0.4 , 0.2

(c) Longitudinal notch (outer surface)

(d) Longitudinal notch (inner surface)



t_0 = 3.8 , t = t_0 ×0.8 , 0.6 , 0.4 , 0.2

t_0 =3.8 , t = t_0 × 0.8 , 0.6 , 0.4 , 0.2

(e) Through hole

(f) Welded model

(g) Na.deposit model

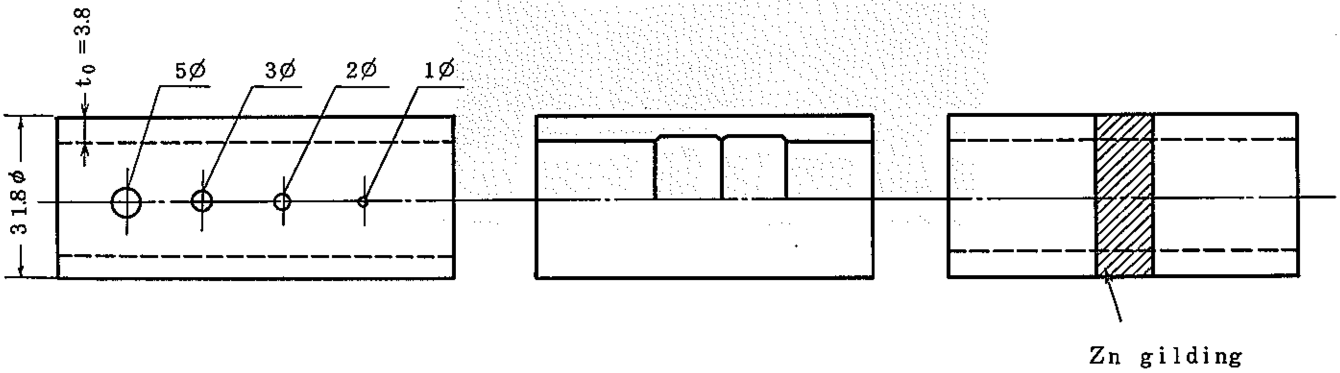


Fig 2 − 4 Dimensions of Test Piece for Eddy Current Examination

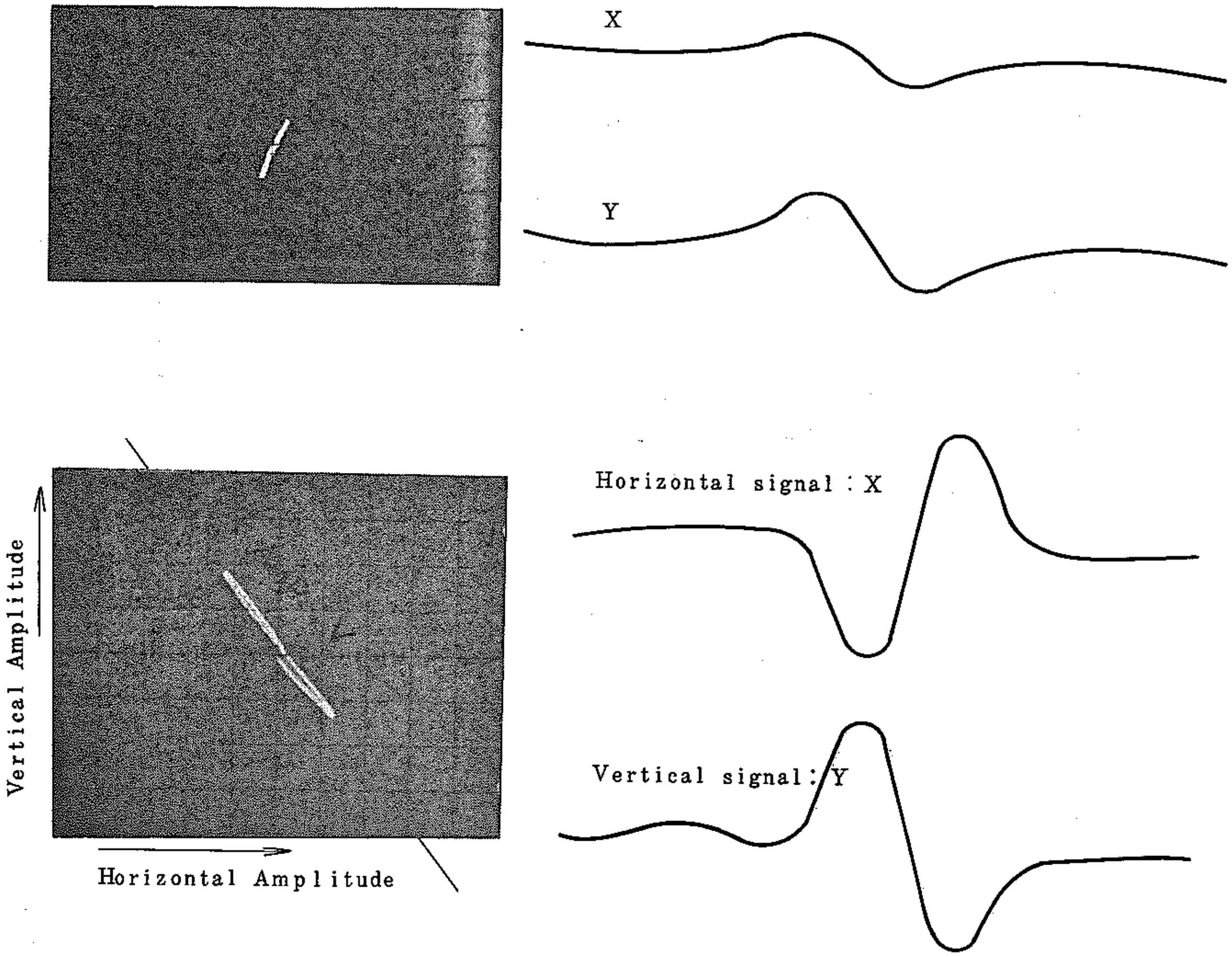
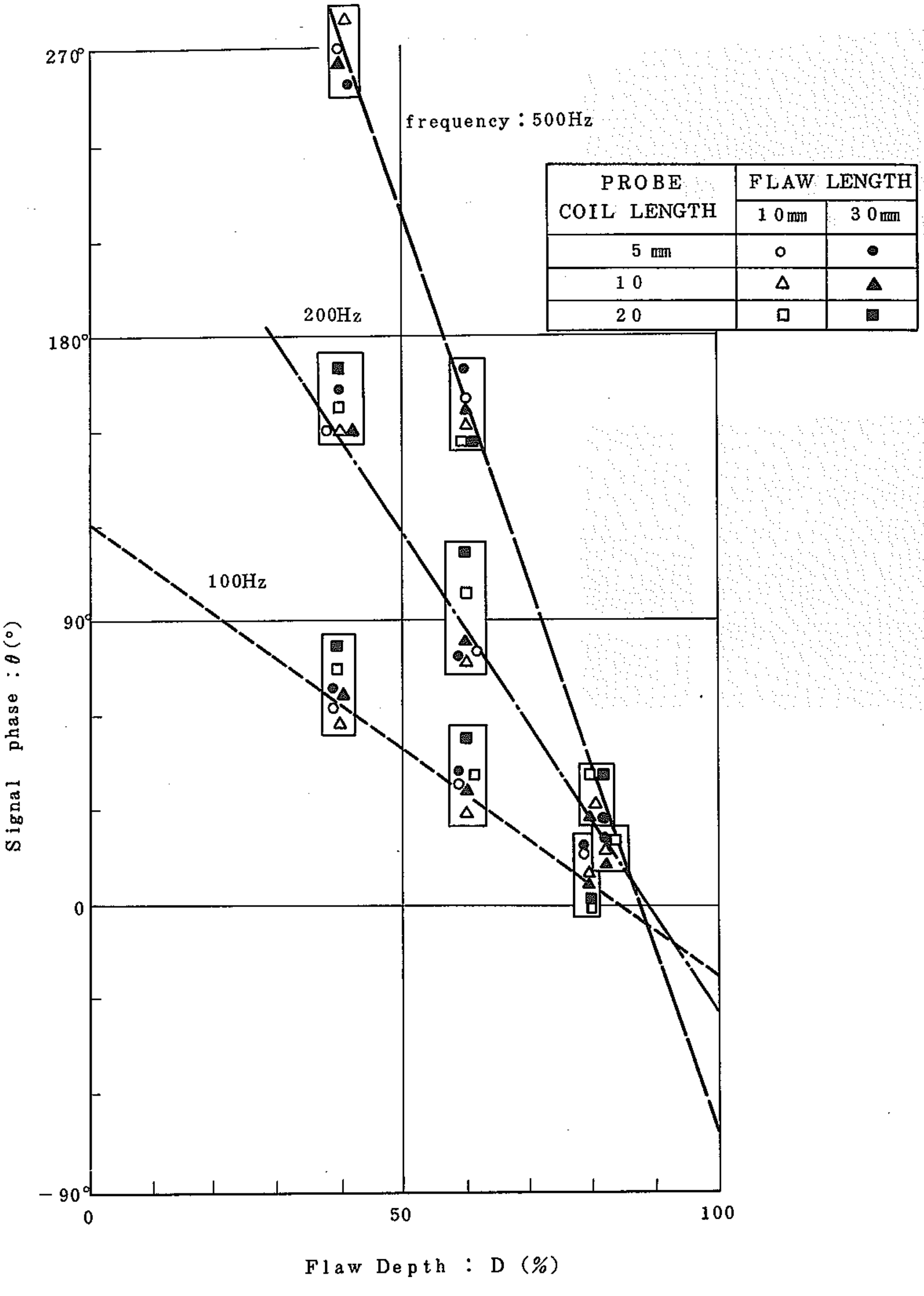


Fig 2－5 Typical Signal Patterns (Test frequency 200Hz) of Eddy Current Examination



PROBE COIL LENGTH	FLAW LENGTH 10mm	FLAW LENGTH 30mm
5 mm	○	●
10	△	▲
20	□	■

Fig 2−6 Relationship Between Signal Phase vs Flaw Depth
(Outer surface wall thinning)

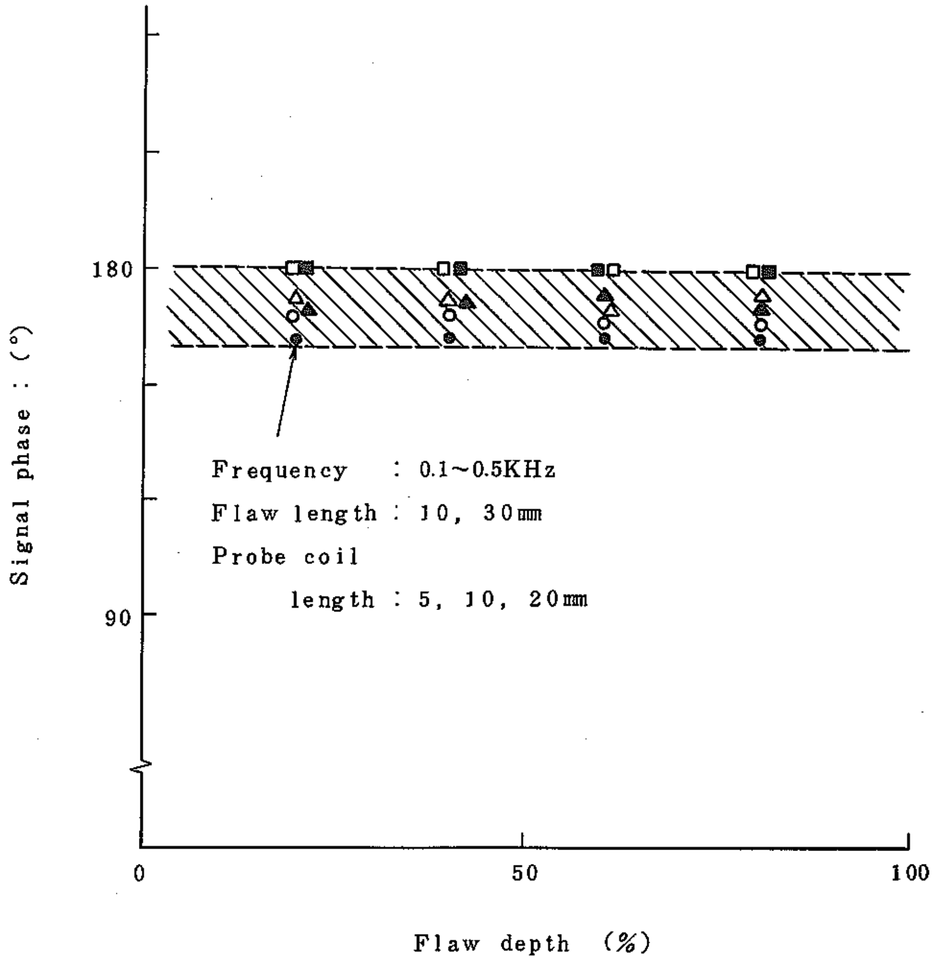


Fig 2 - 7 Relationship Between Signal Phase vs Flaw Depth
(Inner surface wall thinning)

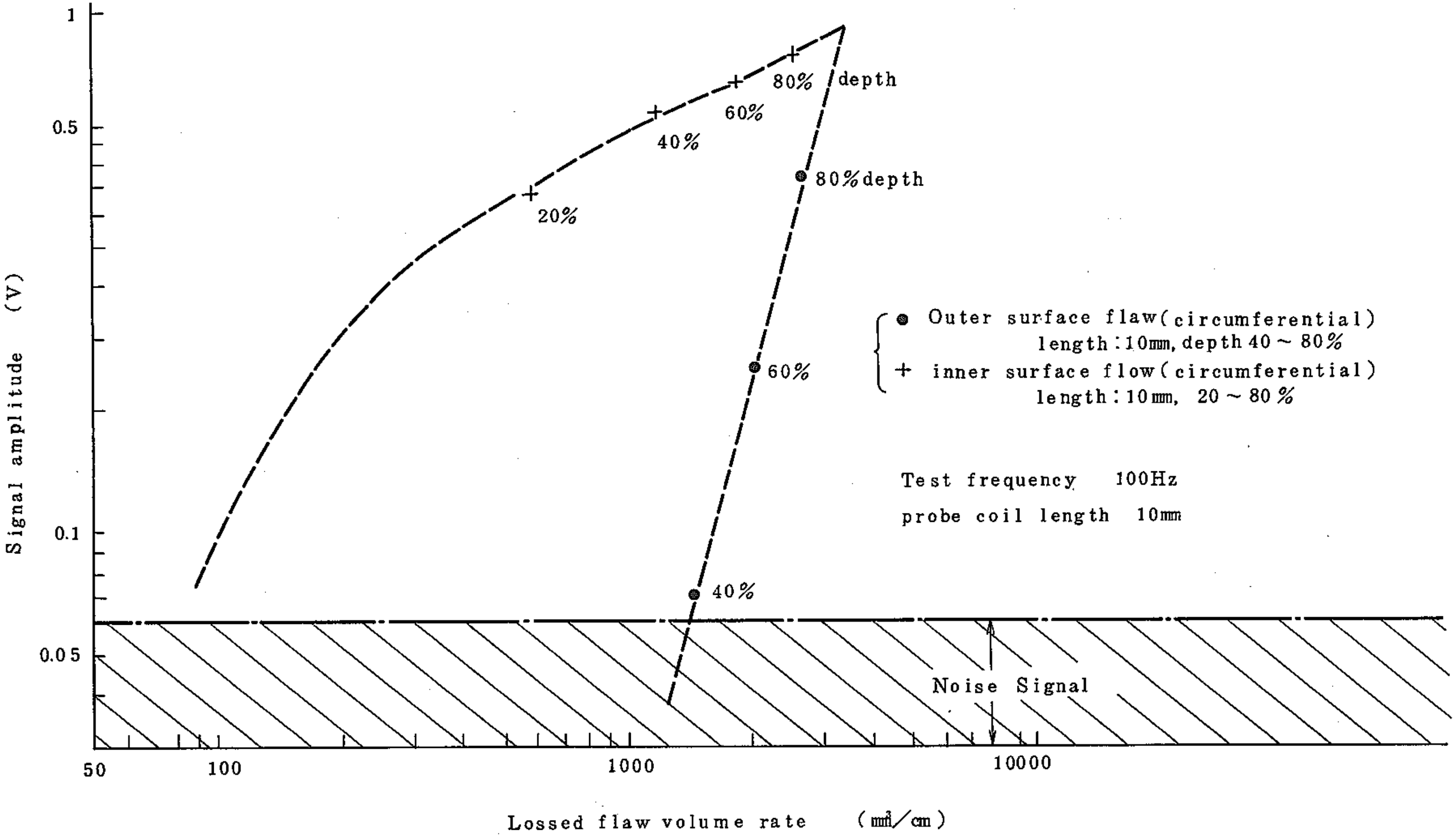


Fig 2-8. Relationship Between Lossed Flaw Volume vs Signal Amplitude

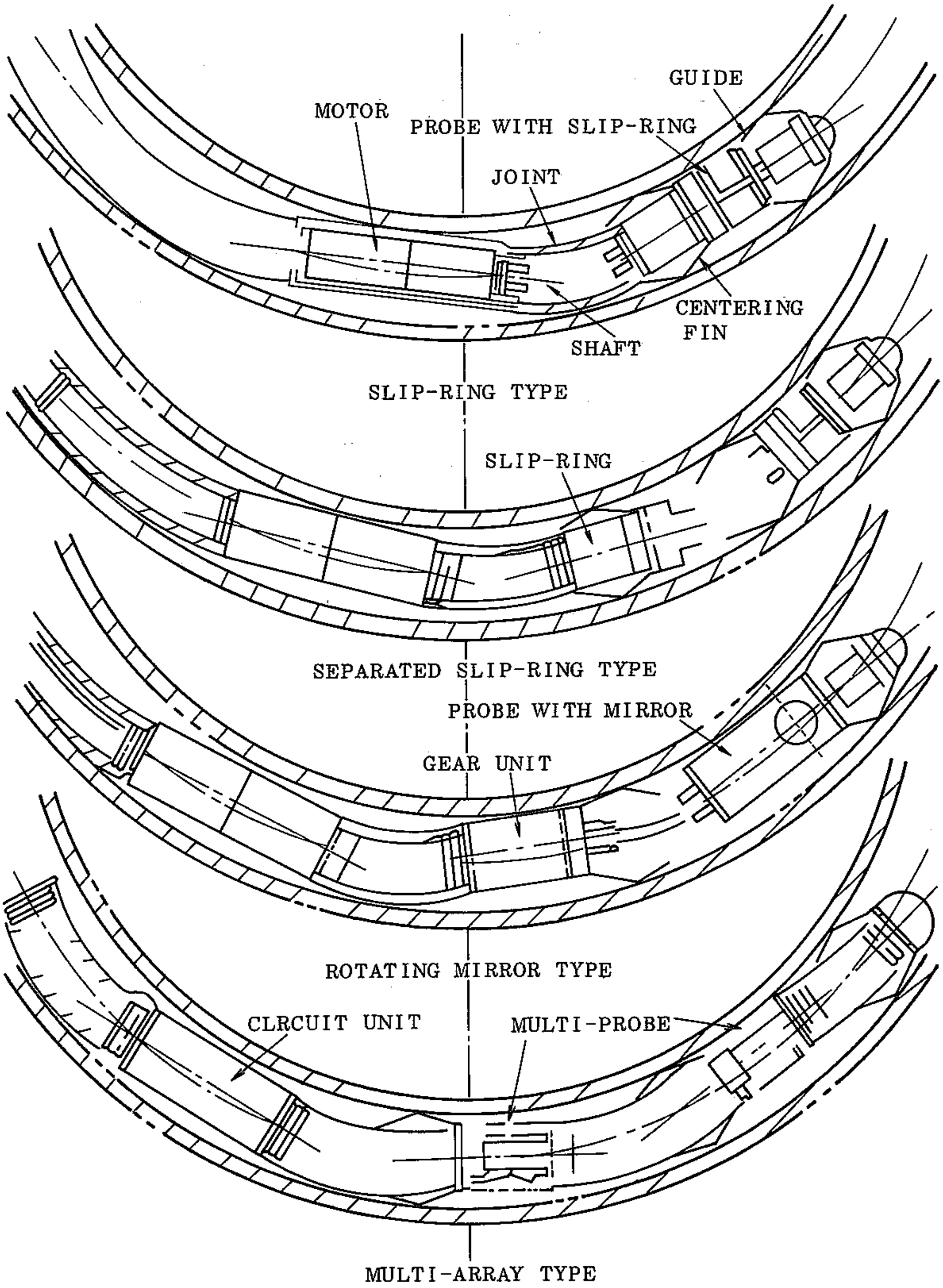


Fig 2 − 9 Probes for Ultrasonic Exmination

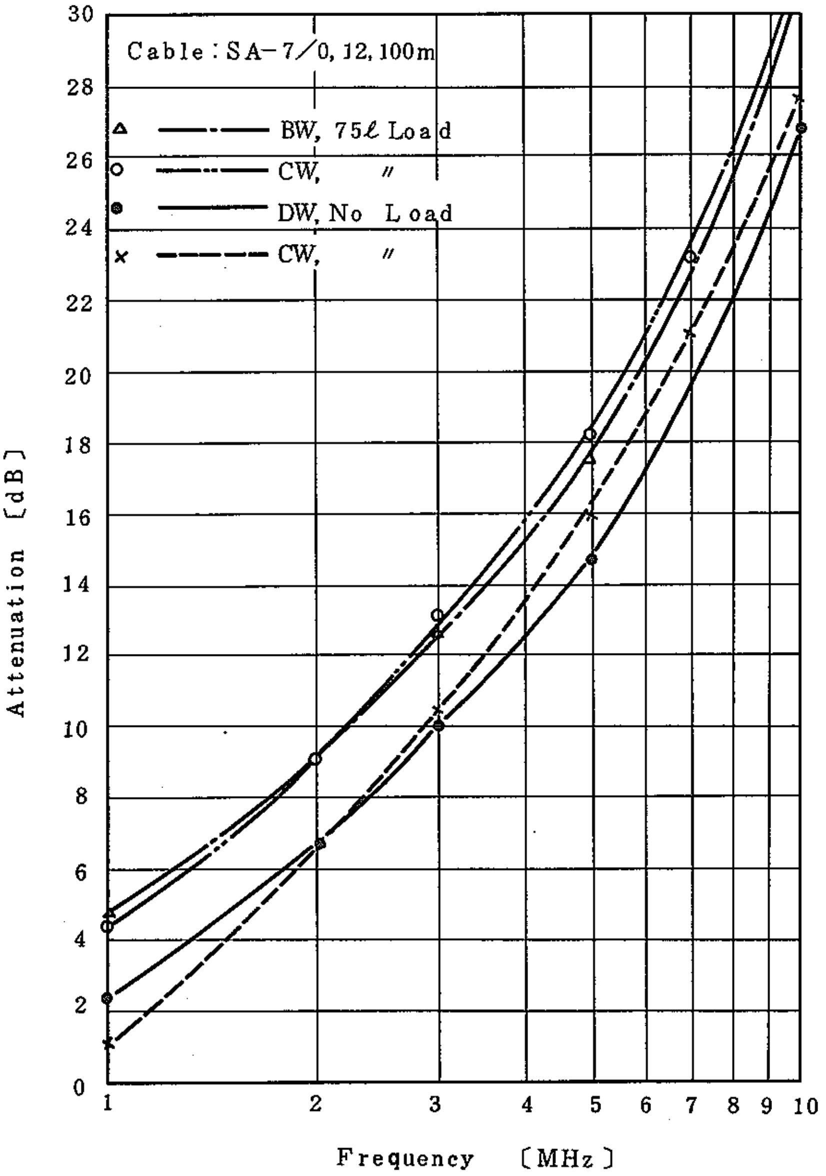
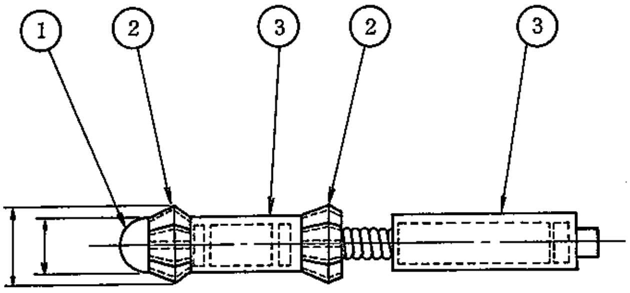
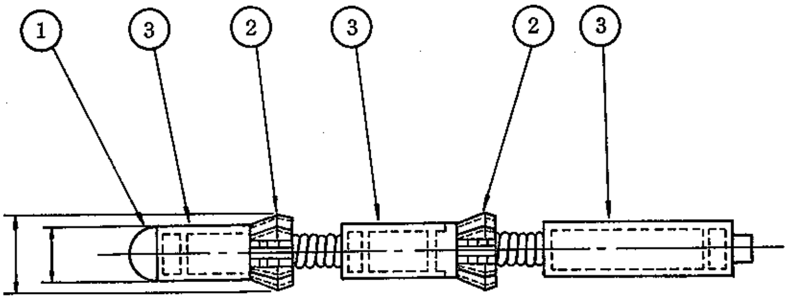


Fig 2 - 10. Frequency Characteristics of Signal Transmission Cable

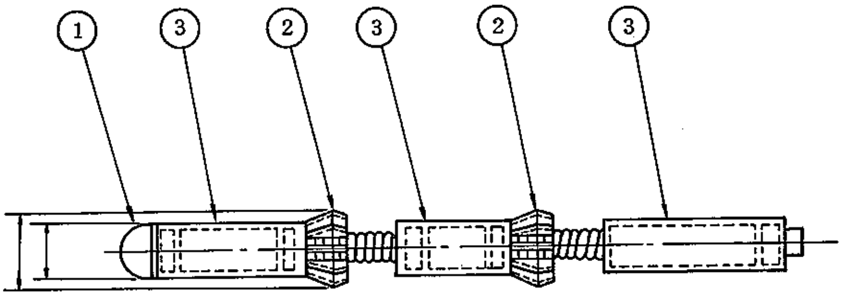


	MATERIAL
①	PCUMERIZED CONPOUND
②	
③	304 SS

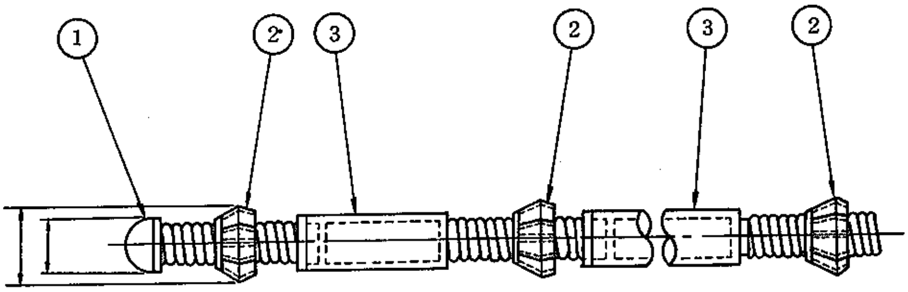
Slip Ring Type



Separated Slip Ring Type



Rotating Mirror Type



Multi-Array Type

Fig 2-11 Configuration of Model Probe

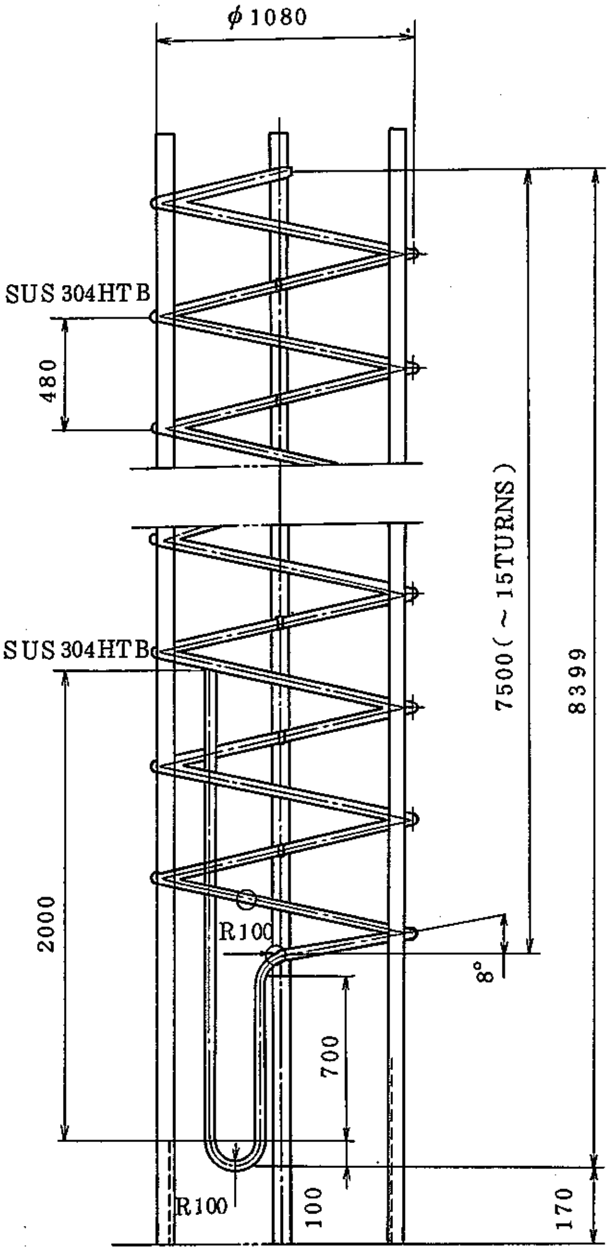


Fig 2 - 12. Configuration of Helical Coil Tube Model

(Sign ⊗ means part of tube-to -tube weld. There are 5 parts of weld.)

Testing Condition

Item	Condition
Tube	Helical Coil Tube
Model Probe	Slip-Ring Type
Outer Diameter-of Cable	ϕ 3.2 mm
Attitude of Coil	Vertical
Atmosphere	Air

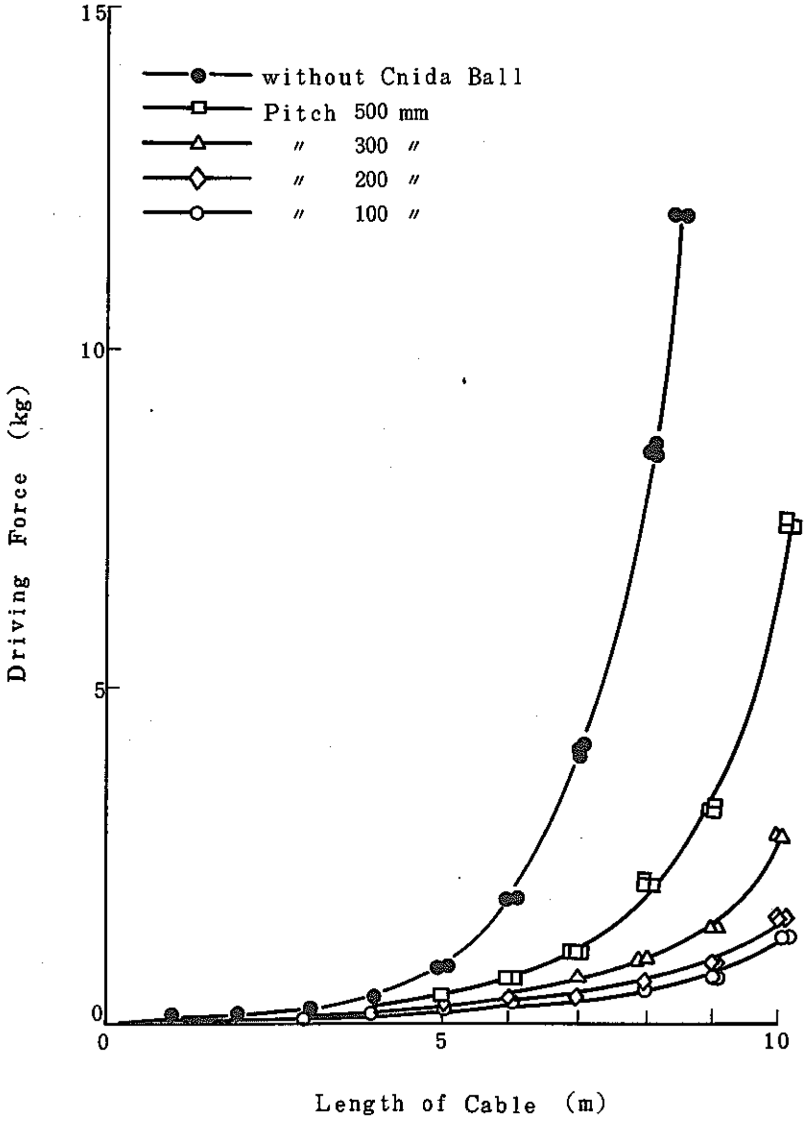


Fig.2−13 Effect of Guide Ball Pitch on Driving Force.(ϕ3.2mm. in Air)

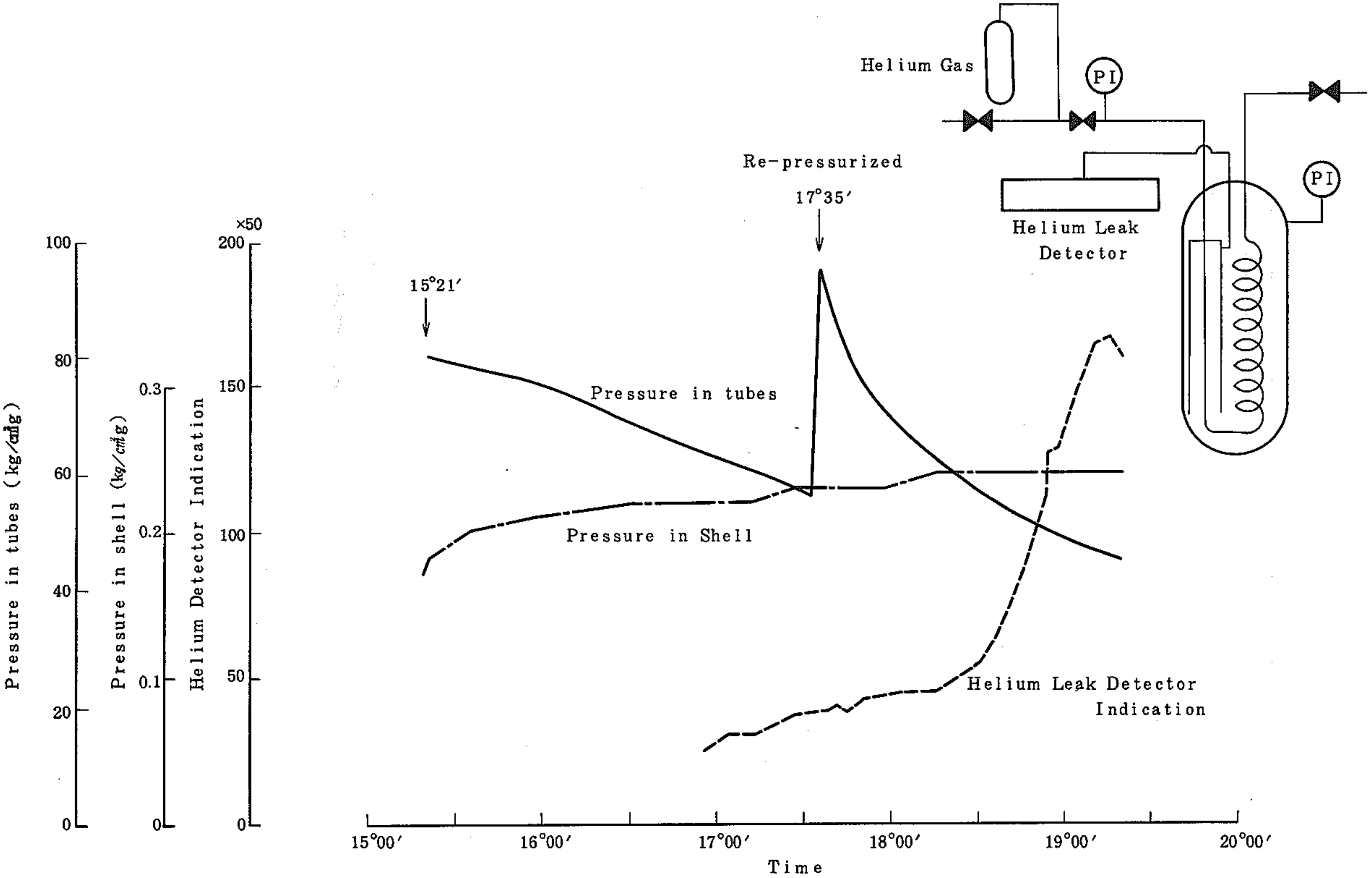


Fig.2-14 Result of Hellium Leak Detection for two Tubes in 1 MW SG

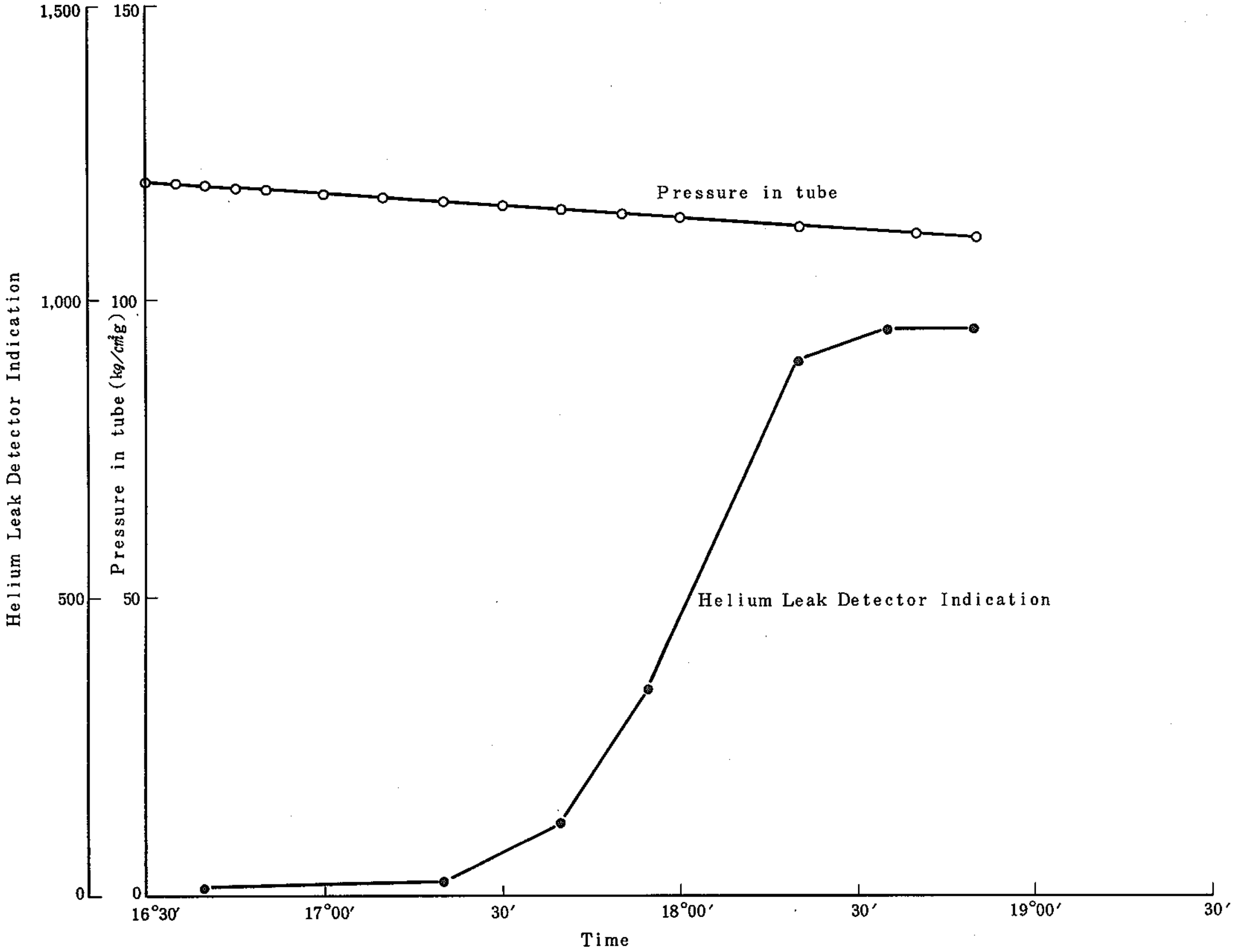


Fig. 2−15 Result of Hellium Leak Detection tor damaged tube in 1MW SG

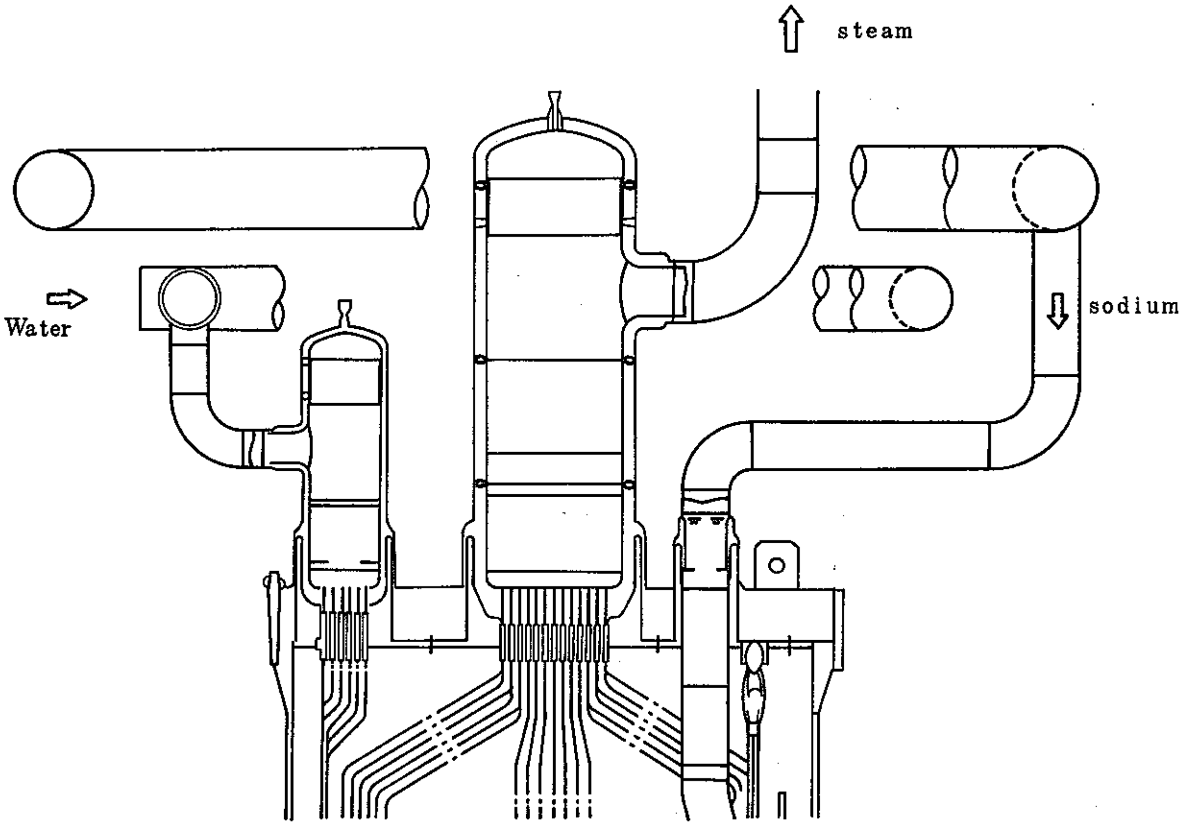


Fig 3 − 1 Schematic Plan of the top of "Monju" Steam Generator