DETECTION OF UNDERCLAD DEFECTS BY NON DESTRUCTIVE TESTING

非破壞試驗에 依한 언더크래드의 探傷

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1. INTRODUCTION

Discovery of underclad cold cracking phenomenon in steam generator tube sheets (fig. 1) and under the cladding of reactor vessel nozzles (fig. 2) led FRAMATOME to study, develop and quality non destructive examination methods capable of detecting and characterizing these types of defects. To reach this objective, FRAMATOME started by studying the possibilities of various NDT methods, after which the following two techniques were retained:

a) ultrasonic testing for examination of tube sheet before drilling of reactor vessel nozzles
b) Eddy current testing by internal probe for examination of drilled tube sheets with tubes installed.

〈概　要〉

Framatome 社는 보일러管板(그림1)에서의 언더크래드 冷間균열의 探知와 反應容器노즐(그림2)등에서 發生되는 결함을 檢出 또는 特性化할 수 있는 非破壞檢査를 硏究, 發展시켜서 規格化함에 이르렀다.
즉 反應容器노즐을 만들기 전의 管板을 검사하기 위한 超音波探傷試驗法
그리고 管에 內藏된 구멍이 뚫린 管板의 檢査를 위한 內部型 탐촉자에 따른 渦流探傷試驗法 등이다.
그리하여 結論的으로는 FRAMATOME 社는 다음과 같은 効果的 成果를 얻었다.
(1) 問題解決에 매우 적합한 方法의 選擇
(2) 안쪽管에서 實施되는 渦流探傷試驗에 있어서의 매우 적합한 方法의 認定

2. CHARACTERISTICS OF DEFECTS TO BE DETECTED

The type of defects to be detected originated from the same source for both tube sheets and reactor vessel nozzles: a cold cracking phenomenon was involved in both cases.

The tube sheets have an inconel cladding with an average thickness of 8mm, and the base metal was up of SA 508 cl. 3 type steel.

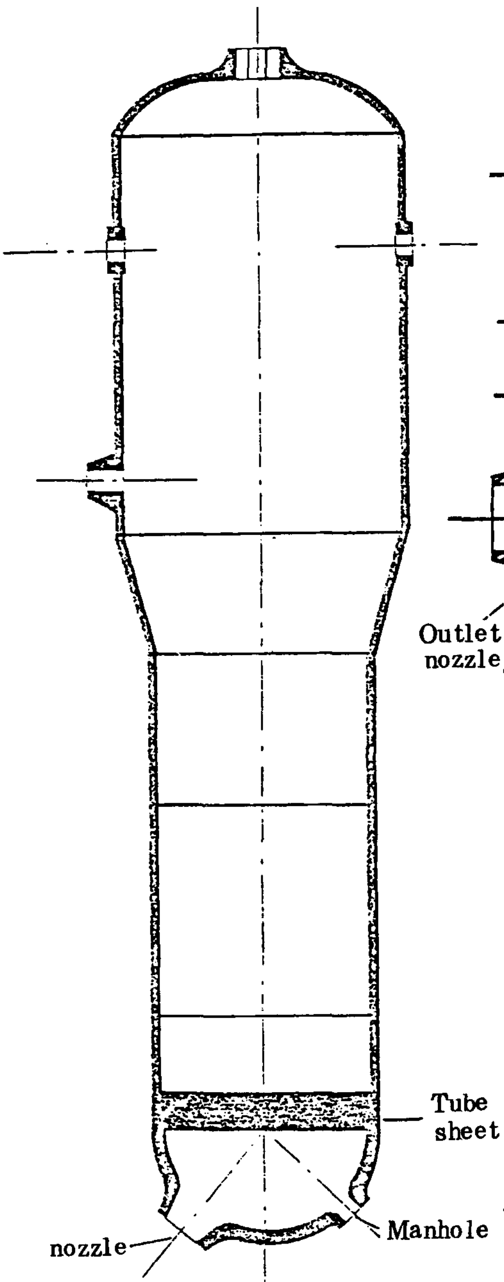


Fig. 1 Steam generator

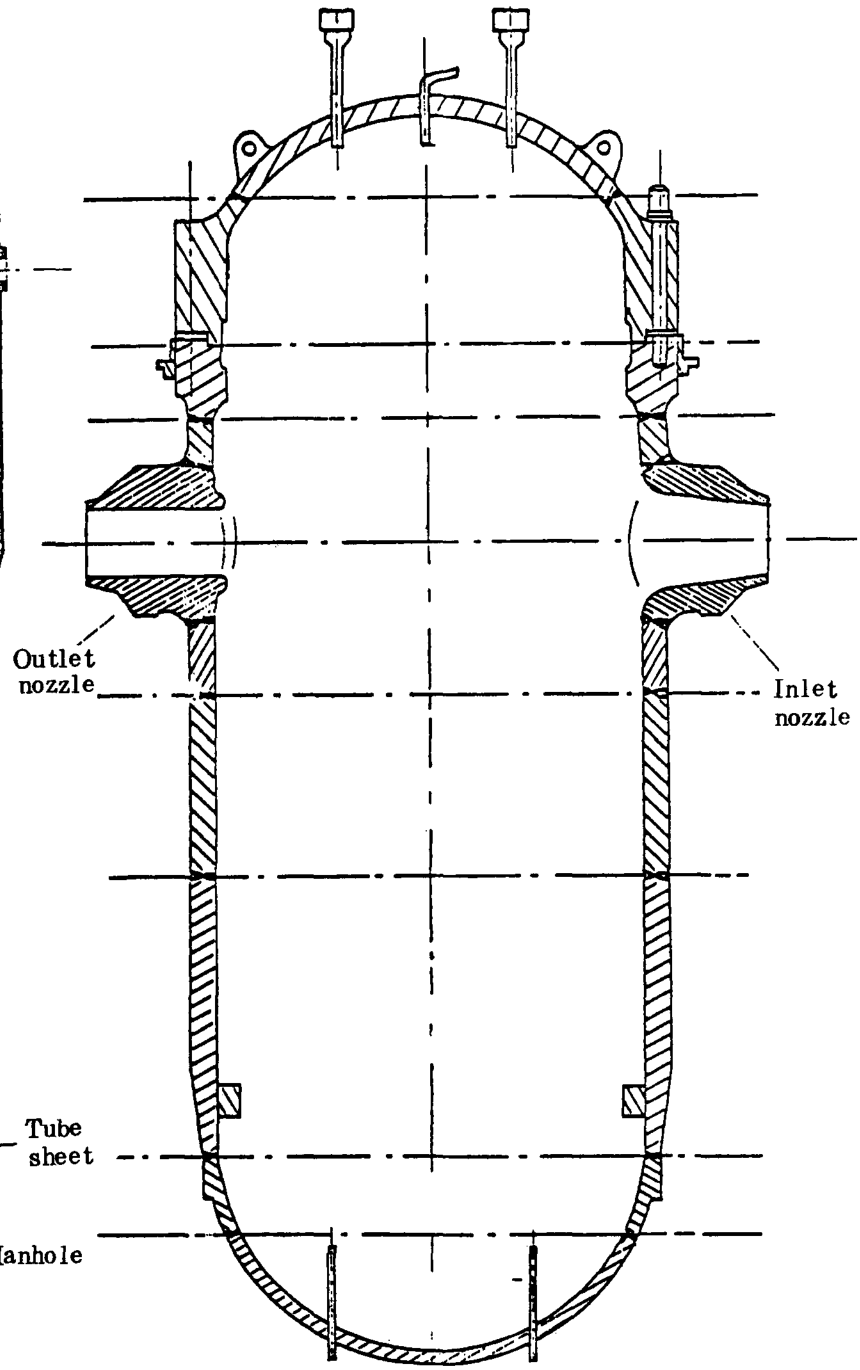


Fig. 2 Reactor vessel

The reactor vessel nozzles have a stainless steel cladding which is also about 8mm thick. The base metal was also made up of SA 508 cl. 3 type steel.

In both cases the cracks are situated in the base metal and stop at the interface between the base metal and cladding. They are perpendicular to the cladding-base metal interface.

3. ULTRASONIC INSPECTION METHODS

The ultrasonic method was chosen for the detection of underclad cracking:

a) in non drilled tube sheets
b) in reactor vessel nozzles.

3-1. Principles of method

Various tests were performed by FRAMATOME in cooperation with the French Atomic Energy Commission (CEA) and Electricite de FRANCE (EDF). These tests were performed on models and on parts containing artificial and actual defects. The tests were mainly concerned with the choice of refraction angle in steel, wave mode and the types of probes to be used. Following these tests FRAMATOME chose the ultrasonic method using inclined longitudinal waves at angle of about 70° in the base metal for detection of cracks. It should be noted that this method was advocated by various research organizations notably for reheat cracking.

FRAMATOME studied and adapted two test techniques based on the inclined longitudinal wave principle: a manual inspection method with separate transmitter/receiver probes.
an automatic inspection method with underwater focused probes (in cooperation with CEA)

3-2. Manual ultrasonic inspection

Two TR type inclined longitudinal wave probes were used depending on the kind of surfaces to be tested:

- the first type of probe is used to inspect even or large radii curved surfaces
- the second type of probe is used to inspect small radii curved surfaces.

3-2-1. Probes used for inspection of even or large radii curved surfaces. (tube sheets, bores of the nozzles)

The probes used by FRAMATOME are BAM SE 70 L2 150 or SONATEST SE 2.25 MHz (the latter attached to a plexiglass probe shoe inclined at an angle of 26°) of the transmitter receiver type.

To compare the different probes used, FRAMATOME performed analysis of acoustic beam behaviour in stainless steel and base metal for both crystals in each probe. The results were recorded at

-6, -12 and -18 dB. fig. 3 shows beam characteristics at -6 dB for both probes (BAM and SONATEST).
Analysis of experimental results produced the following data:

- the refraction angle of both probes is identical: about 61° (fig. 4)
- the crossing of the stainless steel-base metal interface did not appear to affect beam homogeneity
- for each probe isoenergetic curves generated by both crystals were very similar.
- for BAM probe:

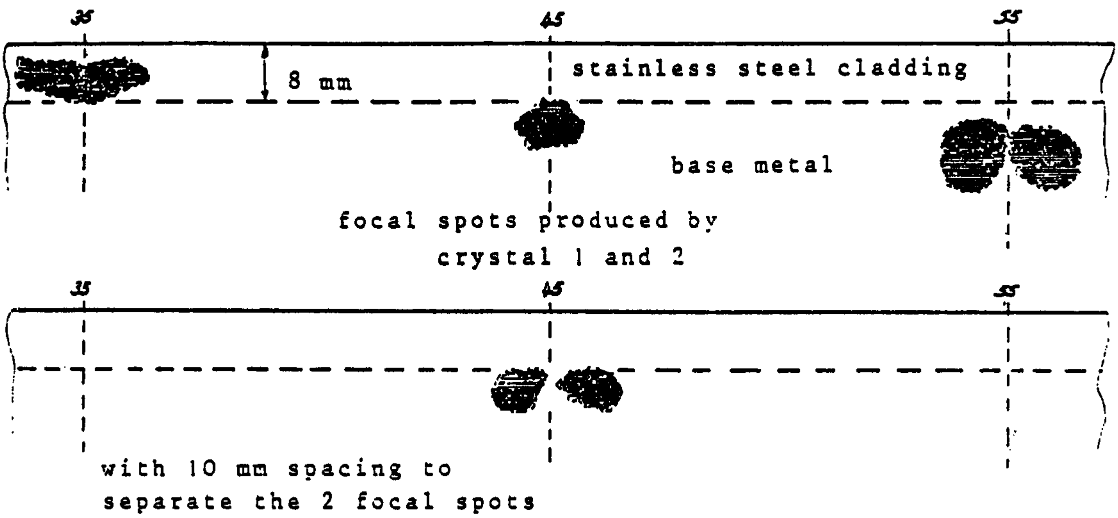
  the beams crossed each other at a depth of about 10mm. At about this depth each beams' dimensions for -6 dB were smallest (limit of near field). Therefore, it is at this depth that the best detection sensitivity and signal to noise ratio is obtained; this is confirmed by the curves given in fig. 5

  However beyond this 10mm depth zone, the beams rapidly separate and this becomes even more marked the deeper one goes.
  Therefore, outside this zone, detection sensibility and signal to noise ratio strongly decreases. This is confirmed by the curves given in Fig. 5.

  For SONATEST Probe "modified stainless steel".
  The beam axes crossed each other at a depth of 16mm. On the other hand the beams emitted by each half-crystal started to converge at a depth of less than 5mm and the minimum dimensions for -6 dB for each beam is located at a depth of about 6mm. Optimal detection sensitivity level and signal to noise ratio is therefore situated at a depth of between 5 and 20mm i-e at a depth where marked beam intersection occurs. This takes place at a depth of 10mm which is confirmed by the curve given in fig. 6.
  Below 10mm, single beam dimensions further decrease as well as the intersection zone. Above 10mm these parameters increase. This phenomenon leads in the case of the SONATEST "modified stainless steel probe" to a lesser reduction in detection sensitivity level and signal to noise ratio at a depth of about 10mm than for the BAM probe.
  If the BAM probe appears to be best suited for detection of defects located at the limit of the interface zone (because at this depth beams cross and dimensions are minimal whilst acoustic pressure is at a maximum its range of use at depth is extremely reduced. Therefore, a reflector with a large vertical measurement risks to have this latter dimension greatly underestimated by the BAM Probe (if the -6 dB method is used).
  If, however, none of the SONATEST "modified stainless steel probe (sensitivity, beam dimensions, common surface) do not appear well suited for applications at the limit of the interface zone, on the other hand, large defects measured in the vertical direction should be evaluated much more accurately than with BAM probe.
  This is because the depth of the detection range is much greater. It should be noted that the BAM probe is more sensitive for the detection of defects located at the limit of cladding area

BAM Probe

Focal spots at - 6 dB



"Modified stainless steal"
SONATEST Probe -

Focal spots at - 6 dB

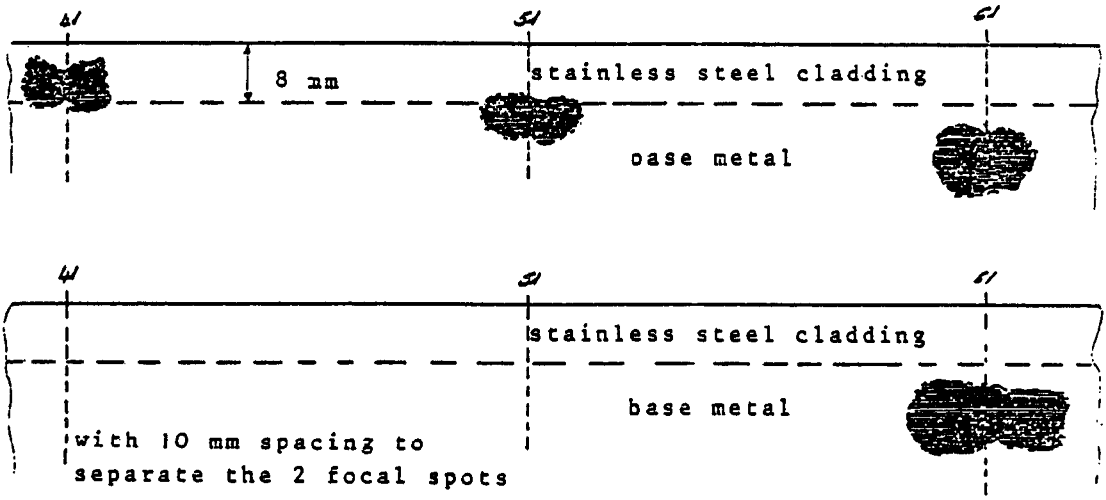
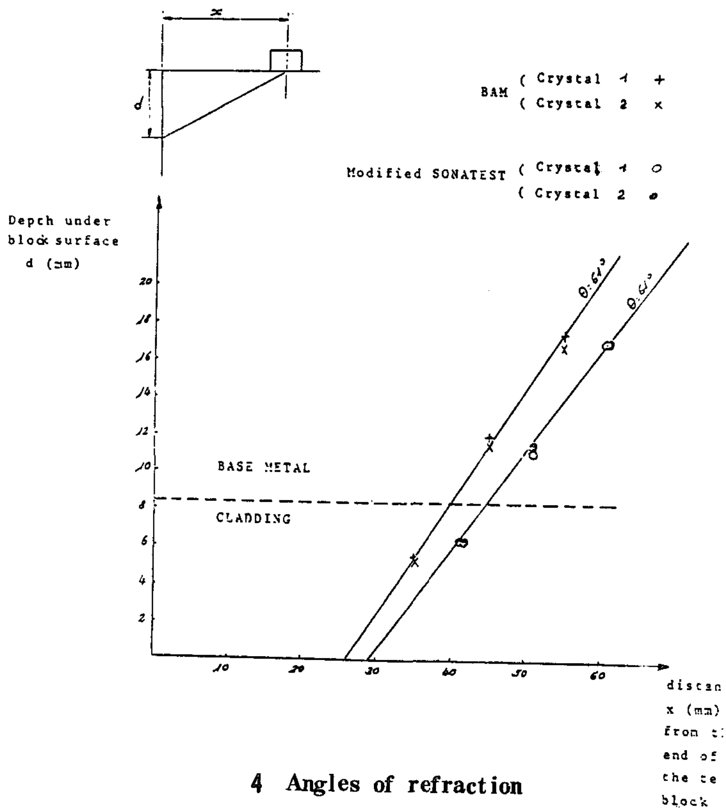


Fig. 3 Focal spots Fig.



4 Angles of refraction

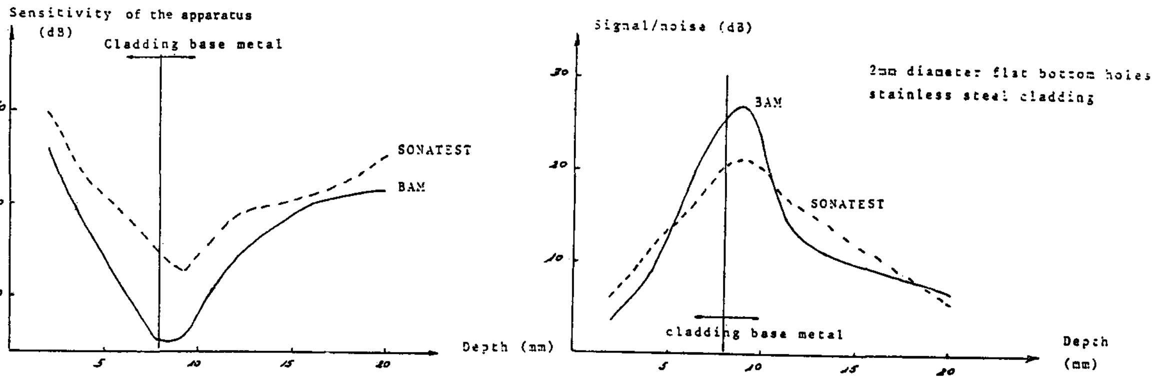


Fig. 5 Graphs:Signal to noise ratio sensitivity

but that the SONATEST "modified stainless steel" probe performs more efficiently when identifying serious defects located at depth. Therefore the two probes appear to have complementary functions.

3-2-2. Probes for inspections of small radii curved surfaces (radii of inlet nozzle)

Probes developed for inspection of even or large radii curved surfaces are not suitable for small radii curved surfaces due to their flat crystals and the small size of shoes used. Therefore FRAMATOME was called upon to develop special probes and to demonstrate that test sensitivity for all radii of curves was equivalent.

The probe developed by FRAMATOME has the following characteristics:

- contact probe with shaped shoe
- diameter crystal: 30mm half cut
- dome shaped crystal
- crystal material: PZT
- frequency: 2MHZ
- type of waves: longitudinal
- separate transmitter and receiver.

A beam analysis (fig. 6) shows that the FRAMATOME probe has almost the same characteristics as BAM's:

- the refracted angle in the block: 66° (BAM: 61°) (fig. 7)
- depth of beam convergence: 9, 5mm (BAM: 10mm)

With a more detailed approach it can be seen that minimum dimensions at -6 dB for each beam are located at a depth of 3mm but these beams do not cross.

However, a marked beam intersection can be observed at a depth of 8mm. At this depth detection sensitivity should be at its most efficient and this is confirmed by the curves given in Fig. 6.

To conclude, although the most efficient sensitivity level is not obtained at the depth where the beam dimensions are at their lowest point (bam probe's characteristics), their dimensions are however lower than BAM's at a depth of 8mm.

The refraction angle is slightly larger than BAM's and at a first sight is more efficient for detecting defects which are perpendicular to the scanning surface.

The inspection methods used on (1) even and large radii curved surfaces and on (2) small radii curved surfaces are identical except for the following two differences:

- the type of probe to be used
- the surface condition of the zone to be inspected and consequently the calibration block which is needed to set the sensitivity level for examination.

All other parameters are identical and may be applied to either of the two surface types. The type of probe which was specially developed to inspect small radii curved surfaces has characteristics which are comparable to or slightly more efficient than the Bam probe's.

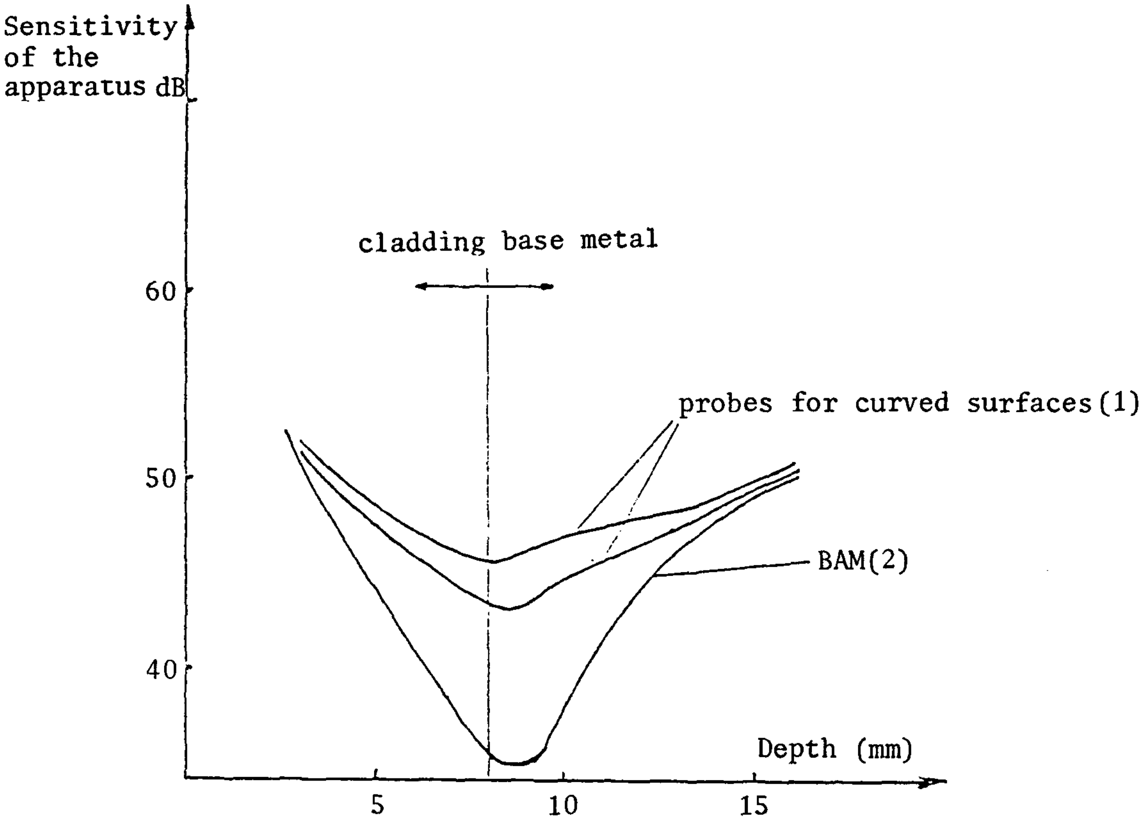


Fig. 6 Comparison between probes used for :
1) Small radius curved surfaces
2) Even and large radius surfaces

In fact:

- at the same convergence depth the beam's measurements are smaller at -6 dB
- the loss of sensitivity around maximum sensitivity is less marked (fig. 6). Therefore at a depth of 5mm, sensitivity level is only 4dB whereas with the Bam probe a comparable loss occurs at 11dB. This gives greater range for detection at depth.
- the signal to noise ratio for holes located at a depth of between 4 to 12mm is greater for 12dB.

Calibration, which is performed using blocks representing the curves (radii-surface condition), ensures a severity level (detection-characterisation) comparable to that obtained when inspection even or large radii curved surfaces.

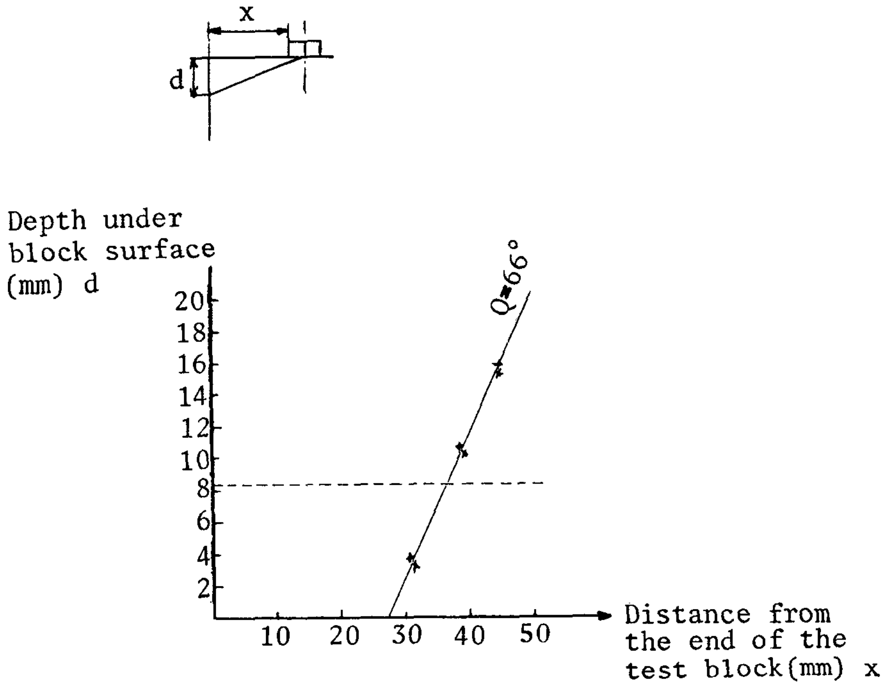


Fig. 7 Refraction angle in part

3-2-3. Operation of manual inspection.

Inspection is performed in two parts:

Part 1: inspection with inclined longitudinal wave probe of the BAM or "modified SONA-TEST" types

Part 2: inspection using KRAUTKRAMER SEB 4 KF 8 type probe with straight beam on the indications detected in part 1.

The setting of apparatus is performed on blocks which represser the part to be inspected and which contain flat bottomed 2mm diameter holes at the base material-cladding interface.

The characterzation of indications into inclusion or non inclusion types is based on the comparison of responses obtained from the above two inspection operations.

The following are considered as being inclusions:

– all indications whose depths determined by the 1st probe are lower than or equal to the thickness of cladding.
– all indications whose depths are greater than the thickness of cladding when a response, obtained with the SEB 4 KF 8 probe, is greater than 50% of the reference level for a depth equal to within 2mm of that obtained with the 1st probe.

In all other cases, indications are to be considered as being cracks.

3-2-4. Results obtained.

Inspection can only be performed using machined or ground surfaces having a roughness of 6.3Ra

- when inspecting tube sheets the manual U.T. method which was developed allowed detection of cracks up to 0,7mm deep and 5mm long.
- when inspecting reactor vessel nozzles, the inspection method applied to the machined surface allowed stainless steel underclad cracks to be detected when their area was slightly greater than 2mm 2.

A small number of cracks were not detected during inspection because of difficulties relating to the small dimensions of the beam in the scanning zone. Nevertheless, efficiency could be improved by increasing the number of tests. Performance of two successive examinations ensures detection of all cracks which are greater than or equal to a height of 3mm.

The inspection method applied to ground surfaces gives results which are comparable to those obtained from machined surfaces. Comparative tests performed showed, however, that difference in surface condition lead to an average loss in sensitivity of 2dB which can reach 4. dB in places. The extent of this difference only has a negligeable effect on inspection operations.

The manual method may be applied with equal efficiency to either even or small and large radii curved surfaces.

3-3. Automatic inspection using underwater focalised probes

Detection of underclad cracks with contact probes becomes complicated very quickly as it involves repeated inspection over large surface areas, as is the case with plant and site equipment (In Service Inspection).

The small diameter of SE type probe's focal spot size leads, in fact, to excessively long examination times.

These factors led FRAMATOME to study and develop automatic inspection methods for examination of reactor vessel nozzles. These studies were performed in cooperation with Electricite de FRANCE (EDF) and Compagnie Genèrale de Radiologie (C.G.R.) insofar as in plant test applications are concerned, and with EDF and CEA for site testing applications.

3-3-1. Technique used.

The method used is again based on use of inclined longitudinal waves entering the steel at an angle of about 70°. These waves are produced by focused underwater transducers mounted on an automatic testing apparatus.

- One of these transducers is adjusted at right angles to the inspection surface. It is designed to obtain an echo from the wall upon which the window is synchronised.
- The two other transducers which are located on each side of the first transducer, are inclined at an angle of 14°. The axes of these two transducers converge with that of the first trans-

ducer on the scanning surface. These transducers are designed to detect cracks (Fig. 8).

The equipment chosen by FRAMATOME is as follows:

– the synchronisation transducer is referenced PANAMETRICS 308 R and has a 19mm diameter crystal working at a frequency of 5 MHZ.
– the other two transducers are both referenced PANAMETRICS V 395 equipped with highly damped crystals 38mm in diameter.

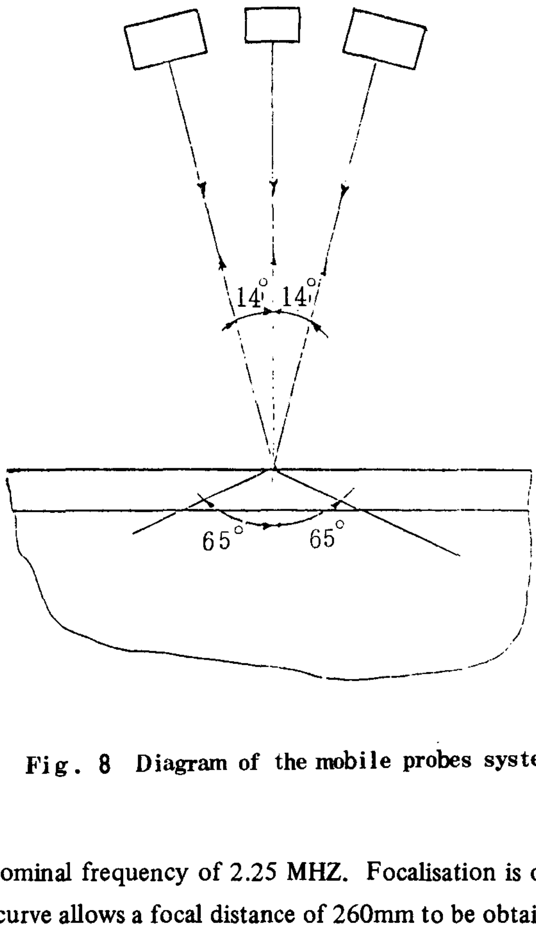


Fig. 8 Diagram of the mobile probes system

They function at a nominal frequency of 2.25 MHZ. Focalisation is obtained through a masked lens. The radii of the lens curve allows a focal distance of 260mm to be obtained underwater. The focal spot is 6mm in diameter at -6 dB. The purpose of the mask is to eliminte spurious echos originating from the condition of the scanning surface.

The analysis of the transducer beam which is used for automatic inspection of the nozzles was also performed. Cross sections of beams were established at the point where the beam enters the part, i-e after travelling 180mm underwater. These cross sections were established at -2, -6, -12 and -18 dB and are given in Fig. 9 for a masked and a non masked transducer (underwater incidence angle of 14°).

It can be seen that the existence of the mask leads to beam decay. From the cross section of the 130mm radii it can be noted that the focus spot increases laterally to about 10mm at -6dB.

In the cross section through the generatrix of the cylindrical lens, the crystallength changes from 38 to 28mm and the apparent near field in this direction is 300mm in length. The 180mm cross section approaches the near field limit (about 2/3) and only measures 17mm at -6dB.

3-3-2. Results obtained.

As is the case with manual inspection using TR probes, the qualification test for the method using focalised transducer was performed on those nozzles having a great number of cracks of various sizes. Insofar as crack detection is concerned, the sensitivity of this method for identifying 2mm 2 surface cracks was proven and no cracks greater than 3mm in height remained undetected.

These results were obtained from both ground and machined surface conditions.

The characterisation into inclusion and non inclusion type indications is not possible, however, at the present time. FRAMATOME is directing its efforts in this direction as well as in the measurement of crack height.

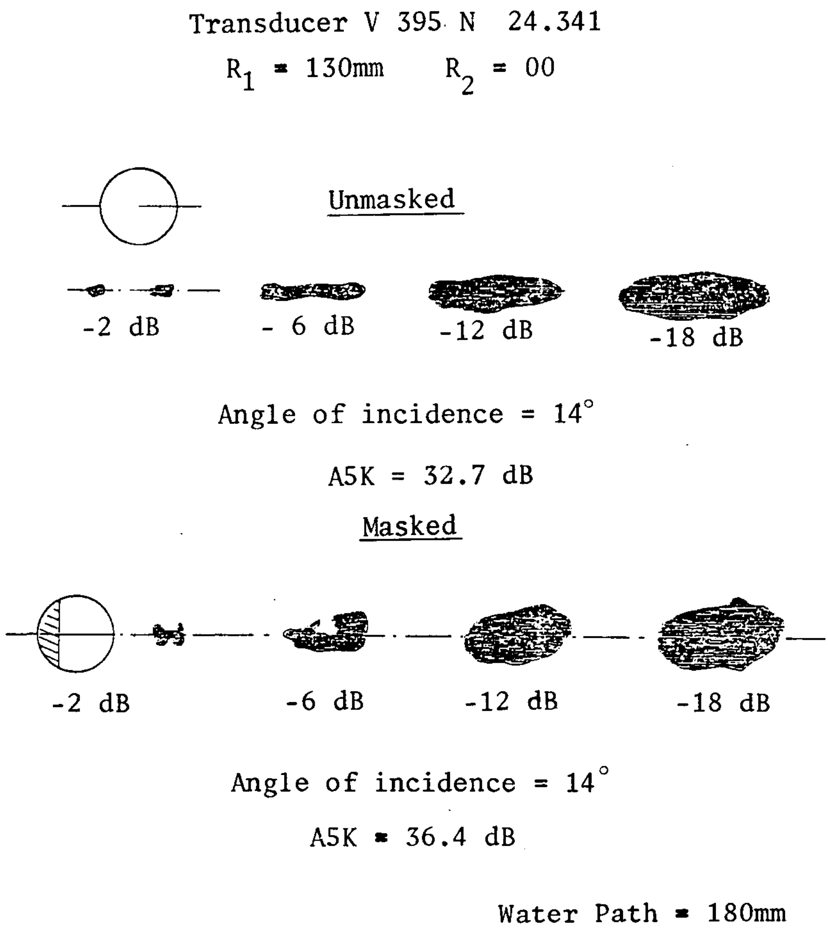


Fig. 9 Beam cross sections

4. EDDY CURRENT INSPECTION METHOD

The specific geometry of drilled steam generator tube sheets with tubes installed raised a delicate problem for the development of a suitable underclad crack detection method. Methods such as R.T., U.T. thermography and Eddy current testing on cladding surfaces were envisaged but dropped after preliminary studies and tests. Finally FRAMATOME chose the eddy current testing method applied to the inside of a tube. The principles of this method were developed by the CEA.

4-1. Description of method.

The method developed uses a differential probe which is rotated inside the tube. This method only allows cracks which emerge on the surface of the tube sheet holes to be detected.

A diagram of the inspection equipment used is given in Fig. 10. It includes a probe with a mobile operation system and control bay.

The probe (fig. 11) includes two coils electrically connected to a balanced impedance bridge. If a discontinvity cause a break in the electromagnetic field, the bridge is unbalanced and gives rise to a variation in measurable voltage.

Calibration is performed using a reference block containing a defect produced by E.D.M. This reference defect is located in the base metal at the limit of the clad-base metal interface. It is 3mm high and 1mm long. A frequency of 25 KHz is used for inspection.

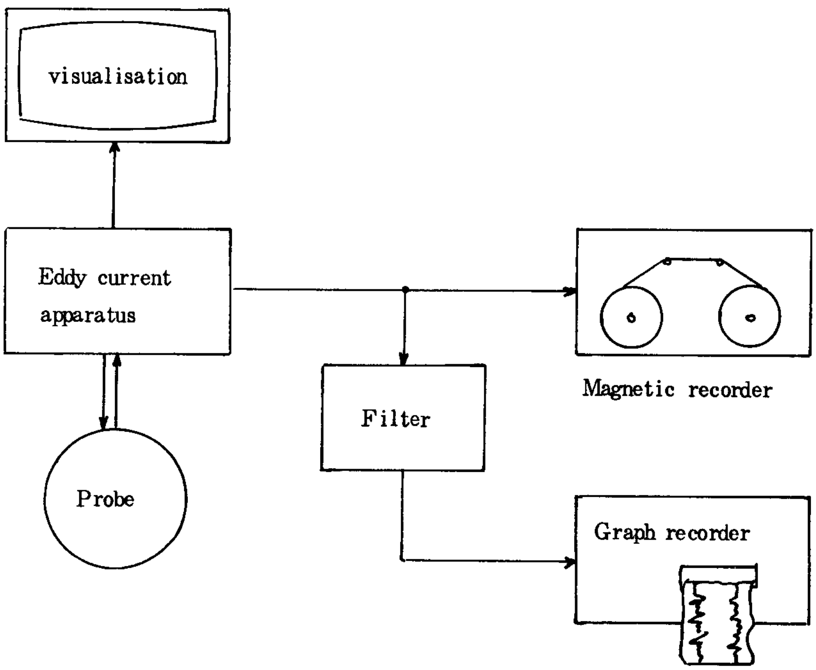


Fig. 10 Diagram of the eddy current testing system

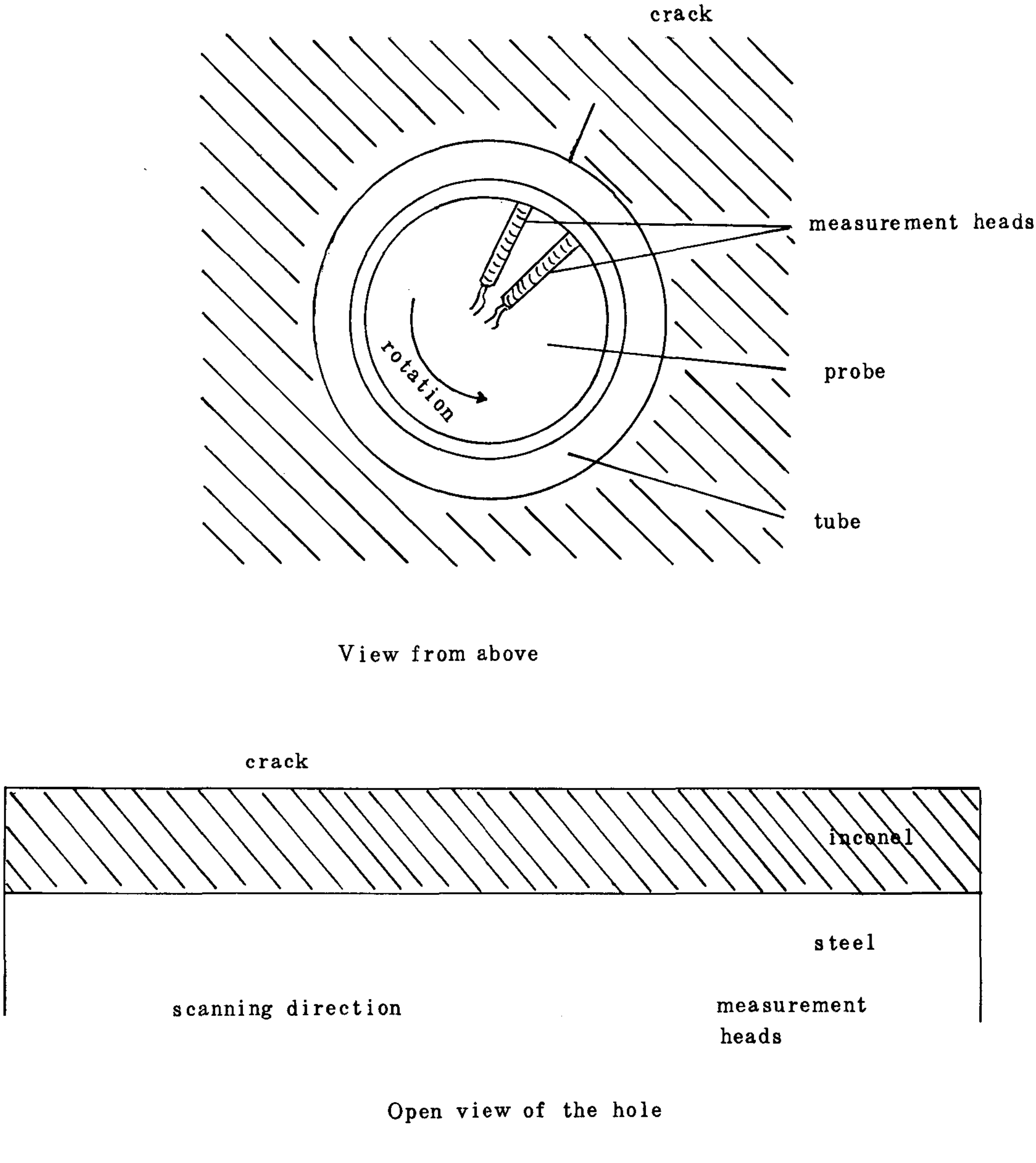


Fig. 11 Differential measurement principle used

4-2. Tests performed and results obtained.

Several tests were performed on:

- representative test blocks with artificial defects produced by E.D.M.
- a tube sheet containing natural defects
- representative models with fatigue cracks obtained from notches produced by E.D.M. and subjected to fatigue test.

4-2-1. Crack detection

Defects identified by dye penetrant test and situated at right angles to the metal base-clad interface were located on tube sheets. Before tubing, all defects were redetected using eddy current.

After tubing and tube expansion, almost all previously detected indications were located.

For the representative model having defects produced by EDM, it can be seen that fatigue cracks are able to be detected when cracks are propagated in inconel and steel sides with or without stressing of test piece.

4-2-2. Characterisation of indications.

Possible defects other than cracks cannot be detected by eddy current.

Characterisation of crack height obtained from a signal following several rotations of the Eddy current probe gave rise to a signal which overestimated height by about 2mm for the inconel side and by about 5mm for the steel side when compared to visual estimation and to results obtained from eddy current examination before tubing. This overestimation occurs systematically and can be attributed to the air-gap caused by the tube thickness and by the difference in magnetic permeability between inconel and steel.

4-3. **Conclusions**

Following the work performed by FRAMATOME concerning:

a) the selection of a method well suited to solving problem

b) the qualification of a well suited method for Eddy current testing from inside tubes

FRAMATOME considered it possible to inspect steam generator tube sheet using this method as all significant crack type indications normally detected by P.T. were located by eddy current after tubing.

Atuomatic testing apparatus which allows inspection to be performed in both radioactive and non radioactive environments has been specially developed to permit on site inspection.