2001

An Evaluation of the influence of vibrations received in the distribution environment to the remaining eddy current probe lifetime

Edo Picek

AN EVALUATION OF THE INFLUENCE OF VIBRATIONS RECEIVED IN THE DISTRIBUTION ENVIRONMENT TO THE REMAINING EDDY CURRENT PROBE LIFETIME

by

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A thesis

Submitted to

the Department of Packaging Science

of Rochester Institute of Technology

Executive Leader Program

April 2001

Master of Science Degree

Department of Packaging Science
of Rochester Institute of Technology
Rochester, New York

CERTIFICATE OF APPROVAL

M.S. Degree

The M.S. degree thesis of Edo Picek
has been examined and approved
by the thesis committee as satisfactory
for the thesis requirements for the
Master of Science degree

Date: 3 JUNE 2001

Dan Goodwin
Carl de Winter
David L. Olsson

ACKNOWLEDGEMENTS

I wish to express my gratitude to all those who have helped me with my work on this thesis. My special thanks go to experts in the companies Inetec, Končar and Veski whose professional advice has helped me to carry out my experiments. I am particularly grateful do Dr. Dusko Čorak, of the Inetec, not only for his kind permission to use **ET** probes and equipment but also for creating excellent environment for this work.

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ABSTRACT

Eddy Current probes are used for the testing of steam generator tubing integrity in nuclear power plants. Their use environment is far more severe than the distribution environment, which includes truck and airplane delivery of small parcels. As each probe has soldered connections susceptible to damage this study was undertaken to investigate a possible influence of vibrations due to transport to a probe lifetime. A sweep vibration test was performed on a product with no packaging. It proved that the probe was able to vibrate in different ways unless restricted by the package. With the packaging solution defined in more detail a sample of 10 probes was exposed to random vibrations on a shaker table. Later these probes were tested for lifetime together with the sample of 10 virgin probes. Results were analyzed for statistical significance and the statistics proved the influence of vibrations to the probe lifetime. Finally, the laboratory testing results were compared with the probe lifetime data obtained during a real steam generator inspection.

LIST OF ABBREVIATIONS

DPS	- Double Guide Tube Probe Pusher/Puller (commercial name for Inetec product)
DQV	- Data Quality Verification Software
ET	- Eddy Current Testing
ID	- Inner Diameter
NPP	- Nuclear Power Plant
OD	- Outer Diameter
RBD	- Retest Bad Data (code used by ET data analysis)
PSD	- Power Spectral Density (method of scaling the amplitude axis of spectra of random signal)
PWR	- Pressurized Water Reactor type of Nuclear Power Plant
RMS	- Root Mean Square (method to display the amplitude axis of a spectrum)
VVER	- Russian Built PWR type of Nuclear Power Plants

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1. INTRODUCTION

The experience gained during the operation of both the western-built Pressurized Water Reactor type of nuclear power plants (PWR) and the same type Russian built plants (VVER), proved beyond any doubt that the integrity of the steam generator tubing is of prime importance. In these two types of nuclear power plants the steam generator tube bundle is the boundary between primary and secondary circuits.

The primary circuit flow cools the reactor and further enters the steam generator tube bundle heating the secondary circuit flow, which evaporates on the OD surface of the tube bundle. Due to the difference in pressure any possible leak escapes from the primary circuit, which is contaminated and radioactive, to the secondary circuit.

The most convenient method for inspection of the steam generator tubing integrity is the eddy current testing (ET). Regarding the inspection time and quality, it has several advantages in comparison with the other methods such as ultrasonic testing and leak testing.

The ET method is based on the appearance of eddy currents induced in the test object by the alternating current excitation of the probe coils. When ET probe passes over a discontinuity in the test object the eddy current flow changes accordingly thus affecting the probe impedance that is monitored on a lissajous. The specific shape of the signal received from the ET probe indicates a possible defect. Its depth and volume are estimated by comparing the signal amplitude and phase angle with the respective ones acquired from the calibration block (which have artificially made defects of known sizes).

The most convenient eddy current inspection technique for tubing inspection is so-called bobbin technique. The bobbin probe consists of two coils electrically connected opposite to each other, as represented in Figure 1.

The subject of this study are the ET probes for inspection of VVER steam generators represented in Figure 2. The tube bundle is placed horizontally between two vertical collectors. The number of tubes for different models ranges from 5500 to 11000.

In order to achieve the penetration into the tube with small bending radiuses the VVER probes are of a relatively small probe head diameter. The so-called fill factor (i.e. a ratio between probe head cross-section and the tube ID cross-section) is 0.8 or less.

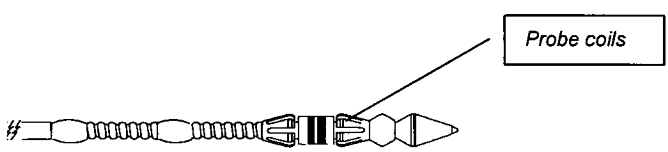

Figure 1: ET Bobbin Probe Head

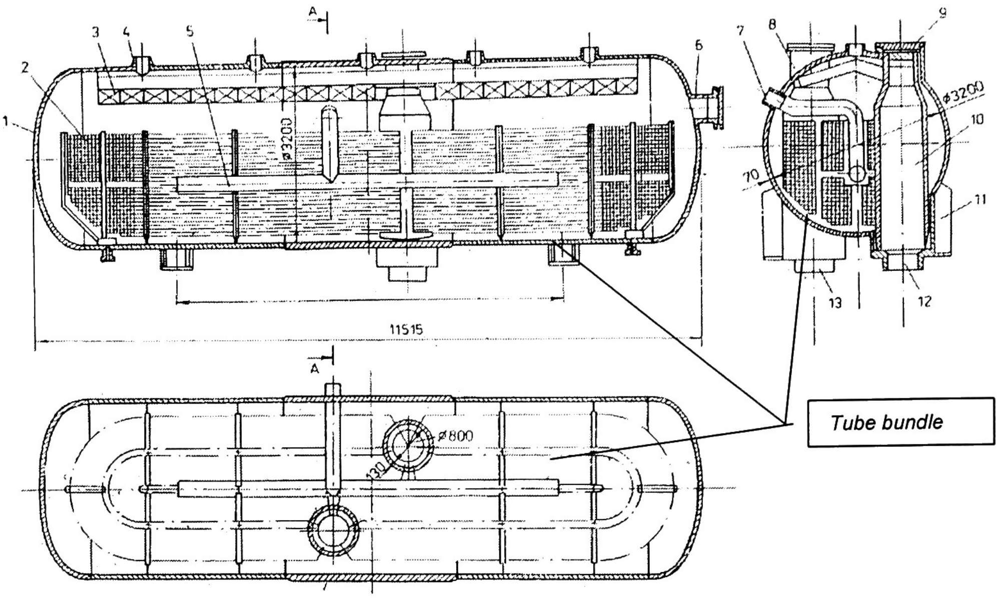

Figure 2: VVER type of steam generator

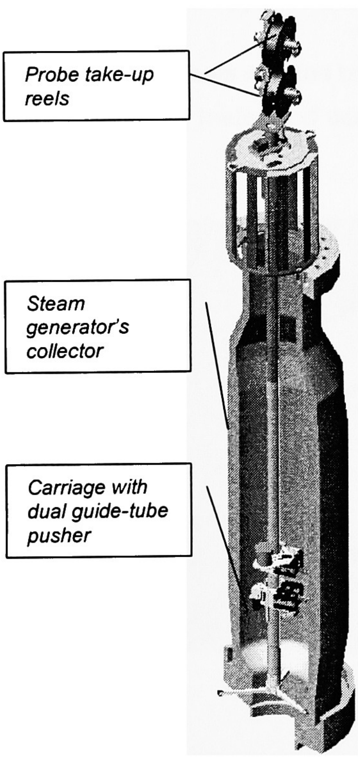

Figure 4: SM-14 Manipulator with Dual Guide-Tube Probe Pusher/Puller

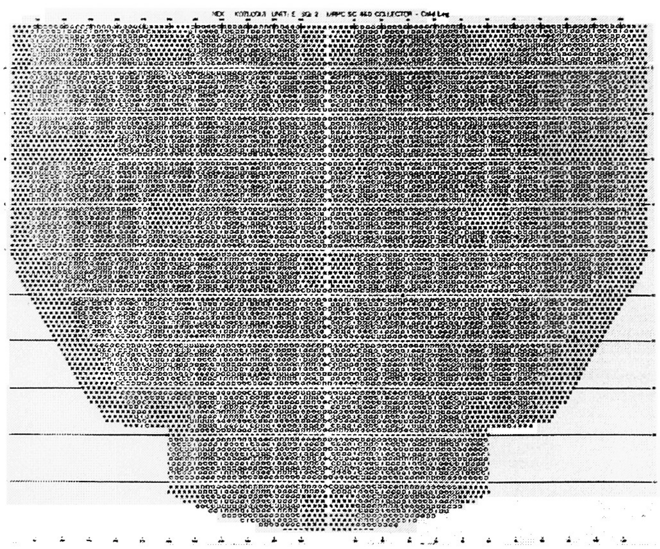

Figure 3: SM-14 VVER Tubesheet Rollout

When performing the ET inspection of steam generator tubing the primary water is removed and the remotely controlled equipment is installed into the collectors. This equipment operates in a highly contaminated and irradiated area (Figure 4). It is used to position the probe over the desired tube locations as well as to perform the pushing of the probe in the tube and pulling it out. ET data are usually collected during the pull.

It is useful to perform the inspection from both hot and cold collectors. The tube length is inspected in the two sections often called entries. Such sections of one tube are of different lengths.

The tubes located at the outer columns of the tubesheet (Figure 3) are often difficult to penetrate. This is due to the smaller bending radiuses of these tubes then are the radiuses of the tubes located at the center of the tubesheet.

Equipment, probes and consumables used for the steam generator inspection must comply with the specification for materials allowed in the primary circuit of the PWR nuclear power plants. The presence of halogen elements is forbidden. This prohibition is to be extended for the packaging materials as well.

1.1 ET Probe Type Used in Research

This study deals with the bobbin probe type 11.7-IPHS represented in Figure 5. It is produced by Inetec and used for inspection of VVER type of steam generators.

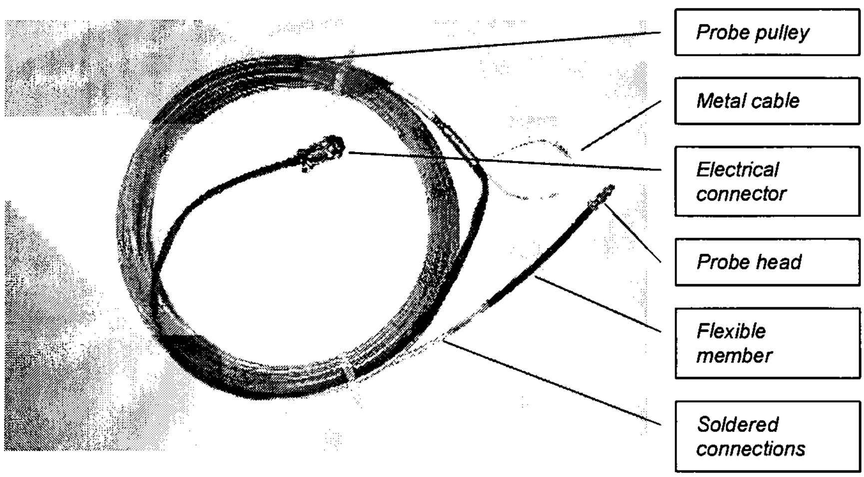

Figure 5: ET Probe 11.7-IPHS

The head extends to a metal piece of flexible tubing (so called flexible member), which is often covered by a heat shrink to avoid metal-to-metal contact with the steam generator tube. The probe pulley is made of nylon flexible tubing.

Two thin coax cables are drawn into the pulley together with a thin metal cable. The function of the latter is the removal of probe debris if the probe is damaged while in the steam generator tube. Coax cables end in an electrical connector.

The soldered connections between the coils and the coaxial cabling are placed within the first 200 mm of the pulley measured from the flexible member side.

1.2 ET Probe Weak Design Points and Damage Mechanisms

Based on the ET probe operating experience its known weak points are shown in Table 1:

Estimate of probe rejection probability	Assembly / Part affected	Suspected damaging mechanisms	Damage due to	Damage appearance
High	Soldered connections between thin coil wires and thick coaxial wires	Cold solder	Problem of both soldering technology as well as mechanical, electrical and thermal loads applied	Probe electrical failure (signal lost)
		Fatigue	Bending during the probe use	
Medium	Probe head/Probe coils	Wear	Friction and wear between probe head and tube to be inspected	Broken "glass-grainy" type of signal
Low	Probe pulley/ Internal wiring	Wear	Friction and callusing in in-between internal wiring and internal cable causing static electricity discharges	Degradation of ET signal (sparks)

Table 1: Assessment of ET probe weak design points

The damage of soldered connections appears to be the main cause of the ET probe being rejected from further use. The second reason is wear of the probe head. The degradation of ET signal caused by static electricity discharge due to friction between internal wiring does not appear very often.

1.3 Overview of ET Probe Packaging

The ET probes are manufactured and packed at the same site. The primary package is a 2.5 mm thick single-wall B-flute corrugated box with dimensions L x W x H = 520 x 75 x 540 mm as represented in Figure 6. Before inserting into the box the probe is wound and partially wrapped into an air bubble sheet.

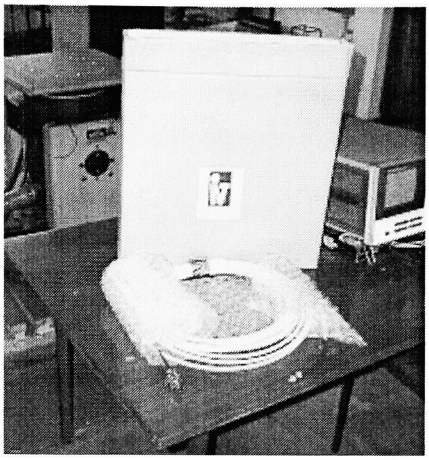

Figure 6: ET Probe And its Package

The packaging procedure does not specify in detail which part of the probe is to be wrapped into the sheet. As so far customers have not complained about the product or its packaging, the packaging has not been considered as a possible cause of the ET probe damage.

1.4 Distribution Environment

Probes are transported as small cargo shipments (of non palletized goods) by truck and/or by air. Typical routes including truck mileages and flight times are shown in the Table 2:

	Route	
	Truck	Airplane + Truck
Paks NPP, Hungary	330 km	1:00 h + 60 km
Kozloduy NPP, Bulgaria	1200 km	3:40 h + 180 km
Liviisa NPP, Finland	2500 km	4:30 h + 60 km
Zaporozhje NPP, Ukraine	2000 km	4:15 h + 120 km

Table 2: Distribution routes

Along with the hazards specific to the transport, both truck/plane loading or unloading as well as warehousing also involve some contingency.

In this part of the world it is usual for small cargo shipments often to be switched from air to truck transport, as for example the route from Vienna to Zagreb is commonly trucked.

1.5 Use Environment

The use environment includes irradiation, bending, friction and wear. In addition, the operation in presence of water and heat could apply occasionally. No vibrations and almost no shocks are present, yet, based on the number of hazards it seems that the use environment is far more severe than the distribution environment.

1.6 Factors Having Influence on Probe Lifetime

Table 3 lists the factors together with the estimate of importance of each factor. The purpose of this table is to illustrate the complexity of the problem.

		Estimate of importance
Equipment factors	Probe pusher model	Low
	Manipulator position accuracy	Low
	Auto-stop device present (probe automatically stops after tube end reached)	High
	Probe falls off the take up reel	High
Operator's factors	Operating skills	High
	Analysis skills	Low
	Probe not properly grounded	Low
Steam generator factors	Tube ovality (at bending radiuses)	High (varies between different steam generators)
	Presence of water in the tubing	Medium (rarely present, see Note 1)
	Presence of sludge and/or particles in the tubing	High (rarely present, see Note 2)
	Increased temperature of the tubing	Medium (rarely present, see Note 1)
	Test plan	Medium
	Irradiation	Low
Transport	Shock	Medium
	Vibration	High (to be proved by this study)

Table 3: Overview of the factors which influence the probe lifetime

Notes:

(1) The NPP Site is responsible to cool down and dry the steam generator before taking it over for the inspection.

(2) Steam generator tubes should be without any particles left in the tubes, since these could cause serious damage of the primary water pumps as well as fuel elements.

1.7 Discussion of Available Probe Lifetime Data

Table 4 shows probe lifetime data gathered during one VVER steam generator inspection. The populations of 20 probes of two types were monitored. For each probe the number of the entries tested (i.e. half of the tube lengths) has been counted.

Probe Type	IPHS-11.7			IPTS-11.7		
Acquisition operator	Operator 1	Operator 3	Operator 2	Operator 1	Operator 3	Operator 2
Number of entries tested	550 280 220 625 30 650	15	667 1100	100 60	916 120 55 415 100 598	200 470 325
Number of probes	6	1	2	2	6	3
Average entries tested	393	15	884	80	367	332
Number of probes	9			11		
Average of entries tested	460			305		
Number of probes	20					
Average of entries tested	375					

Table 4: Site Use Probe Lifetime

The ET probe rejection criteria were in accordance with the valid procedures and ET operators' practice (probes were rejected from further use as mechanical failure occurred or Eddy Current signals quality became unacceptable).

The average ET probe lifetime is 375 entries, ranging from 15 entries as a minimum and up to 1100 entries as a maximum. The dissipation is due to numerous factors; some of them may contribute to its stochastic nature.

Today, both the above-mentioned packaging and the ET probe lifetime data are typical for this product and common to all manufacturers.

2. OBJECTIVES

This study deals with accumulated effects of the stress induced by vibration due to transport that influence the product (ET probe) lifetime. It is a previously unexplored area. The emphasis is on the product and its protective package.

Hypothesis

Vibrations received in the transport contribute to the loss of the Eddy Current probe lifetime.

Additional objectives

The "on site" probe lifetime will be revealed on the example of probe use at one particular nuclear power plant.

The improvements in packaging will be re-considered in order to minimize the loss of probe lifetime due to transport whereas the probe design weak points will be pointed out.

3. EXPERIMENTAL DESIGN

A series of laboratory experiments are to be carried out according to the following table:

	TEST DESCRIPTION
Test 1	Initial vibration response investigation.
Test 2	Subjecting packaged ET to random vibration on a shaker table.
Test 3	Laboratory testing for ET probe lifetime.
Test 4	Packaged ET probes subjected to transport and tested for lifetime during on site use.

Table 5: Test Planned

The purpose of Test 1 is to investigate the vibration behavior of the product (no packaging).

During the Test 2 a sample of 10 probes is to be subjected to random vibration on a shaker table. The purpose of this test is only to expose the probes to vibration, which is followed by the Test 3.

During the Test 3 a sample of 10 virgin probes as well as 10 probes previously subjected to vibrations are to be tested for lifetime. On the basis of the statistics derived from this test results the hypothesis of this work will be rejected or accepted.

Test 4 will take place during a real steam generator inspection. Based on the results of this test, an estimate of the total loss of probe lifetime due to numerous factors (including the transport) is to be made. Finally, Test 2 and Test 3 results are to be compared with the results of this last test.

3.1 Methodology

The sequence of vibration testing follows a flowchart for vibration tests as proposed by the IEC 68-2-24 (see Appendix A Figure A-1).

Test 1 is performed on a sample of 4 ET probes as proposed by IEC 68-2-64 Appendix A: Vibration response investigation.

Test 2 is to be performed based on IEC 68-2-64 Method 1 (see Appendix A Figure A-2 for the PSD profile type).

Test 3 will follow a valid Eddy Current field service procedure that is in accordance with ASME B & PVC Section V, 1986:"Nondestructive Examination" and ASME B & PVC Section XI, 1986:"Rules for In-service Inspection of NPP components".

Test 4 is to be performed on site based on the same regulatory requirements as Test 3.

4. TEST1: INITIAL VIBRATION RESPONSE INVESTIGATION

The purpose of initial vibration measurements is to compare particular parameters in order to assess the effect of vibration on the specimen. IEC 68-2-64 allows the choice between the sweep test and the random test with decreased amplitude. For this study the sweep test has been chosen.

4.1 Purpose

This test is to be performed in order to avoid missing a structural resonance due to a chosen response point being a nodal point for particular mode of vibration. The measuring arrangement is to be made so that the dynamic behavior of the specimen as a whole shall not change substantially. In the case of non-linear resonance the dependence upon the direction of the frequency variation during the sweep is to be expected. Similarly, the transmissibility depends on the magnitude of the input vibration.

4.2 Description

Bare ET probes are subjected to vibration (ET probes shall be removed from package).

4.3 Criteria

The test is to investigate of ET probe's dynamic properties. At the completion of the test ET probes shall be without damage and operable.
If the initial vibration response results in the discovery of an unexpected characteristic of the product and/or package (for example if product damage occurs) further testing will be ceased and the test plan for further testing of both the product and its package will be subject to revision.

4.4 Equipment

Vibration equipment shall be capable of covering the frequency range and acceleration levels as specified in this chapter section 4.5. Instrumentation shall be capable of both measuring the frequency and amplitude of the vibrations and calculating the product vibration response (i.e. transmissibility plot). If necessary temperature conditioning equipment shall be applied to establish and maintain the ET probes at standard temperature level of 23°C ±10 °C

An optional fence type of mounting fixture is to be applied to prevent the probe from falling off the shaker table.

The system used comprise of:

- LDS Model 712 electro-dynamical shaker with the power amplifier;
- HP 3562 Dynamic Signal Analyzer (FFT);
- Bruel&Kjaer Charge Amplifiers;
- measuring accelerometer;
- control accelerometer.

4.5 Procedure

The ET probes shall be preconditioned to temperatures specified in this paragraph section 4.4 for either a minimum of 16 hours or until the internal temperature of the fuse has reached specified level.

The ET probe shall be placed on the shaker table with an optional fence preventing it from falling off the table.

The control accelerometer shall be mounted at the shaker table while the test accelerometer to be mounted onto the probe head by the decision of the test engineer and measuring acceleration along the shaker table axis.

Vibration conditions as summarized in the Table 6.

	SETTING	COMMENT
Type of test	Sinusoidal vibration, Sweep test	
Frequency range	5 Hz to 100 Hz	
Acceleration amplitude	Up to 10 m/s²	Whatever is less
Displacement	Up to 5 mm	
Sweep rate	Linear; 0.5 Hz/sec	

Table 6: Sweep Test Parameters

Upon the completion of the vibration schedule the probes shall be removed from the shaker table and examined against the criteria for passing the test (see this chapter section 4.3).

4.6 Test results

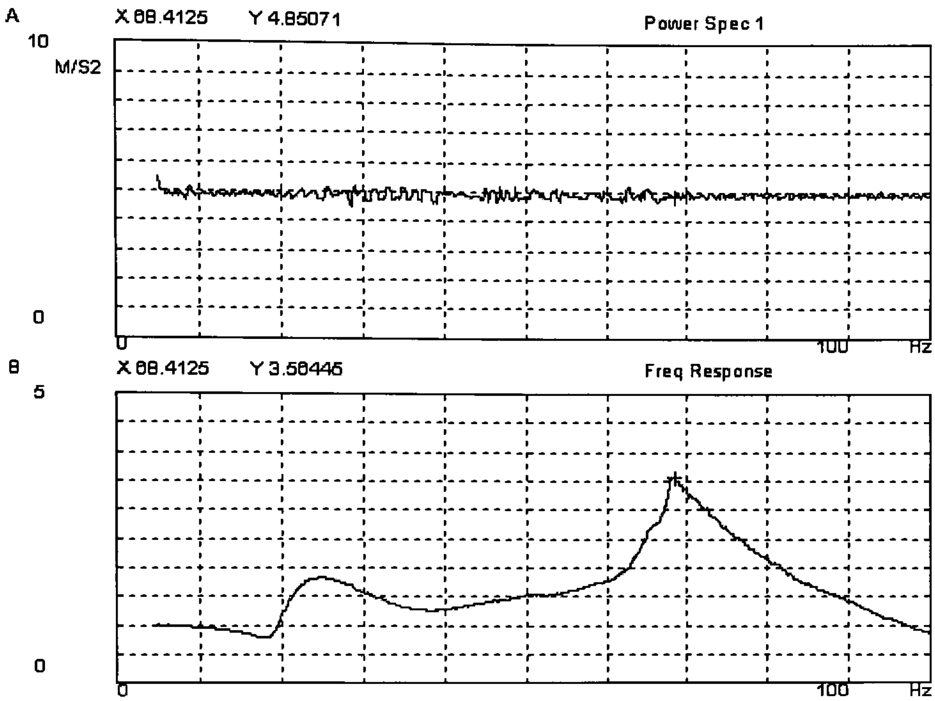

Figure 7. ET Probe S/N 0091 Sweep Test Response

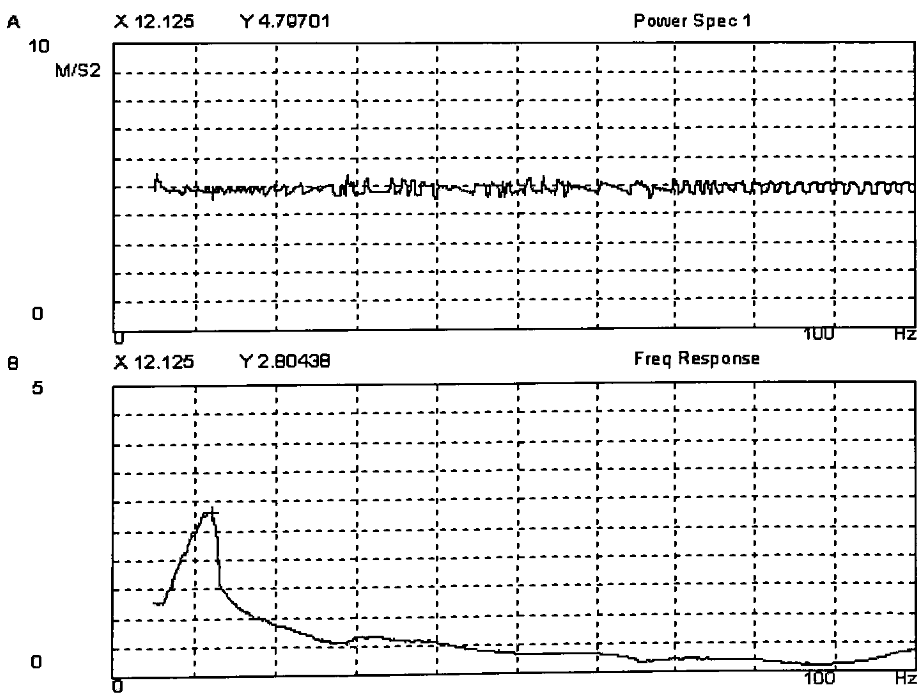

Figure 8: ET Probe S/N 0253 Sweep Test Response

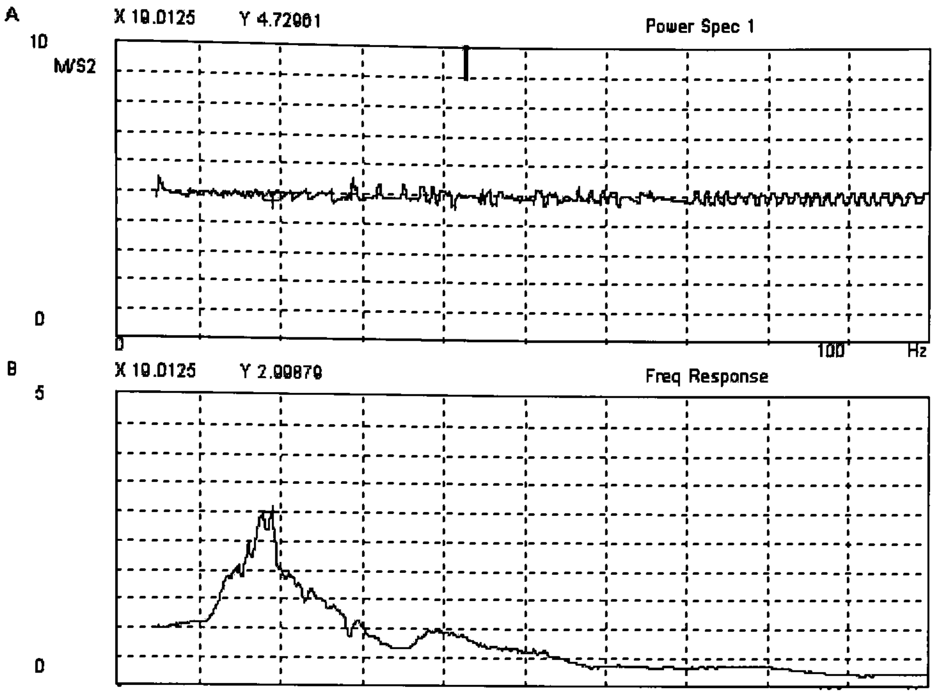

Figure 9. ET Probe S/N 0095 Sweep Test Response

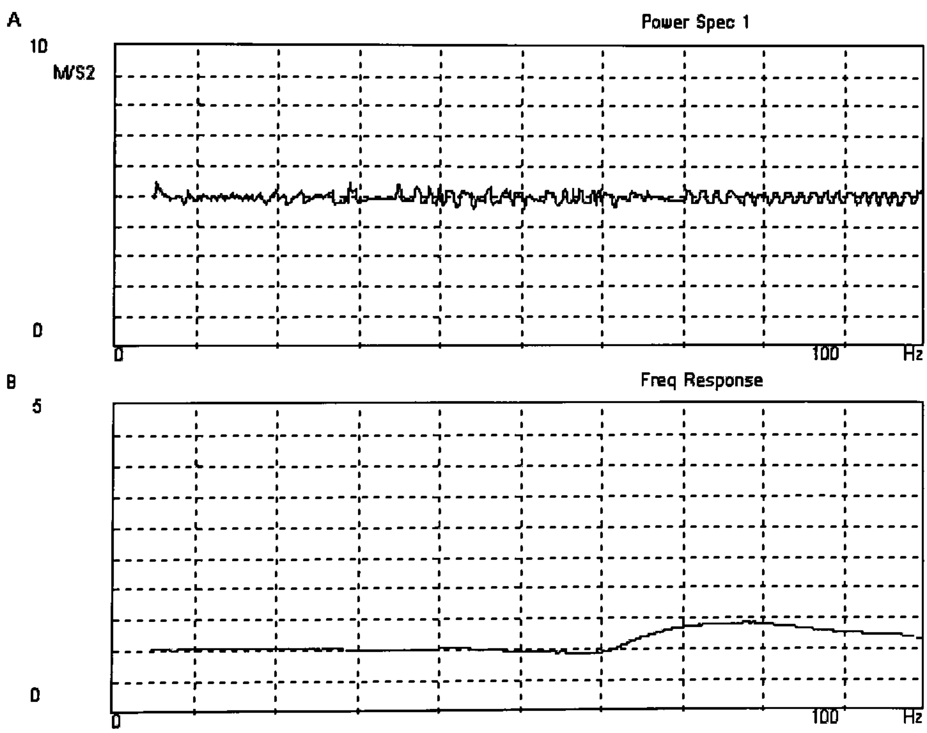

Figure 10. ET Probe S/N 0094 Sweep Test Response

4.7 Findings

The test results proved that ET probes show resonance in the frequency range of interest.

Different vibration spectrum diagrams were measured due to variances in probe winding and fixation techniques applied during the packaging process.

Upper diagrams in the Figures 7 through 10 represent the typical sweep test vibration power spectrums measured by the control accelerometer mounted on the shaker table.

Lower diagrams in the Figures 7 through 10 represent typical frequency responses (i.e. transmissibility plots) in those cases in which the test accelerometer was placed close to the anti-node point with respect to a particular mode ET probe was vibrating in. The lower diagram in Figure 10 represents the same in the case in which the test accelerometer was positioned near to the nodal point.

During the sweep test the vibration behavior of the ET probe internal parts was not been monitored. On resonance a strong hammering between the probe pulley windings was detected. It is reasonable to assume that the damaging processes taking place in the probe internals (cold solder effect, wear, fatigue) were affected hard by this effect, as the "thin to thick wire soldered connection" is almost a model example of the component highly susceptible to damage due to vibration exposure.

Because of the packaging procedure with no explicit requirements for either probe-winding diameter, the application of ty-raps (i.e. cable ties) or bubble sheet wrapping some probe head may have been left uncovered by the bubble sheet. Therefore, shock and vibrations from the transport may have caused the probe head to hammer against the corrugated box wall. It is reasonable to assume that the probe internals are highly affected with shocks produced by hammering, which include high frequencies in the spectrum. This would cause breaking of the soldered connections and/or contribute to the development of cold-solder effect.

The above discussion proves that the ET probe design is highly susceptible to damage due to vibration exposure. It is crucial to revise the packaging procedure in order to prevent the hammering effects and restrict the probe from vibrating in many different modes. The latter could be suspected as the cause of the dissipation of the ET probe lifetime data.

This phase of the testing proved that the probe structure dynamic behavior is affected by the packaging which has not been fully defined so far and which, for this reason, obviously needs to be revised.

5. REVISION OF PACKAGING PROCEDURE

After manufacturing each probe is wound in a bundle and secured with ty-raps (i.e. cable ties). The probes are usually warehoused on the same site in order to keep the stock of probes. Before the distribution each probe is wrapped with the bubble sheet and placed into the corrugated box.

The details that should be regulated by the packaging procedure are the following:

- the probe head is to be protected by wrapping into the piece of 3/16" thick (3/8" bubble) bubble sheet of the dimension 100 x 100 mm, and secured with a rubber band;
- probe head shall be at the inner diameter of the bundle;
- the probe bundle diameter (outer measure) shall be 500 mm;
- the first ty-rap is to be placed at the junction between probe pulley and the flexible member.
- place three more ty-raps 90° offset from each other;

This packaging is sufficient for the probe to be warehoused on the stock (on the probe manufacturing site). For the final packaging the following sequences are to be applied:

- the probe head to be wrapped into the ½" thick (3/8" bubble) bubble sheet of the dimension 300 x 500 mm;
- the whole probe is wrapped in the same type bubble sheet of the dimension 300 x 1800;
- the probe is to be put into the corrugated box.

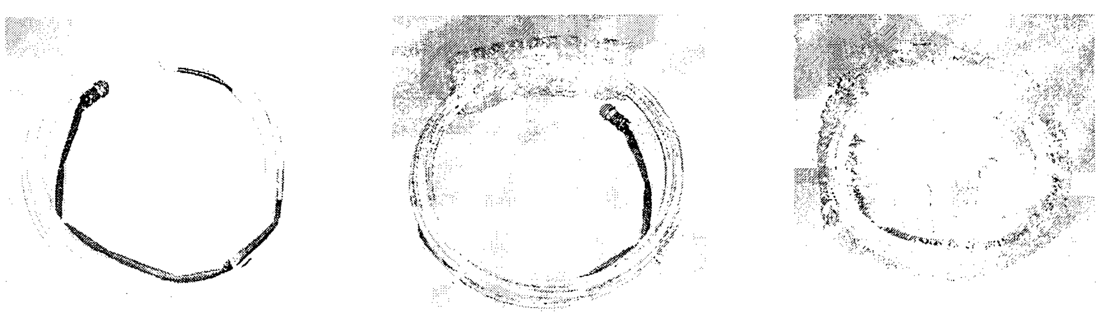

Figure 11. Sequence of probe wrapping into the bubble sheets

6. TEST2: SUBJECTING OF PACKAGED ET PROBES TO RANDOM VIBRATION ON SHAKER TABLE

6.1 Purpose

This is a laboratory test simulating vibrations due to transport. The packaged products are exposed to broadband random vibrations of the profile specified by IEC 68-2-64. The intention of this test is to adjust the severity level as close to the ASTM D-6169: Schedule E–Vehicle Vibration; Air profile–Assurance Level II, as the equipment used is able to reproduce (see example in Appendix A Figure A-3).

6.2 Description

During the test the packaged probes will be placed on the shaker table laid on top one another (which is the usual transport position). The vibration will be applied along the single axis only (i.e. no turning of the packages during the test).

6.3 Criteria

At the completion of the test the probe packages shall be without any damage and the probes shall be operable.

6.4 Equipment

Vibration equipment shall be capable of covering the frequency range and acceleration levels as specified in this chapter section 6.5. Instrumentation shall both measure the frequency and amplitude of the vibrations and have to be capable of at least displaying the on-line PSD profile and acceleration RMS value. If necessary temperature conditioning equipment shall be applied to establish and maintain the ET probes at standard temperature level of 23°C ±10°C.

The particular equipment set is comprise of:

- LDS Model 712 electro-dynamical shaker with the power amplifier;
- HP 3562 Dynamic Signal Analyzer (FFT);
- Equalizer unit, set of digitally controlled programmable filters (Precision Filters) with the specific laboratory unit for summation of analog signals;

- prototype
- Bruel&Kjaer Charge Amplifier;
- Measuring and control accelerometer.

6.5 Procedure

During this test the probes will be secured from falling off the shaker table (See Appendix B Figure B-2).

The test will be performed in two runs, each of them exposing 5 packaged probes to the vibration according to the Table 7:

S/N	0092	0098	0103	0228	0231	0233	0240	0242	0244	0252
Run order	1					2				
Placement on stack	1	2	3	4	5	1	2	3	4	5

Table 7. Run order and placement on the stack

Explanation of the placement on the stack: "1" means that the probe package is placed on the shaker table; "5 "means the last probe package on the stack.

Vibration parameters are summarized in the Table 8:

	SETTING	COMMENT
Type of test	IEC 68-2-64 Method 1	Open loop vibrator with manual equalization
Frequency range	f1=10 Hz, f2=100Hz	
PSD	0.01 g/Hz	1 $(m/s^2)^2/H$
Shape of PSD curve	Flat horizontal portion	See Appendix A Figure A-2
Duration of testing	300 min	Per each run.
Overall RMS	0.97 g	9.5 m/s^2

Table 8: Random Vibration Test Parameters

Prior to test the programmable filter set needs to be adjusted in order to achieve the appropriate PSD profile measured by the control accelerometer. During the test it is allowed to readjust filter settings in order to keep the PSD profile within the tolerance boundaries.

Upon the completion of the vibration schedule the probes shall be removed from the shaker table and examined against the criteria for passing the test (see this chapter section 6.3).

6.6 Test results

Test parameters have been monitored during the test by the use of FFT signal analyzer:

- random vibration spectra (shape and level), as presented in Figures 12 and 13;
- acceleration RMS value (by integrating of averaged acceleration power spectrum integration in the frequency range of interest);
- acceleration signal histogram (to confirm probability density of signal to be of normal distribution);
- max recording peak (Crest factor).

6.7 Findings

No damage on the probe packages was noticed. Al probes that passed the test were in the operable condition.

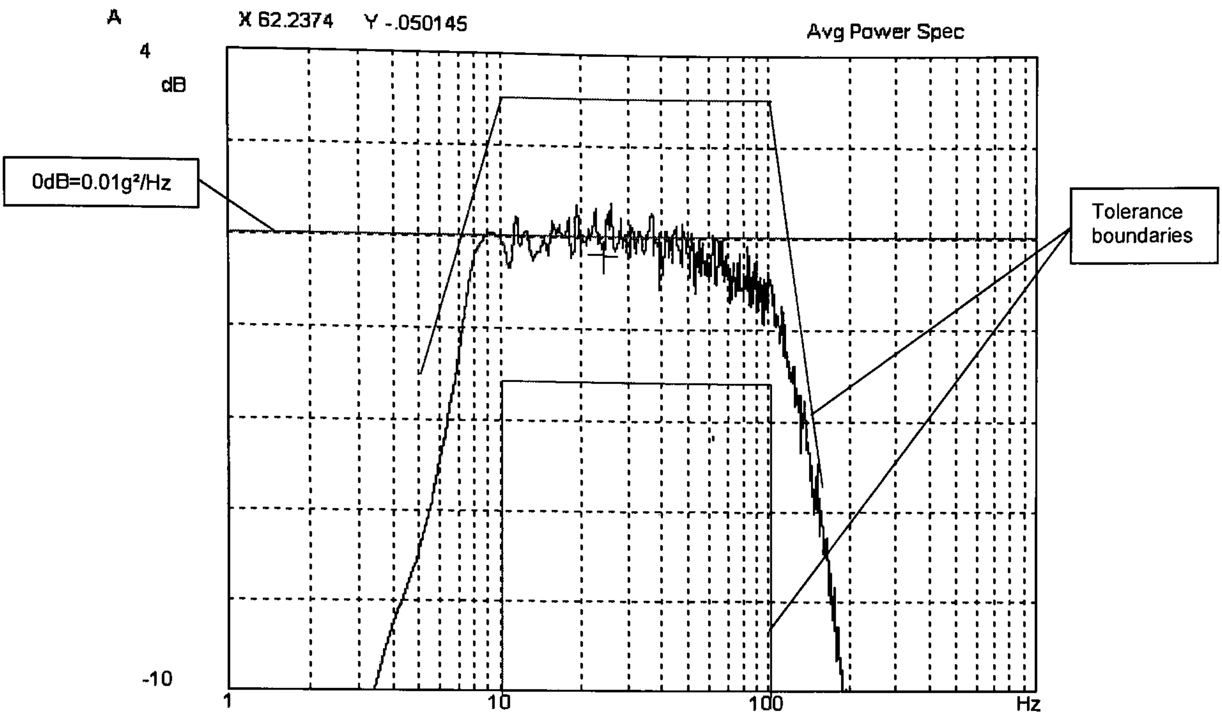

Figure 12. Power spectral density measured on shaker table, 1st run.

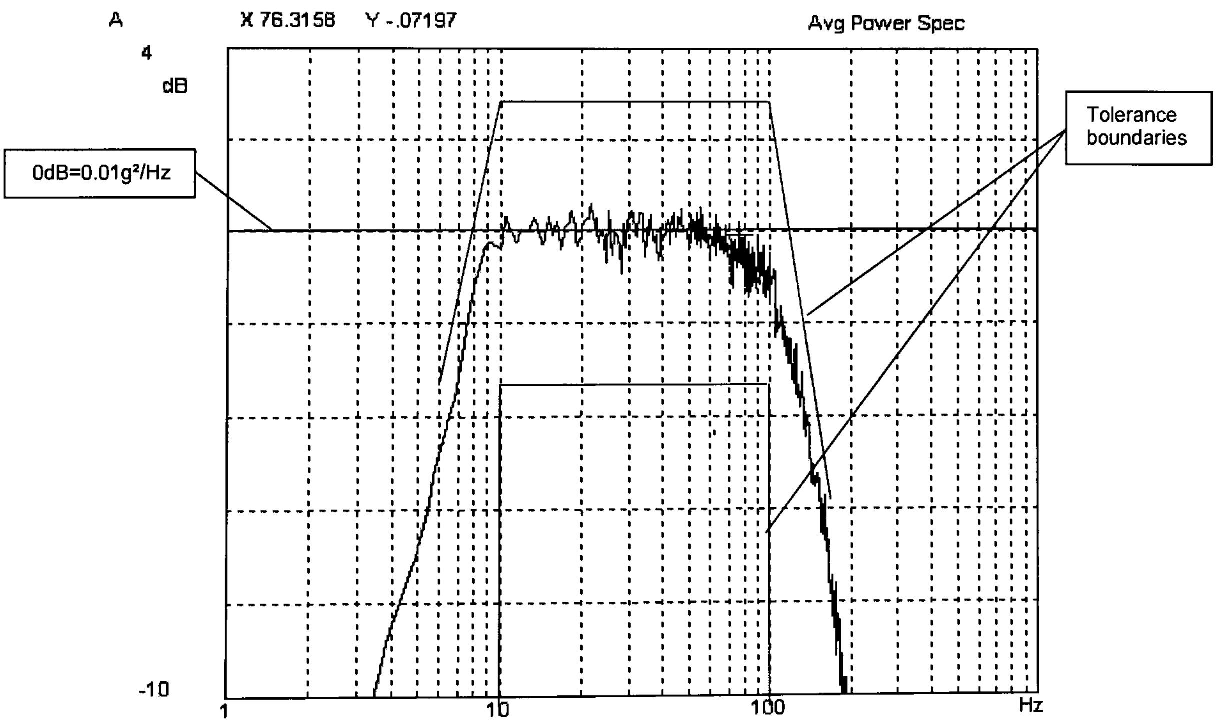

Figure 13. Power spectral density measured on shaker table, 2nd run

7. TEST3: LABORATORY TEST FOR PROBE LIFETIME

7.1 Purpose

This is a Lab test to be performed at the probe-manufacturing site on the population of 10 "virgin" probes and 10 probes which have been previously subjected to random vibrations (during the Test 2). Counting the number of tube entries inspected before each probe fails to satisfy a test criteria will reveal the lifetime of every individual probe.

7.2 Description

Testing will be performed on a VVER-440 steam generator mockup by subjecting the probes to pushing into the tubes and pulling them out.

The factors which are rarely present during the probe use on site, as well as those whose influence is rated low, will not be simulated during this test. These factors are: presence of water in the tubing; increased temperature; sludge and particles left in the tubes, as well as exposure to irradiation.

It is reasonable to assume that the probe lifetime is influenced by the operator's factor as well as the factor of guide tube used with the probe (i.e. upper or lower, see Equipment). These influences will be further investigated in the statistical analysis.

During the test Eddy Current data will be monitored permanently. The probes having experienced the mechanical failure will be later inspected visually.

7.3 Criteria

In the theory of Eddy Current the signal to noise ratio is used as a measure of data quality. With the data to be good it should exceed 3:1. It is defined as the ratio between the indication amplitude and amplitude of noise. In addition, the EPRI PWR Steam Generator Examination Guidelines: Revision 5 has introduced a probe wear checking. It is often applied on when the steam generator tubes are plugged according to a voltage (amplitude) plugging criteria. For the VVER steam generator inspections this criteria has never been applied due to a small fill-factor (typically 0.8 or less).

The probe rejection criteria used on site is regulated by the procedures as well as the code of practice. During the acquisition operator permanently monitors data quality and replaces probes as the data become unacceptable. With the increase of probe speeds and testing productivity (i.e. simultaneous testing with two probes) this task becomes difficult. The latest version of the acquisition software (i.e. Eddynet98 Version 4 Patch 2.9) has the feature called

DQV (Data Quality Verification) which perform a kind of on-line data analysis in order to check the probe. For the bobbin probe it reports the signal saturation and it is also able to distinguish the electrical spikes from the other type of Eddy Current signal structures (such as tube supports, top of the tubesheet, tube-end and indications). The Data Analysis is responsible for the final data quality check. Each tube entry that is reported as a bad data (RBD) is later retested. It is often carried out for the single tube entry rather than for groups of tubes.

In the case of this test the data will be checked during the acquisition only. The DQV makes the primary check quality. Since there is no data analysis during this test, the acquisition operator retains the discretionary right to reject the probe if the data quality does not comply with either the procedure requirements, or with the operator code of practice. The probe rejection criteria are summarized in the Table 9.

	Detected by:	Criteria in details	Additional checks
Probe mechanical failure	Acquisition operator	None.	Visual inspection for the cause of failure
Probe electrical failure (no signal on any channel)	DQV software	None.	None
Signal Saturation on any channel	DQV software	Probe to be rejected on first entry showing saturation on any channel	None
Spikes in the signal	DQV software	Third consecutive entry having spike(s) >0.2V at any location	None
All other signal abnormalities	Acquisition operator	Valid procedure, operator practice	None

Table 9. Probe rejection criteria

7.4 Equipment

The test system is comprised of the following components:

- Zetec MIZ-30 Eddy Current Instrument;
- Inetec SM-14 Fixture with appropriate control box;
- Inetec DPS (double guide tube) pusher-puller with appropriate control boxes (see Figure 12);

- HP Workstation with Eddynet98 Version 2 Patch 2.9 software package.

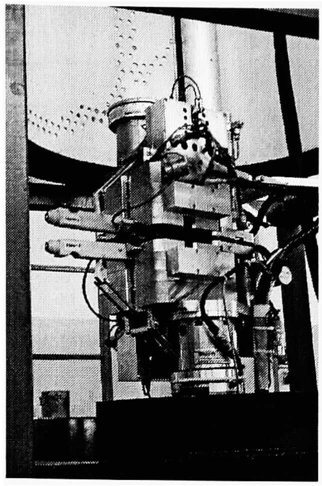

Figure 12: DPS double guide tube pusher–puller mounted on VVER-440 steam generator mockup

DPS is the prototype equipment that has passed product certain verification procedure (i.e. PDV-DPSHER-E, November 2000) what allows it to be used on NPP sites. This test is actually combined with the performance testing of new equipment before its first site use.

7.5 Procedure

In order to prevent the effects of unknown nuisance variables this test is carried out in random run order as presented in the Table 10. The probes with even run order numbers will tested at the upper guide tube while the probes with odd run orders will be run at the lower guide tube.

Probes subjected to vibration on the vibration table										
S/N	0092	0098	0103	0228	0231	0233	0240	0242	0244	0252
Run Order	9	18	5	19	6	14	8	15	10	17
Virgin probes										
S/N	0097	0100	0229	0230	0236	0239	0241	0246	0247	0254
Run Order	16	7	13	2	3	12	20	11	4	1

Table 10. Run order during ET Probe test for lifetime

When the probe from either upper or lower guide tube is rejected (i.e. damaged or its data are unacceptable) this test continues with the remaining probe (on a single guide tube) until it is also rejected. The change of operator is allowed at both guide tube probes replacement.

All test parameters and requirements other than those specified above (i.e. Eddy Current test configuration, probe speeds, guide tube positioning accuracy, operator requirements etc.) are according to the valid field service procedure "SGP-ET-01 Rev.4, Examination of VVER Steam Generator Tubing by Using EC Method – Data Collection Procedure (Bobbin Probe)". Appendix C summarizes these parameters.

7.6 Test results

Run order	S/N	Guide tube	Vibrated	Operator	Number of tube entries tested	Reason for rejection from further resting
1	0254	LOWER	NO	Operator 1	1025	Damage of head centering device (Operator)
2	0230	UPPER	NO	Operator 1	751	Spikes (DQV).
3	0236	LOWER	NO	Operator 2	594	Spikes (DQV).
4	0247	UPPER	NO	Operator 2	651	Saturation (DQV).
5	0103	LOWER	YES	Operator 1	414	Spikes (DQV).
6	0231	UPPER	YES	Operator 1	588	Saturation (DQV).
7	0100	LOWER	YES	Operator 2	643	Spikes (DQV).
8	0240	UPPER	YES	Operator 2	801	Saturation (DQV).
9	0092	LOWER	YES	Operator 1	658	Saturation (DQV).
10	0244	UPPER	YES	Operator 1	482	Spikes (DQV).
11	0246	LOWER	NO	Operator 1	870	Spikes (DQV).
12	0239	UPPER	NO	Operator 1	776	Spikes (DQV).
13	0229	LOWER	NO	Operator 2	749	Saturation (DQV).
14	0233	UPPER	YES	Operator 2	318	Damage of probe head
15	0242	LOWER	YES	Operator 2	707	Spikes (DQV).
16	0097	UPPER	NO	Operator 2	830	Bad signals (Operator).
17	0252	LOWER	YES	Operator 2	803	Damage of flex member /probe pulley joint (operator)
18	0098	UPPER	YES	Operator 2	369	Spikes (DQV).
19	0228	LOWER	YES	Operator 1	598	Spikes (DQV).
20	0241	UPPER	NO	Operator 1	954	Spikes (DQV).
Virgin probes			Average	784.3	Standard deviation	151.1
Probes subjected to vibration on the vibration table				573.8		173.56

Table 11. Results of Test 3

7.7 Findings

As represented in the Table 11, the probes which were subjected to vibrations show a significantly smaller number of entries tested (i.e. the average of 573 entries)in which a slightly bigger dissipation of results occurred than it was the case with the virgin probes (i.e. the average of 784 entries).

The most of the probes were rejected due to the electrical problems. Only the small number of probes were affected by the mechanical failures as documented in Appendix D Figure D-1.

8. STATISTICAL ANALYSIS

8.1 Purpose

Test 3 is a factor screening type of the experiment. The factors involved are: the probe subjected to vibration (yes or no), the guide tube used (upper or lower), the operator running the Eddy Current equipment (Operator 1 or Operator 2). There is a single dependent variable: the number of the tube entries tested before the probe is rejected.

The analysis of variance (ANOVA) method will be utilized to prove that, among the other factors, the factor of vibration is statistically significant.

8.2 Description of the statistical method

Based on the input data the so-called level of statistical significance (p-level) is calculated. It represents a probability of error involved in either the rejection of so-called null hypothesis: “there is no relation in the population” or the acceptance of the alternative hypothesis: "the means (in the population) are different from each other”. More specifically, the p-level represents the probability of error which is involved in accepting our observed result as valid, that is as ”representative of population”. The higher the p-level the less we can believe that the observed relation between variables is the reliable indicator of the relation between the respective variables in the population. In many areas of research the p-level of 0.05 is customarily treated as a “border line acceptable” error level.

This method is based on the assumption that the variances in different groups are equal (homogenous). The Levene test is often applied to check this hypothesis. For each dependent variable the analysis of variance is performed on the absolute deviations from the respective group mean. If the Levene test is statistically significant then the hypothesis of homogeneous variances should be rejected.

The ANOVA module of the software package “Statistica” is used for the calculation.

8.3 Discussion of results

The input data as well as the results of statistical analysis are shown in the Appendix E.

The summary of all effects proved that the effect of vibration is statistically significant. The statistical null hypothesis (saying that in the population of probes there are no differences due to the effect of vibration) is to be rejected, with the 0.007985 probability of making an error.

According to [5], if a hypothesis is rejected with the probability of error less or equal to 0.01 this unconditionally means that the hypothesis does not match the experimental data.

With the "cut off" level of significance of 0.005, the effects of different guide tubes and different operators as well as the interactions between these two factors, are statistically not significant.

For this particular set of input data, the Levene test proved that the hypothesis of homogeneous variances was acceptable.

9. TEST4: SITE TEST FOR PROBE LIFETIME

9.1 Purpose

By comparing the lifetime which the probes experienced "on site" with the results of the Test 3, it is possible to estimate the loss of probe lifetime due to transport with regard to the efficiency of the Test 2 simulating the distribution environment.

9.2 Description

This test is actually gathering the probe lifetime data during the performance of a commercial steam generator inspection. It is performed in the scope of 50% (every second row inspected by the ET) on Paks NPP (Hungary) Unit 2 Steam Generator 2.

9.3 Criteria

The probes are rejected from further testing according to the valid procedures: "SGP-ET-01 Rev.4, Examination of VVER Steam Generator Tubing by Using EC Method – Data Collection Procedure (Bobbin Probe) " and "SGP-ET-06-E Rev.2, Examination of VVER Steam Generator Tubing by Using Eddy Current Method – Data Interpretation Procedure (Bobbin Probe)" as well as according to the code of practice. The final decision on data quality is made by the data analysis.

9.4 Equipment

Physically the same set of equipment as used for Test 4 is used for this test.

9.5 Procedure

When the probe from either upper or lower guide tube is rejected (i.e. damaged or the data unacceptable) the bad probe is to be replaced with a new one and the test continues with both probes. At the end of inspection scope the upper guide tube collects the remaining data tube entries. Retests are to be performed by the upper guide tube only.

All test parameters and requirements other than those specified above (i.e. Eddy Current test configuration, probe speeds, guide tube positioning accuracy, operator requirements etc.) are in accordance with the valid field service procedure "SGP-ET-01 Rev.4, Examination of VVER Steam Generator Tubing by Using EC Method – Data Collection Procedure (Bobbin Probe)". Appendix C summarizes these parameters.

9.6 Test results

Run order	S/N	Guide tube	Operator	Number of tube entries tested	Reason for rejection from further testing
~~1~~	~~0148~~	~~LOWER~~	~~Various~~	~~0~~	Operator's error (see note 1)
~~2~~	~~0198~~	~~UPPER~~	~~Various~~	~~0~~	Operator's error (see note 1)
3	0210	LOWER	Various	465	Probe head broken.
4	0299	UPPER	Various	477	Damage of the probe pulley (see note 4)
5	0105	LOWER	Various	340	Bad signals.
6	0106	UPPER	Various	367	Bad signals.
7	0107	LOWER	Various	480	No signal at U-band.
8	0203	UPPER	Various	628	Electrical problems (spikes).
9	0250	LOWER	Various	250	Electrical problems (spikes).
10	0108	UPPER	Various	444	Bad signals on 25KHz.
11	0113	LOWER	Various	323	No signals on CH#6 & 8.
12	0112	UPPER	Various	172	Damage of probe pulley (see note 4)
13	0111	LOWER	Various	260	Bad signals
14	0104	UPPER	Various	344	No absolute channels.
15	0167	LOWER	Various	280	Bad signals.
16	0194	UPPER	Various	114	Bad signals.
17	0199	LOWER	Various	310	Bad signals.
18	0089	UPPER	Various	180	Probe head cut-off.
~~19~~	~~0251~~	~~LOWER~~	~~Various~~	~~90~~	See note 2
~~20~~	~~0254~~	~~UPPER~~	~~Various~~	~~104~~	See note 2
~~21~~	~~0248~~	~~UPPER~~	~~Various~~	~~RETEST~~	See note 3
Average			339.6	Std. deviation	134.8

Note: The following cases are excluded form statistics:

(1) Probes damaged during the installation of manipulator into the collector.

(2) Probes that finished inspection (before retest of indication).

(3) The probe used for retest of indications (upper guide tube only).

(4) Broken joint between the flexible member and the probe pulley.

Table 12. Results of Test 4

9.7 Findings

As during the laboratory test for lifetime most of the probes were rejected due to the electrical failures.

The probes tested by Test 4 showed a significantly shorter lifetime (on average 340 entries) as compared with the results of the laboratory testing of the vibrated probes (537 entries). This is due to various factors that were not present during the laboratory testing. In addition, it is known that the deposits on the secondary side of tubes cause the ET signals which are often hard to distinguish from the similar signals which are due to the bad probe. In such cases the operators used to change probes more often.

Due to the these facts it is not possible to quantify the loss of probe lifetime due to the transport by simply comparing the results of the laboratory test for lifetime with probe lifetime of the probes tested on site.

10. CONCLUSIONS

The sequence of vibration tests in this study followed the IEC 68-2-64 flow-chart for performance of broadband random vibration test.

Initial response vibration investigation showed that the package must restrict the probe from vibrating in different modes and thus prevent the resonance(s), which the bare product showed between 10 and 100 Hz.

During the random vibration testing the packaged probes were exposed to the vibration profile, which is as close to ASTM D-4160 Air Profile Assurance Level II as applicable by the equipment used. Frequencies bellow 10Hz were not applied since vibration investigation did not find resonance in this part of the spectrum as well as due to the equipment limitations.

The Final Vibration Response Investigation according IEC 68-2-64 flow-chart is not to be applied. This is determined by the fact that the probe lifetime is affected prior to noticing any change in the vibration properties of the product.

The test for probe lifetime was performed as the Final Measurement according to the IEC 68-2-64 flow-chart. The statistical analysis unconditionally proved the influence of vibrations on the probe lifetime (in the population of probes that have been previously exposed to vibrations).

The comparison of the "on site" and "in lab" probe lifetimes showed that along with the vibration due to transport there were many other factors contributing to the loss of lifetime. The population of virgin probes demonstrated that its expected lifetime was almost twice as long as that of the probes tested on site. Both these facts are due to the factors which have not been explored in this study. Probably the strongest influence is that of the tube ovallity which varies a great deal between steam generators. In addition to that, on some sites there are deposits on the tube secondary sides which are often the source of "bad probe" like signals.

The assumption that the loosely defined packaging design increases the dissipation of the probe lifetime (made after the initial vibration response was performed) has not been proved after revision of the packaging procedure. Even so, the dissipation for the virgin probes and the vibrated probes is not significantly different. In connection to this, anther assumption can be proposed: the dissipation of probe lifetime data is probably due to the probe design as well as due to insufficient quality control during the production.

10. RECOMMENDATIONS FOR FUTURE STUDY

The probe production should either introduce a better quality control on its "loose" technologies, such as manual soldering, or replace them by more advanced technologies.

If the dissipation of the probe lifetime data would still be significant the next step is to apply cushioning as the part of the probe design (for example, filling the probe pulley with expanded foam). It would be probably cheaper than the development of a special package with cushioning.

The ASTM D-6169, Schedule **E**, Vehicle vibration testing is to be applied in order to quantify the influence of vibrations. A special care and special packaging as well as vibration monitoring are to be applied in the transport of probe samples in order to distinguish the effect of "artificial" vibrations from the effect of transport.

A study of noise that is present in the eddy current signal is to be performed. Based on that, the analysis techniques are to be developed by which it will be possible to clearly distinguish between the noise originating from the tube material (and deposits on the tube surfaces) on one hand, and, on the other, the noise that is due to the bad probe. So far, the operators have been distinguishing between these two noises by their experiences only.

Two additional specific tests are to be developed to further investigate the bending of the "soldered" connection area of the probe as well as to reveal the effect of the probe penetration through the ovaled tube radiuses.

12. BIBLIOGRAPHY

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[5] Spiridonov, V.P and Lopatkin A.A, *Matematička obrada fizikalno-kemijskih podataka* [Mathematical Analysis of Data in Physics and Chemistry], Skolska knjiga, Zagreb 1974.

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[8] ASTM D 4169-99 Standard Practice for Performance Testing of Shipping Containers and Systems.

[9] IEC 68-2-64 ENVIROMENTAL TESTING; Part 2: Test methods; Test Fh: Vibration, broad-band random (digital control) and guidance.

[10] EPRI PWR Steam Generator Examination Guidelines: Revision 5: Volume 1: Requirements, Report TR-107569-V1R5, September 1997.

[11] EPRI PWR Steam Generator Examination Guidelines: Revision 5: Volume 2: Technical Basis, Report TR-107569-V2R5, September, 1997.

[12] INETEC Procedure SGP-ET-01 Rev.4, Examination of VVER Steam Generator Tubing by Using EC Method – Data Collection Procedure (Bobbin Probe), March 1998.

[13] INETEC Procedure SGP-ET-06-E Rev.2, Examination of VVER Steam Generator Tubing by Using Eddy Current Method – Data Interpretation Procedure (Bobbin Probe), Margh, 1998.

APPENDIX A

Samples form Relevant Regulations

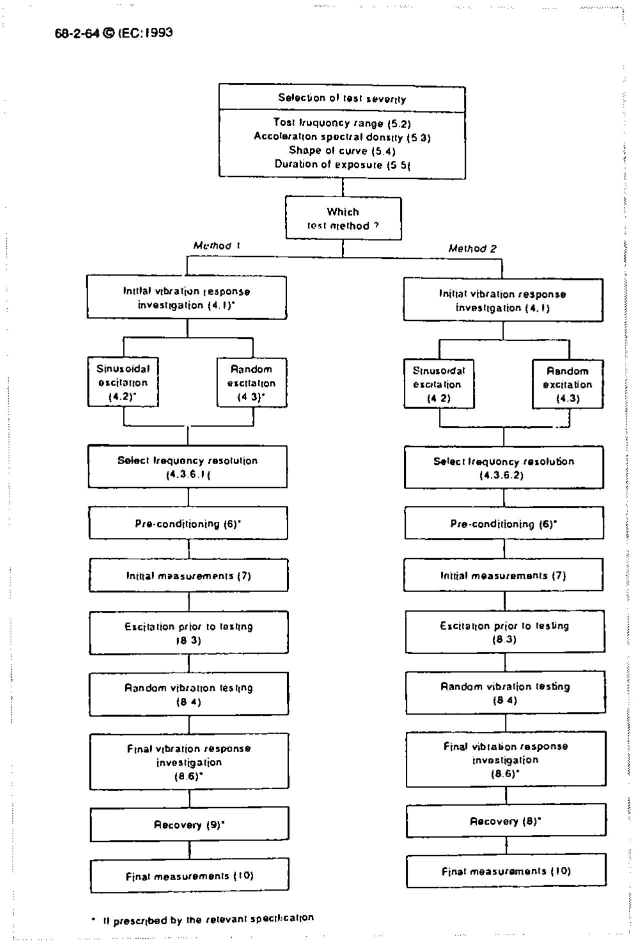


Figure A-1: IEC 68-2-64 Flow chart for performing vibration testes

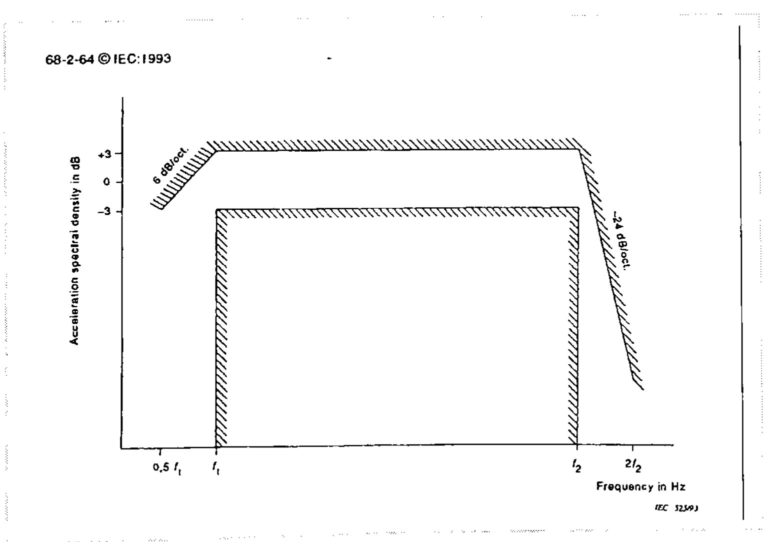


Figure A-2: IEC 68-2-64 Tolerance boundaries for acceleration spectral density

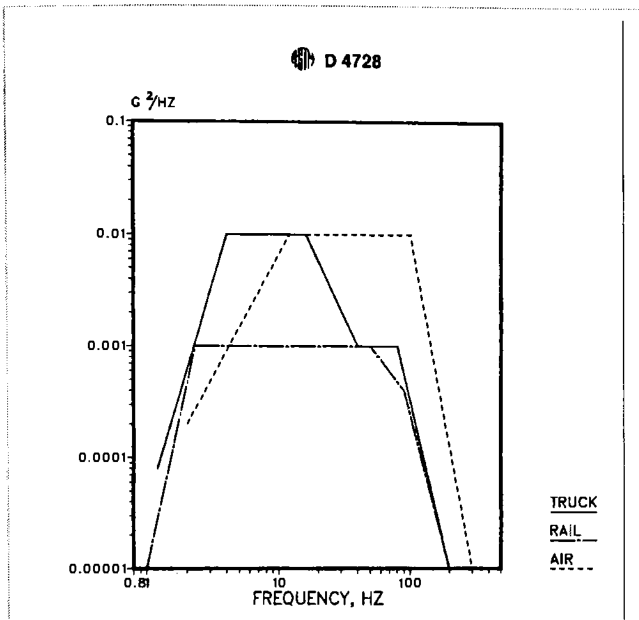


FIG. X1.1 Commercial Transport Random Vibration Spectra Summary

Figure A-3: Sample PSD Profiles

APPENDIX B

Vibration Equipment and Instrumentation

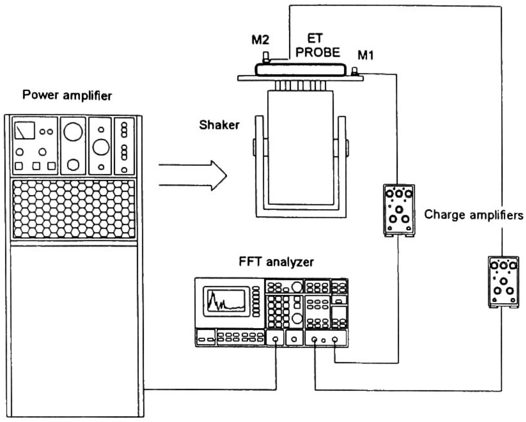
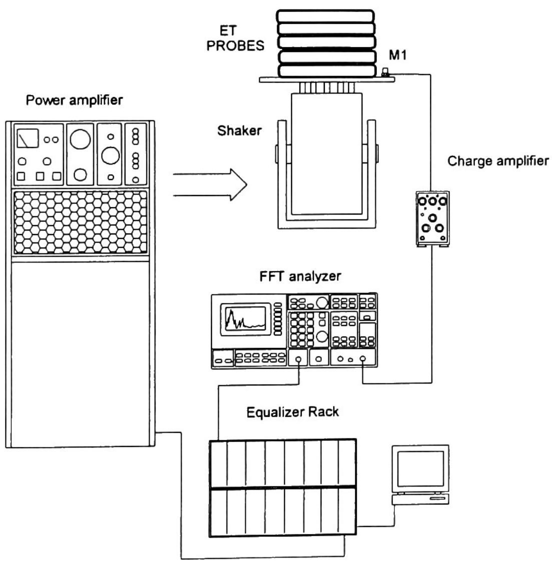


Figure B-1: Sweep Test Equipment Setup



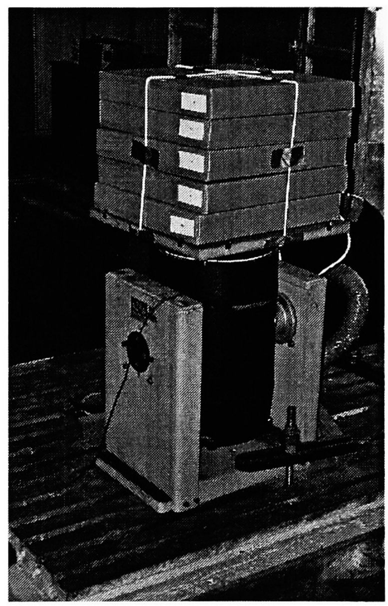


Figure B-2: Random Test Equipment Setup

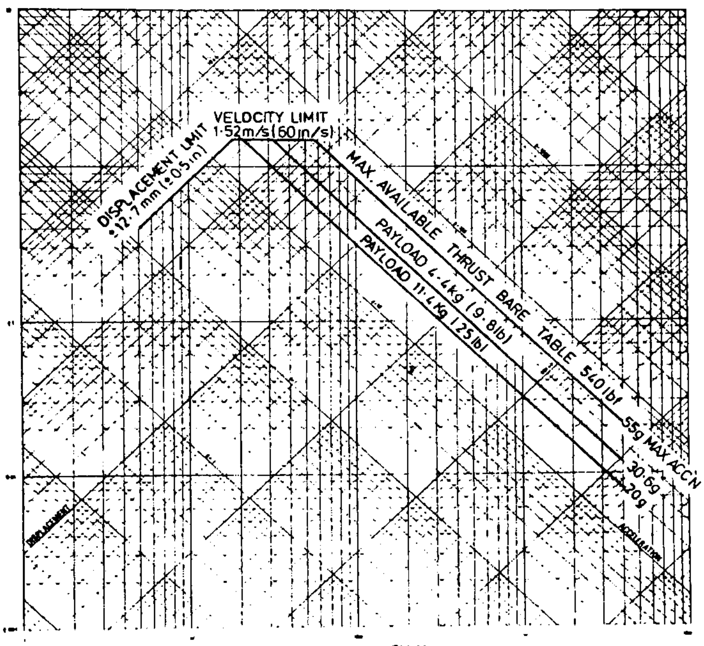
APPENDIX B

Vibration Equipment and Instrumentation

LING DYNAMIC SYSTEMS — **VIBRATION NOMOGRAPH**

NOMINAL SYSTEM PERFORMANCE DATA. SHEET REF. V 712, 600, MPA 2   24·10·77

VECTOR THRUST	2669 N(600 lb f.)	
SHAKER TYPE V712	AMPLIFIER MPA 2	2 kVA
DIRECT COUPLED		
EFFECTIVE ARMATURE MASS	4·45 kg (9·8 lbs)	
RANDOM RATING	1161 N.r.m.s.(261 lb f.r.m.s.)	DIRECT COUPLED



Example Given Frequency = 20Hz
and Displacement = 25mm P-P
then, Acceleration = 20g (vector)
and, Velocity = 1.6m sec. (vector)

Our policy is one of continuous development. Current production models therefore may differ in minor details from this specification.

1 lb = 0.45Kg.   1g. = 9.81m sec.^{2} 1 lb f. = 4.44N

LING DYNAMIC SYSTEMS LIMITED   BALDOCK ROAD   ROYSTON   HERTS   ENGLAND
Telephone: ROYSTON 42424   Telex: 81174   Cables: Vibration Royston

FIG 10   AMENDMENT 6   13 - 7 - 79

Figure B-3: Characteristic of Shaker Table

	EXAMINATION OF VVER STEAM GENERATOR TUBING BY USING EC METHOD - DATA COLLECTION PROCEDURE (BOBBIN PROBE)	SGP-ET-01-E Rev. 4 Page 38 of 12

FIG.1. JOB DATA SHEET

EXAMINATION TECHNIQUE :

TYPE OF TEST :	BOBBIN - TUBES	TYPE (S/G) :	VVER 440 or 1000
TUBE MATERIAL :	GOST 08H18N10T	TUBE SIZE :	ϕ16x1.4 or 1.5 mm

ET EQUIPMENT :

REMOTE DATA ACQUISITION UNIT	MIZ-18A or MIZ-30 - Zetec
ACQUISITION SYSTEM SOFTWARE	EDDYNET ACQUIRE - Zetec

CALIBRATION STANDARDS (example) :

TYPE	ACTUALS (%)	TSP	Cu RING	DENT	OTHER
ASME	100,80,60,40,20	N/A	N/A	N/A	N/A

PROBES (example) :

PROBE TYPE AND SIZE	LENGTH	ANALOG PROBE EXTENSION
Bobbin ϕ0.41"–0.47" (10.41–11.94mm)	40'-83'(12-25m)	30'-100' (9-30m)

KINEMATICS:

SCAN DIRECTION	PULL
PROBE SPEED	12"/sec or 18"/sec (305 or 457 mm/sec)
SAMPLE RATE	400 (12"/sec) or 600(18"/sec)
ROTATING SPEED	N/A

Note : Probe pulling speed will be determined by SGS Manager

CONFIGURATION :

When using MIZ-30, gain shall be 2 and Probe Drive 12 for all channels.
Note : Settings given in () are applicable for MIZ-30.

Ch#	kHz	Diff.	Abs.	Coil#	Signal source	Signal amplitude, % of FSHP	Signal source	Phase rotation
1	210	D		1(A)	4 X 20%	> 30%	100% TWH	40±1 °, INIT.DOWN
2	210		A	5(B)	4 X 20%	> 30%	100%, TUBE	FLAW UP,NOISE HOR.
3	140	D		1(A)	4 X 20%	> 30%	100% TWH	40±1 °, INIT.DOWN
4	140		A	5(B)	4 X 20%	> 30%	100%, TUBE	FLAW UP,NOISE HOR.
5	70	D		1(A)	4 X 20%	> 30%	100% TWH	40±1 °, INIT.DOWN
6	70		A	5(B)	4 X 20%	> 30%	100%, TUBE	FLAW UP,NOISE HOR.
7	30	D		1(A)	TSP	> 30%	TSP	VERT., INIT. UP
8	30		A	5(B)	TSP	> 30%	TSP	INIT. DOWN,NOISE HOR.
CONFIGURATION NAME :						VVER-BOBBIN		

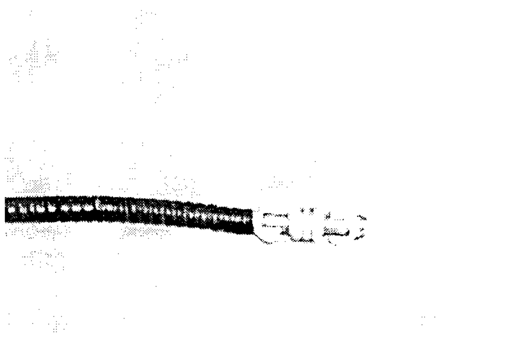
FSHP – full screen horizontal presentation

GRAPHIC DISPLAY :

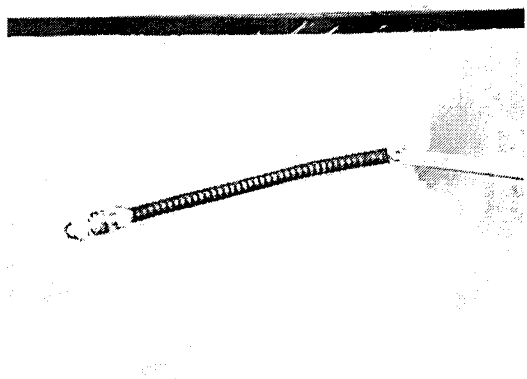
LISSAJOUS Ch#	3	LEFT STRIP CHART Ch#	3V	RIGHT STRIP CHART Ch#	8V

APPENDIX D

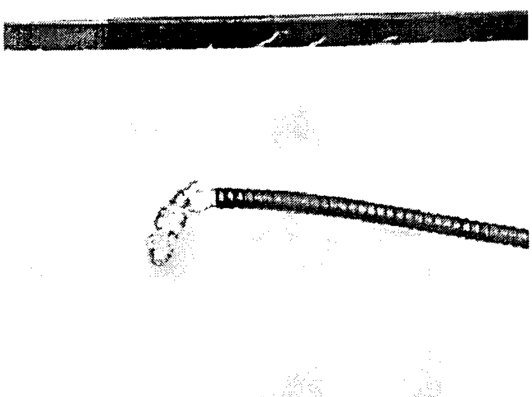
Samples from Laboratory Test for Lifetime



S/N #0254



S/N #0252



S/N #0233

Figure D-1: Mechanical damages of ET probes

APPENDIX E

Input data and Results of Statistical Analysis

```
  DESIGN: 3 - way ANOVA        , fixed effects
DEPENDENT: 1 variable:        ENTRIES
  BETWEEN: 1-G_TUBE  ( 2): UPPER LOWER
           2-OPERATOR( 2):    1    2
           3-VIBRATED( 2): YES NO
   WITHIN: none
```

0 CASE NAME	1 G_TUBE	2 OPERATOR	3 VIBRATED	4 ENTRIES
S/N 0254	LOWER	1	NO	1025
S/N 0230	UPPER	1	NO	751
S/N 0236	LOWER	2	NO	594
S/N 0247	UPPER	2	NO	651
S/N 0103	LOWER	1	YES	414
S/N 0231	UPPER	1	YES	588
S/N 0100	LOWER	2	NO	643
S/N 0240	UPPER	2	YES	801
S/N 0092	LOWER	1	YES	658
S/N 0244	UPPER	1	YES	482
S/N 0246	LOWER	1	NO	870
S/N 0239	UPPER	1	NO	776
S/N 0229	LOWER	2	NO	749
S/N 0233	UPPER	2	YES	318
S/N 0242	LOWER	2	YES	707
S/N 0097	UPPER	2	NO	830
S/N 0252	LOWER	2	YES	803
S/N 0098	UPPER	2	YES	369
S/N 0228	LOWER	1	YES	598
S/N 0241	UPPER	1	NO	954

Table E-1: Input data for analysis of variance

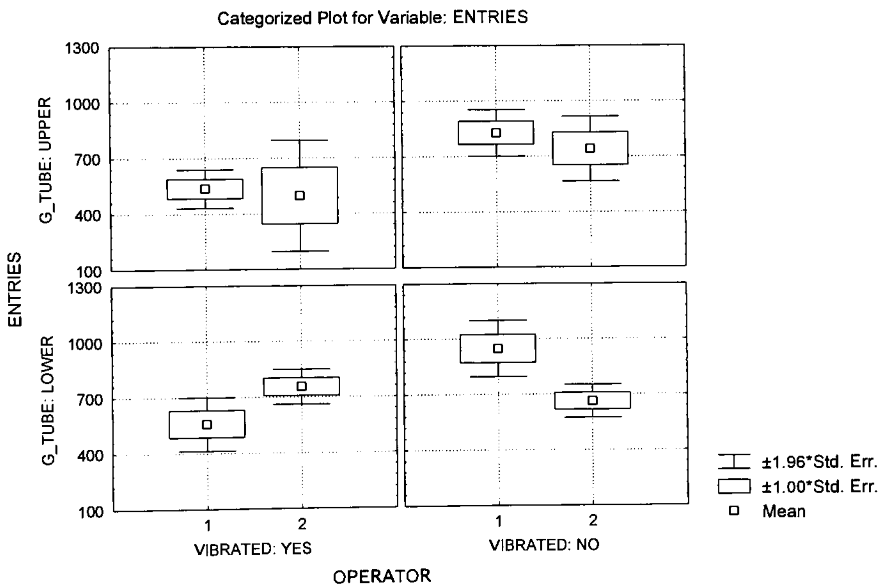


Figure E-1: Categorized plot of number of entries tested by the probe

STAT. GENERAL MANOVA	Summary of all Effects; design: (probes1.sta) 1-G_TUBE, 2-OPERATOR, 3-VIBRATED					
Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
1	1	31234.1	12	20707.30	1.50836	.242934
2	1	13568.1	12	20707.30	.65523	.434005
3	1*	208833.6*	12*	20707.30*	10.08502*	.007985*
12	1	440.8	12	20707.30	.02129	.886417
13	1	17088.5	12	20707.30	.82524	.381534
23	1	84694.5	12	20707.30	4.09008	.066006
123	1	57116.0	12	20707.30	2.75826	.122637

Table E-2: Summary of all effects

STAT. GENERAL MANOVA	Levene's Test for Homogeneity of Variances (probes1.sta) (ANOVA on absolute within-cell deviation scores) Degrees of freedom for all F's: 7,12			
variable	MS Effect	MS Error	F	p-level
ENTRIES	6881.714	2288.302	3.007345	.045329

Table E-3: Levene test