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DEVELOPMENT OF NONDESTRUCTIVE TESTING METHOD FOR TUBE INSPECTION IN FIN-FAN COOLERS IN KAZAKHSTAN'S OIL/GAS, CHEMICAL AND POWER INDUSTRIES

ҚАЗАҚСТАННЫҢ МҰНАЙ-ГАЗ, ХИМИЯ ЖӘНЕ ЭНЕРГЕТИКА ӨНЕРКӘСІБІНДЕГІ ҚАБЫРҒА-ЖЕЛДЕТКІШ САЛҚЫНДАТҚЫШТАРДЫҢ ҚҰБЫРЛАРЫН БАҚЫЛАУ ҮШІН БҰЗБАЙТЫН БАҚЫЛАУ ӘДІСІН ӘЗІРЛЕУ

РАЗРАБОТКА МЕТОДА НЕРАЗРУШАЮЩЕГО КОНТРОЛЯ ДЛЯ КОНТРОЛЯ ТРУБ РЕБЕРНО-ВЕНТИЛЯТОРНЫХ ОХЛАДИТЕЛЕЙ В НЕФТЕГАЗОВОЙ, ХИМИЧЕСКОЙ И ЭНЕРГЕТИЧЕСКОЙ ПРОМЫШЛЕННОСТИ КАЗАХСТАНА

Abstract. *This paper describes the development of a non-destructive testing (NDT) method that improves the reliability of air-cooled heat exchangers by reducing down-time related to corrosive and erosive failure of finfan tubes. The project goal was to maximize the output of oil and gas plants, refineries, chemical plants, power generation, and similar industrial establishments while simultaneously reducing the plant operating cost. The work first identified those NDT requirements for air-cooled heat exchangers damage assessment that would provide the greatest economic benefit for Kazakhstan industry.*
Keywords: *nondestructive testing, electromagnetism, heat exchangers, tube, oil/gas, permanent magnets.*

Аңдатпа. *Бұл мақалада бұзбайтын бақылау (ББ) әдісінің дамуы сипатталған ауамен салқындатылған жылу алмастырғыштардың сенімділігін арттыру, коррозиялық және эрозиялық бұзылған құбырларға байланысты тоқтап қалу уақыты арқылы қысқарту. Жұмыстың мақсаты – пайдалану шығындарын азайта отырып, мұнай-газ, мұнай өңдеу, химия зауыттарының, электр станцияларының және осыған ұқсас өнеркәсіптік кәсіпорындардың өнімділігін барынша арттыру. Жұмыста алғаш рет қазақстандық өнеркәсіп үшін ең үлкен экономикалық пайданы қамтамасыз ететін ауамен салқындатылған жылу алмастырғыштардың зақымдануын бағалау үшін бұзбайтын бақылауға қойылатын талаптар айқындалды.*
Түйін сөздер: *бұзбайтын бақылау, электромагнетизм, жылу алмастырғыштар, құбырлар, май / газ, тұрақты магниттер.*

Аннотация. *В этой статье описывается разработка метода неразрушающего контроля (НК) повышающий надежность работы теплообменников с воздушным охлаждением за счет сокращения времени простоя по причине коррозионного и эрозионного разрушения оребренных труб. Цель работы – максимальное увеличение производительности нефтегазовых,* *нефтеперерабатывающих, химических заводов, электростанций и аналогичных промышленных предприятий при одновременном снижении эксплуатационных расходов. В работе впервые были определены требования к неразрушающему контролю для оценки повреждений теплообменников с воздушным охлаждением обеспечивающие наибольшую экономическую выгоду для казахстанской промышленности.*

Ключевые слова: *неразрушающий контроль, электромагнетизм, теплообменники, трубы, масло/газ, постоянные магниты.*

Introduction. Basic engineering principles dictate that the heat exchangers tube condition plays a key role in determining the remaining safe operating life. Current methods for performing these measurements, based on ultrasonics, eddy current and magnetic methods provide only a sparse data and take a long time to complete due to both extensive cleaning requirements and testing time. The objective of this project was to develop a new testing method that 1) will be especially suited to local conditions experienced in Kazakhstan, i.e. will address specific damage mechanisms experienced in Kazakhstan oil/gas and other industrial plants, and 2) will be a major technical improvement to presently used methods in the world. It needs to emphasize that the tube inspection must be conducted from tube internal surface, which dictates a miniaturization of test sensors and application of newest materials and technologies to acquire the data and further to process and analyze it. The first stated goal was met by visits to selected industrial plants, discussions with engineering personnel and obtaining tube samples with various degree of deterioration. The technical approach has included designing the magnetic flux leakage modern sensors using new generation of permanent magnets and coil configurations to make it more sensitive to any kind of sharp damage, such as pits, cracks, grooving. Additionally, the Hall-effect sensors were incorporated into the internal sensors in order to measure the magnetic flux flowing through the tube wall and indirectly determine the wall thickness and its gradual variations along the tube. This allows for fast detection of all type of damage mechanisms active in tube with a minimum need for tube cleaning and preparation..

Материалы и методы исследования (Материалдар және зерттеу әдістері) (Materials and methods of research). Technical requirements for finfan tube testing. The project goal is the development of innovation technology for tube testing in fin-fan coolers (Figure 1) for oil/gas plants, chemical, steel, and other industries. Tube inspection is an important tool to determine their conditions and detect damage at initiation stage [1].

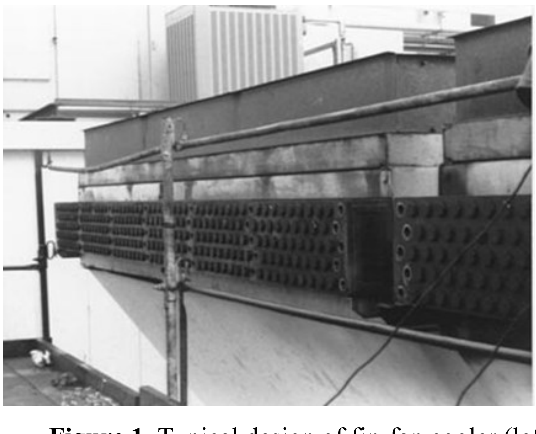
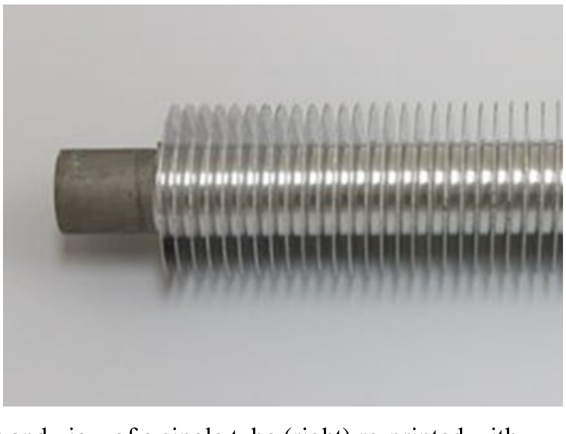

Figure 1. Typical design of fin-fan cooler (left) and view of a single tube (right) re-printed with permission from Magnetic Development, Inc.

Description of the new ndt method for fin fan tube inspection.

The objective of this project was to develop a much-improved approach to evaluating the condition of tubes in fin-fan coolers by determining their overall wall thickness and detecting any defects in form of pits, cracks, grooves, etc. The failures of air-cooled heat exchangers are responsible for a significant number of outages. Operating experience around the world has demonstrated that both downtime and maintenance costs are reduced significantly when tube condition is evaluated regularly by NDT methods [8,9,17]. It allows to predict the possibility of failure and estimate the remaining safe life for the heat exchanger. Plants managers are able to schedule maintenance and plant shutdown instead of being forced to shut down by tube leak.

The main requirements was to develop a state-of-an-art nondestructive test method for air-cooled heat exchanger tubes, capable to: a) detect any damage mechanism while testing from tube internal diameter, b) accurately determine the damage in terms of wall loss, c) perform inspection quickly and expediently, d) requires minimum tube cleaning.

Our approach was based on developing a magnetic test method with multi-sensor including coils and semiconductor sensors. This offers a significant improvements to present methods and procedures, which are commonly employed in the routine nondestructive testing (NDT). Specifically, the test system based on a combination of a Magnetic Flux Leakage (MFL) together with measurement of the entire magnetic flux induced in a tube wall was developed and adapted to typical industrial conditions. This work was made possible by recent advances in magnetic materials, electronics, computer modelling and robotics.

In order to undertake this project, our team has conducted a thorough state-of-an-art study, reviewing more than 200 publications, patents, websites and reports issued throughout the world. In addition, numerous discussions were conducted with plant engineers and test practitioners. Conclusions of our state-of-the-art study were following:

A majority of defects are due to internal pitting corrosion, general corrosion causing gradual wall thinning, external erosion/corrosion, internal inlet-end erosion and external grooving under and close to tubesheets [6,14,22,23,24,25]. Many NDT methods have been used in the past to assess tube condition with various degree of accuracy and internet search brings hundreds of such websites [26,27,28]. Table I at the end of this paper shows the advantages and disadvantages of each method and can be treated as a state-of-an-art study and answers the question how the newly developed MFL technology differs from the others. The typical equipment cost and level of inspectors' qualifications are also shown. The most common procedure involves conventional tube cleaning and then fast internal inspection (with ID sensor) of 100% tubes with one of electromagnetic methods (RFET, MFL, NFEC or biased EC) and then re-testing of a small sample with ultrasonic rotating probe – commonly known as IRIS. IRIS, although capable of detecting and evaluating most of damage conditions, requires extremely clean tubes, usually achieved only by chemical cleaning, which is inconvenient and sometimes even impractical for plant operators. This approach usually provides highly reliable results but, for reasons of measurement time (cost), the data set is sparse. It has to be noted that there is only a limited literature in scientific journals regarding the problem of air-cooled heat exchanger inspection and most of it is written by practitioners working for companies that either produce or test such heat exchangers and/or manufacture testing instrumentation. For that reason, the data available is rather biased because each author is trying to promote his own company or test method.

Summarizing, if any new testing method is developed it needs to be better, cheaper and easier to use than other methods. For that purpose, our work had concentrated to combine a known magnetic flux leakage (MFL) method [4], with other innovative technologies in order to achieve the capability to test relatively un-cleaned tubes at the high rate (300 tubes per shift and more).

Further, the required specifications has included: 1) possibility of testing thicker tubes, with the goal to detect 20% deep defect in tube 1”x.130”, 2) possibility of detection of either internal or external gradual wall thinning and accurately measuring the remaining wall thickness, 3) possibility to distinguish the defect origination point, whether ID or OD, and 4) improving the accuracy of quantitative data analysis in terms of percentage wall loss for each detected defect with desired accuracy +/-10%. The final objective of this project is a development of a new NDT method capable of fast evaluation of 100% tubes without necessity of expensive cleaning and partial re-testing with ultrasonic IRIS. Further, the testing had to conform to existing standards such as API661/GOST ISO13706-2011 (Air cooled heat exchangers for general refinery service), ASME Section VIII, Shell DEP 31.21.70.31. Most tubes are 1 inch outside diameter (25.4mm) and wall thickness from 0.083 to .130 inch (2.1 to 3.3mm). Rarely, tubes are 1.25 or 1.5 inch diameter. Tube material is either Carbon steel A-179, A-243 or ferritic low-alloy steel with max 9% of Chromium.

Based on the results obtained in both laboratory and field condition, the developed technology differs substantially from previous work. Novel features involved in our approach are:

1) New method for testing air-cooled heat exchanger tubes, based on combined principles of flux leakage with measurement of magnetic flux inside the tube wall. This permits to detect both sharp and gradual defects, thus eliminating a major limitation of MFL method.

2) Study on various arrangements of MFL sensors to allow for determining point of damage origin: internal vs. external. This has a potential to greatly improve the accuracy of data analysis and can even permit in the future to develop magnetic imaging of tube condition.

3) Innovative research on: a) practical measurements of magnetic fields around defects for new magnetic materials (Neodymium-Iron-Boron) and their effect on the signal waveform generated in sensors, b) study of new configurations of electromagnetic coils and high-energy permanent magnets.

Scientific methods used in the development process. Major scientific questions.

Both technical and practical issues were considered for maximum commercial usefulness of the new technology. Technically, the method has to be superior to presently used tests as shown in Table I. This means that it has to be capable of testing even thickest tubes encountered, to detect both sharp and gradual defects, to determine the damage point of origin, to be fast, accurate and field-hardened. Many practical restrictions were considered right at the point of research, so developed technology fits the real world. An important problem to overcome was the access to fin-fan coolers – they are located on the top of refining units in full sun and heat where it is not easy to carry heavy instrumentation and then make it work. Heavy deposits inside of tubes, most often of ferromagnetic nature, limits many test techniques, such as IRIS ultrasonics and RFET eddy current. Further, Aluminum fins over carbon steel tubes produce excessive noise that mask defect indications for majority of NDT methods used.

Description of experiments.

The following methods and approaches were used to achieve the best performance

1. The possibility of testing thicker tubes was evaluated. When MFL was originally developed in late 1980’s, it used strongest permanent magnets at that time, which were either Samarium Cobalt with 28-30 MGsOe power or Neodymium magnets with 32-36 MGsOe. Now, Neodymium magnets have been produced commercially with power of 56 and experimentally up to 64 [5]. The new magnetizing circuits were therefore designed and produced to magnetize the tube from its internal diameter with various strength of Neodymium magnets and with different design of a circuit itself. While the great number of scientific papers describing modelling of leakage field around defects has been published [13,15,16,20], our approach concentrated on physical

measurement of flux field and designing appropriate sensors to be able to detect such fields. Previously, the tubes could be tested with MFL when the ratio of tube ID-to-wall thickness was greater than 7. Our research with new magnetic materials has brought the possibility to achieve appropriate magnetization for the ratio of 5, which permits testing of thickest tubes in fin-fan coolers, i.e. 1” x .130” for carbon steels, ferritic low-alloy steels and Cr-Mo steels.

2. Gradual wall thinning and measurement of wall thickness was achieved by installing an additional sensor into the internal probe that continuously measures the magnetic flux through the circuit that includes a magnetizing circuit and a tube wall. This is a major novelty that was fully proven during numerous field inspections.

3. Recognizing the point of defect origin, ID vs. OD. This always represented a greatest challenge since all previous literature stated that this is not possible with MFL method [18]. These authors however, had developed the theoretical background for such analysis that might include various approaches. One possibility involves two pick-up coils with radial offset that react in different way to the same defect. Another option will be to add additional coil in the passive magnetic field that reacts only to internal defects and is “blind” to external ones. Eventually, we have settled on this latter approach.

4. Various approaches were investigated for improvement of the accuracy of data analysis with the goal to stay within +/- 10% of the tube wall [19,21]. They included: a) speed compensation either electronically or by adding speed sensor detecting the speed of a plastic sheath as it enters/leaves the tested tube, 2) designing a software that automatically measures amplitudes of each channel (coils and Hall-effect) and selects appropriate data correlation for a specific type of damage. The work is continuing under the second approach and it will be reported shortly.

5. Wear resistance – probe body was Chrome plated. This was proven during the field inspection in one of German nuclear plants. The feedwater heater was tested with 3/4x0.083” Carbon Steel tubes, 8m long, which had heavy and abrasive Fe_3O_4 deposits inside. The original probes with stainless steel sheath were wearing out after only 20-30 tubes, which was unacceptable due to high cost of each probe (around $1,000 each). Different coatings were then tried, such as Nickel plating, ceramic coating and Chrome plating. Eventually, Chrome plating was proven most effective with one probe lasting over 5,000 tubes. The photo of a final probe design is shown in Figure 2.

Figure 2. Internal MFL probe for finfan tube inspection

6. Following the extensive laboratory experiments, field inspections were performed in UK and USA oil refineries. The major difficulty appear to be the double tubesheet in most of finfan heat exchangers with tubes starting at the second one. The distance between two tubesheets was approximately 10 cm and that caused the magnetic probe to "stick" to the the first tubesheet and being unable to enter the tube. The problem was solved by using the conduit, made of nonmagnetic piece of tubing that penetrated both tubesheet and allowing the probe to easily enter the tube. Probe was pushed and then pulled from the tube over its entire length (typically 18-12m) by hand as the most expedient way to test without the necessity to carry any heavy mechainical pusher-puller device. It needs to note that in order to access the tubes, one needs to climb a ladder, so the equipment should be as small and light as possible. The photo of the inspector is operating the probe is shown in Figure 3 below.

Figure 3. Field data acquisition for finfan MFL inspection. Note the conduit inserted into the outside tubesheet that allows for the probe to enter the tube, starting at the second (internal) tubesheet

7. Data were acquired for each tube tested and stored on the computer. They were in the form of signals for three (3) independent channels:

− Channel 1: signals from active coil (Coil A in Fig.4), installed in the center of the magnetizing circuit. This coil records all sharp defects on the tube, originated both from internal and external surface

− Channel 2: signals from passive coil (CoilB in Fig. 4), installed in the front of the probe. This coil senses the area on the tube in passive magnetic field, thus only sharp defects originated from internal surface and very deep defects originated from external surface are detected. By comparing the amplitude and shape of signals from both coils, it was possible to first, determine the defect point of origin and second, approximate the percentage wall loss associated with the defect.

− Channel 3: signals from the sensor that constantly measures the magnetic flux flowing through the probe-tube circuit. In our case, Hall effect sensors are used for this purpose, however other type of sensors could be also applied, such as megantoresistors, etc. The correlation exists between the amount of magnetic flux and the wall thickness of tube, thus, the wall thickness and its gradual variations can be detected and quantified.

− The details of probe design as well as indications obtained for various depth of defects and their point of origin is explained in Figure 4 below:

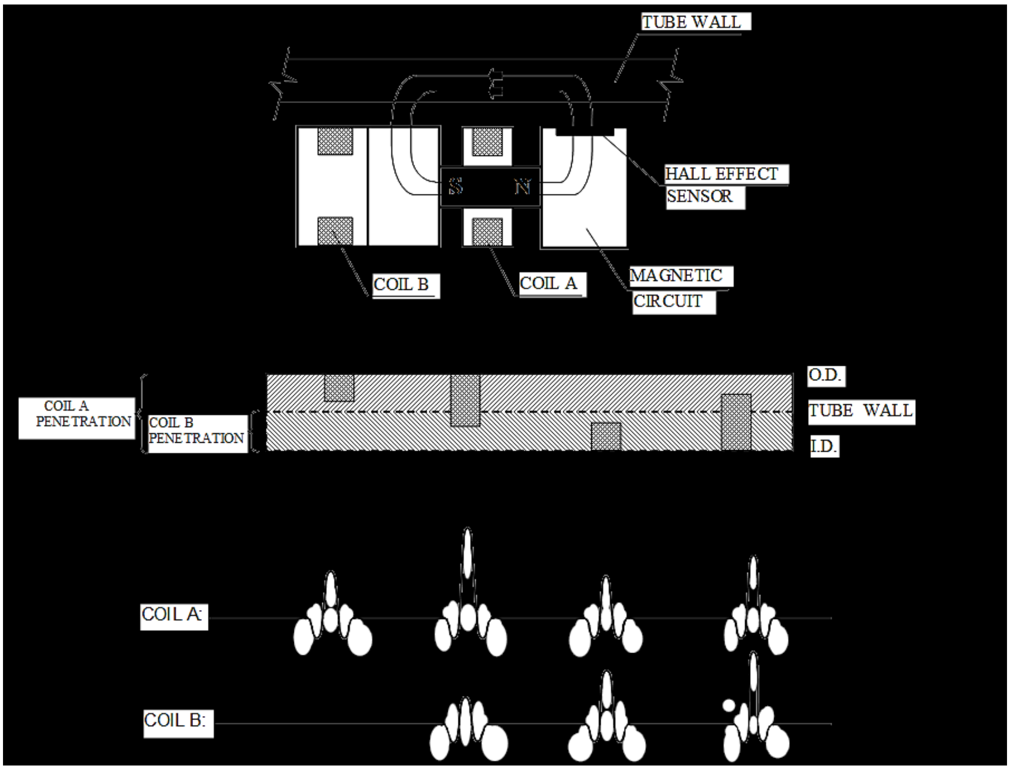

Figure 4. Details of MFL probe design showing three sensors installed: Coil A in active magnetic field, Coil B in passive magnetic field and Hall effect sensor for detection of gradual wall thinning (assuming probe travels from left-to-right). Lower pictures show the response of Coils A and B to various defect depth and origin, and the principle of data analysis, which is done by measuring signal amplitudes and their ratios from both coils

In order to assess the accuracy of the newly develop test m(3) ethod, the results from several inspections were compared to the results obtained with IRIS (Internal Rotating Inspection System) results. This is an ultrasonic imaging method, that provides fairly accurate results, usually within 10% of wall thickness, however it requires extremely clean tubes (such degree of cleanliness can be usually achieved only with chemical cleaningand is very slow, only maximum of about 50 tubes can be tested during one 8 hrs shift. Figure 5 below shows the correlation between those two methods, which is relatively high with calculated coefficient of correlation reaching 89% . This confirms that the accuracy of this new MFL methods is similar to this, achieved by IRIS, i.e. +/- 10%. Indeed, numerous analysis performed on tubes removed from heat exchangers have proven that conclusion.

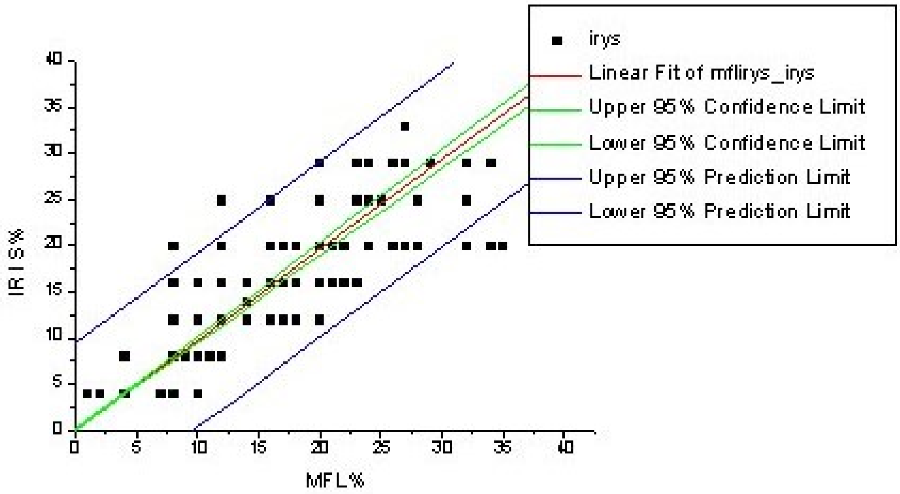

Figure 5. Data correlation in terms of percentage wall thickness determined from the results of MFL vs. IRIS inspection methods

Results and discussion. In conclusion, the newly developed MFL combination method was compared with all other methods, which are currently used in industrial testing of finfan coolers/heat exchangers. Table 1 shows such comparison, which was based on publication search, discussion with plant engineering personel and authors' personal experience. The data on Table 1 demonstrates that most of design assumptions were met with the new method and with proper use, it can be superior to all test methods used to-date.

Table 1. Comparison of NDT different methods for detecting specific finfan cooler defects (per published and unpublished data plus our Consultant's personal experience)

	IRIS Ultrasonics	RFET	Near Field Eddy Current	Classic MFL	Magnetic Biased Eddy Current	New MFL Method
Requirement for clean tubes	very clean	clean	clean	somewhat clean	clean	somewhat clean
Interference from Aluminum fins	No	Yes	Only ID screened	No	Yes	No
	IRIS Ultrasonics	RFET	Near Field Eddy Current	Classic MFL	Magnetic Biased Eddy Current	New MFL Method
Detection of ID sharp defects (pits)	Yes	Yes	Yes	Yes	Yes	Yes
Detection of OD sharp defects	Yes	Yes	No	Yes	No	Yes
Detection of OD defects close to tubesheets or	Yes	No	No	Yes	No	Yes

supports						
Detection of gradual wall thinning – erosion/corrosion	Yes	Yes	No	No	No	Yes
Accuracy of quantitative data analysis	Very Good	Good	Satisfactory	Satisfactory	Satisfactory	Good or Very good
Recognize ID vs. OD defects	Yes	No	No	No	Limited	Yes
Inspection speed Avg tubes per shift	Very slow 50	Medium 150-200	Fast 300	Fast 300	Fast 300	Very fast 300-500
Limits for testing thick tubes	No limit	No limit reported	Only ID defects detected	Ratio of ID-to-wall >7	Unknown	Ratio of ID-to-wall >5
Typical equipment cost	$100K	$50K	$50K	$20K	$50K	$20K
Level of Inspector Qualifications Required	High	High	Medium	Medium	Medium	Medium

Notes: IRIS – Internal Rotating Inspection System; RFET – Remote Field Eddy Current; MFL – Magnetic Flux Lekage

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