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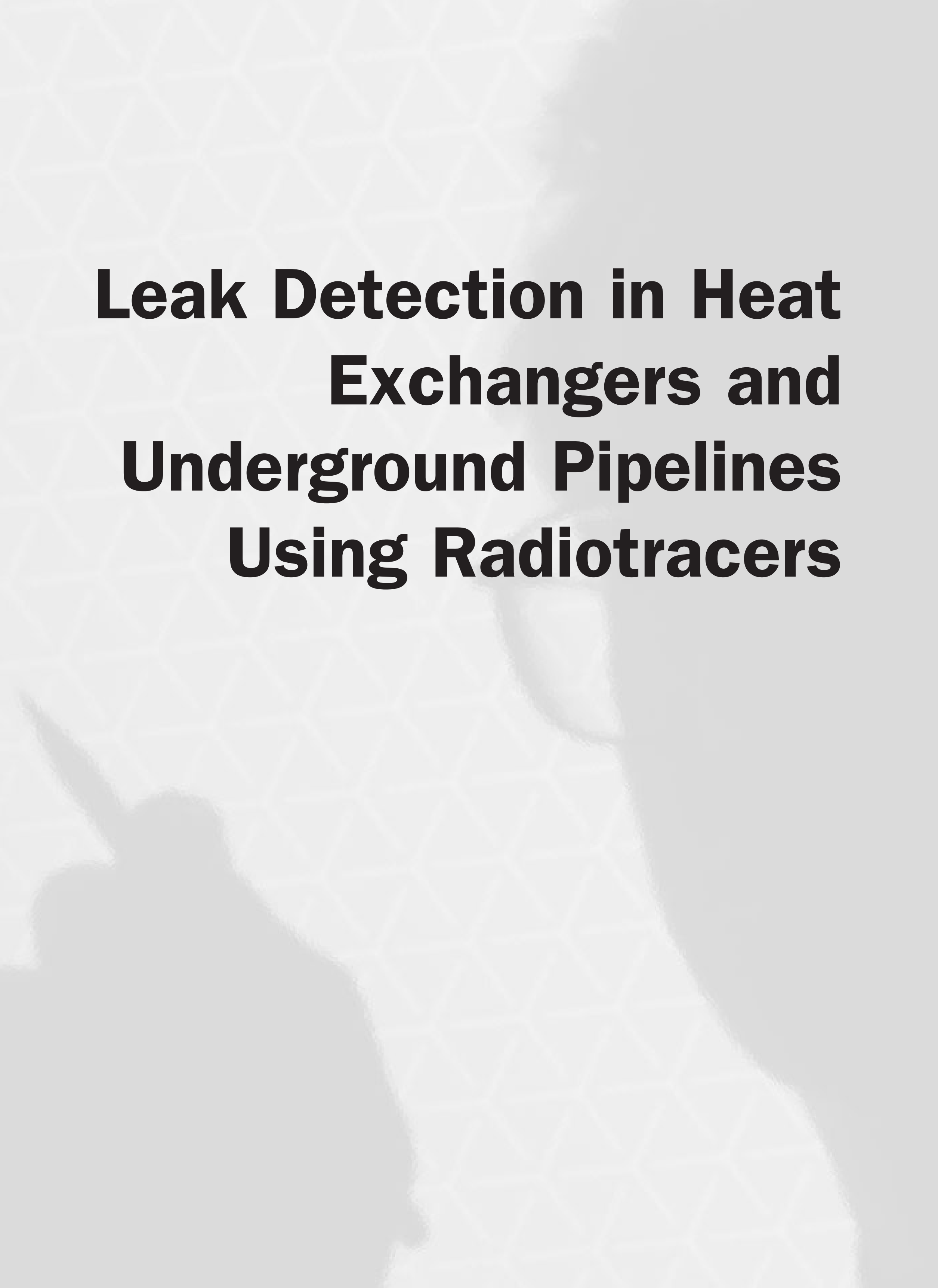

Leak Detection in Heat Exchangers and Underground Pipelines Using Radiotracers

VIENNA, 2009

TRAINING COURSE SERIES 38

LEAK DETECTION IN HEAT EXCHANGERS AND UNDERGROUND PIPELINES USING RADIOTRACERS

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TRAINING COURSE SERIES No. 38

LEAK DETECTION IN HEAT EXCHANGERS AND UNDERGROUND PIPELINES USING RADIOTRACERS

MATERIAL FOR EDUCATION AND ON-THE-JOB TRAINING FOR PRACTITIONERS OF RADIOTRACER TECHNOLOGY

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FOREWORD

The International Atomic Energy Agency plays a major role in facilitating the transfer of radiotracer technology to developing Member States. The use of radiotracer techniques is well established in many Member States; some hundred radiotracer and end user specialists have been trained in radiotracer techniques and their applications; nearly 50 radiotracer laboratories have been working in this field. The training of radiotracer practitioners is vital for the provision of quality services to industry.

Leak detection using radiotracer techniques is probably one of the most widespread applications of radiotracers in industrial troubleshooting. Radiotracer techniques are the most competitive for on-line leak inspection of heat exchangers and buried pipelines. Radiotracers help in early detection of leaks in heat exchangers and underground transporting pipelines, thus saving money, reducing shutdown time, ensuring safe operation and protecting the environment from pollution.

The training course series on leak detection in heat exchangers and underground pipelines using radiotracers addresses the needs of the radiotracer groups and their end users. Besides training purposes, this material will assist radiotracer groups in establishing their quality control and accreditation systems.

This training course material is based on lecture notes and practical work delivered by many experts in IAEA-supported activities. In particular, the Technical Cooperation Projects implemented under the Regional Cooperative Agreement (RCA) of the IAEA Member States in the Asia and the Pacific Region have been successful in transferring and implementing radiotracer techniques for leak detection to many end users from oil and gas production, oil refineries and the petrochemical industry. The experience obtained in the RCA Region is presented in the training material illustrated with many case studies carried out in several RCA Member States. Lectures and case studies were reviewed by a number of specialists in several RCA meetings. The IAEA wishes to thank all the specialists for their valuable contributions.

The IAEA officers responsible for this publication are M.P. Dias of the Department of Technical Cooperation, and J-H. Jin of the Division of Physical and Chemical Sciences.

EDITORIAL NOTE

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INTRODUCTION

In modern, highly complex, large-capacity chemical plants, the necessity to minimize expensive down time has led to increased use of radiotracer techniques. Leak detection using radiotracer techniques is one of the most widespread applications of radiotracers in industry. The economic benefit is considerably high and recognized by the end users. In absolute term, savings of the order of million US$ can be obtained, in particular in petrochemical plants and oil and gas transporting pipelines.

Any undesirable interconnection between isolated parts of a system or between two systems is a leak. A leak is suspected if there is any abnormal behavior of a system, such as loss of pressure, contamination of product or loss of process efficiency. A leak could be the result of an unintended crack, hole or porosity in an enveloping wall or joint. There is a constantly growing need for products and technologies that for their realization require hermetically closed elements, vessels and tubes. Leaks create serious problems in process plants or in pipelines, spoiling the quality of the final product or reducing the transportation capacity of the water, oil and gas pipelines. The safety problems are also related with leaks. The contamination of surface and ground water, and soil could happen as well in the case of oil or toxic fluids. There is an increasing demand for sensitive inspection methods to avoid pollution incidents caused by subsurface leakage from oil transmission pipelines. A pipeline section leaking few liters of oil per hour to the environment has the potential to contaminate tens of thousands of cubic meters of groundwater per day.

The basic functions of leak detection are the location and size measurement of leaks in sealed systems. Radiotracer techniques are very sensitive, effective and competitive for on line leak detection, especially in heat exchangers and underground pipelines. Radiotracers allow an early detection of small leakages before these develop into major pollution incidents. Radiotracer methods used for on-line leak detection in heat exchangers and underground pipelines can achieve the detection limits up to 0.1% of stream flow.

Heat exchangers are the most important hermetically closed vessels in petrochemical and chemical plants. Leak inspection in heat exchangers is crucial for the performance of processing lines and the quality of final products. On-line detection of leaks in heat exchangers is very difficult task due to their complexity and harsh operational conditions. Radiotracer method for leak detection in heat exchanger is applied in commercial routine service to petrochemical and chemical industries in many developed and developing countries.

For the transportation of water, oil and gas, a lot of pipelines are installed underground. Leaks in the pipelines reduce the transportation capacity of the pipeline, as well as create serious environmental contamination. Detection of leaks in buried pipelines is also very difficult task due to lack of access to the pipeline. Radiotracer method is employed successfully in searching for leaks in buried pipelines.

Radiotracer methods are non-intrusive methods of choice for early detection of leaks in heat exchangers and underground transporting pipelines. The benefits using radiotracer methods are: reducing shutdown time, ensuring safe operation, protecting environment from pollution and saving money. A radiotracer test for leak inspection in heat exchanger costs several thousand US$ while in underground pipelines costs some tens of thousand US$ (cost of the radiotracer and labor) but the benefit for end users is huge, hundred times more (saving in routine maintenance, material and labor cost). There are few short-term investments, which will give a return of this magnitude. The cost effectiveness of radiotracer applications for leak detection should be widely promulgated to encourage industrialists to take full advantage of the technology.

There is little experience in training radiotracer practitioners on radiotracer techniques for leak detection. This text is the result of the belief that there is a need to preserve, promote and transfer the practical knowledge accumulated over years in this field.

The training course material is organized into two main sections, an introduction and an annex. The introduction presents the objective of the training course series. Leak inspections in heat exchangers and underground pipelines call for two different methodologies. The methodologies and technologies of leak detection in heat exchangers and underground pipelines are provided in the first and second section respectively.

The first section describes the radiotracer methods for leak detection in heat exchangers. A general view of heat exchanger principles, their designs and problems is provided for better understanding of radiotracer results. The section treats the radiotracer methods for leak detection in heat exchangers only; nevertheless, a short comparative view is given to highlight the advantages of radiotracer to conventional methods, in particular for on line inspection. Principle of radiotracer methods, selection of radiotracers, and radiotracer experimental design and execution are described in detail. Several real case studies are presented in this section.

The second section provides the radiotracer methods for leak detection in underground pipelines. Principle of radiotracer methods and radiotracer detection techniques are described in detail. Some real case studies illustrate the application of radiotracer methods for solving various problems.

The guideline for testing heat exchangers using radiotracers is provided in the annex. This guideline facilitates promotion and acceptance of the radiotracers to end users, and it can be utilized also for accreditation purposes.

1. RADIOTRACER METHODS FOR LEAK DETECTION IN HEAT EXCHANGERS

1.1. HEAT EXCHANGERS

A heat exchanger is a device built for efficient heat transfer from one fluid to another. They are widely used in petroleum refineries, chemical and petrochemical plants, natural gas processing, refrigeration, power plants, air conditioning and space heating. Heat exchangers may be classified as concurrent or countercurrent flow type according to their flow arrangement (Fig. 1). In concurrent flow heat exchangers, the two fluids enter the exchanger at the same end, and travel in parallel to the other side. In countercurrent flow heat exchangers the fluids enter the exchanger from opposite ends. The countercurrent design is most efficient, in that it can transfer the most heat.

A typical heat exchanger, usually for higher-pressure applications, is the shell and tube type heat exchanger (Fig. 2). The shell and tube type heat exchanger consists of a bundle of tubes, through which one of the fluids runs. The second fluid runs outside of the tubes.

Fig. 3 shows a typical shell and tube type heat exchanger, which is the most common type of heat exchanger in oil refineries and other large chemical processes, and is suited for higher-pressure applications. It consists of a shell (a pressure vessel) and a bundle of tubes inside it.

Heat is transferred from one fluid to the other through the tube walls, either from tube side to shell side or vice versa. The fluids can be either liquids or gases on either the shell or the tube side. In order to transfer heat efficiently, a large heat transfer area should be used, so there are many tubes.

To be able to transfer heat well, the tube material should have good thermal conductivity. As heat is transferred from a hot side to a cold side through the wall of tubes, there is a temperature gradient on the wall of the tubes, which creates thermal stress. In addition, the pressure stress is present due to pressure difference between the two sides of the tube. Variation in pH of fluids causes corrosion of the tube wall. All of these deterioration factors may create faults in a heat exchanger. Fig. 4 shows typical faults experienced in heat exchangers

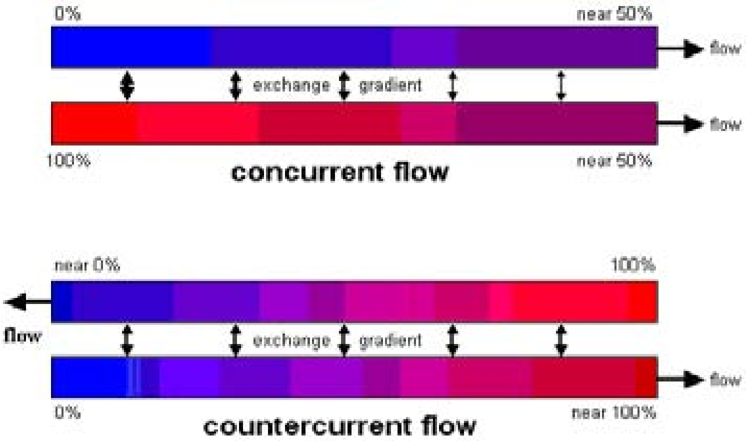


FIG. 1. Concurrent and countercurrent flow type of heat exchangers

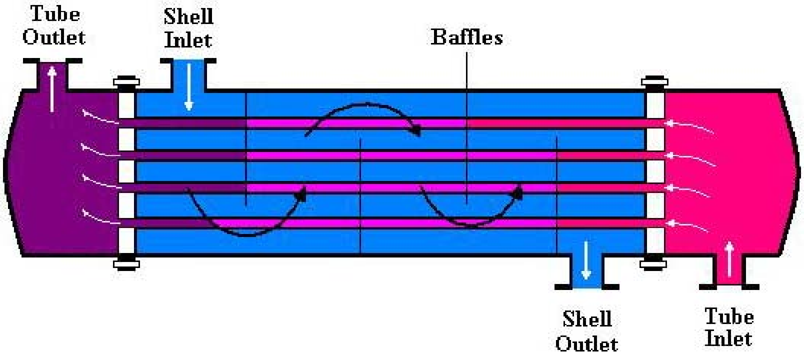


FIG. 2. Typical shell and tube type heat exchanger

FIG. 3. A typical shell and tube type heat exchanger

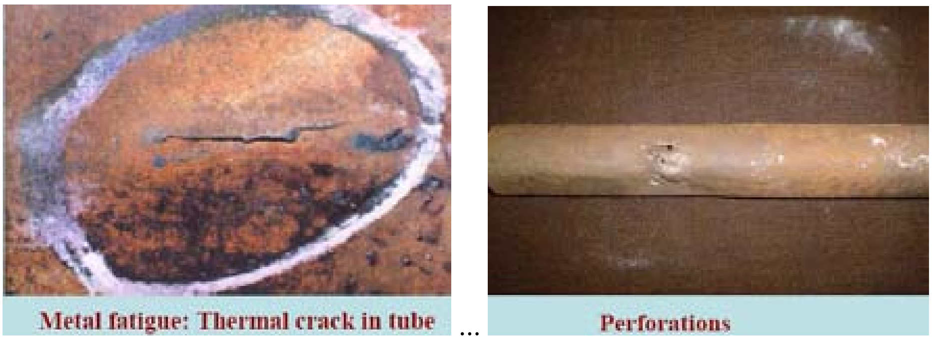


FIG. 4. Typical tube deterioration and faults in heat exchangers

1.2. ADVANTAGES OF RADIOTRACER METHODS FOR LEAK DETECTION IN HEAT EXCHANGERS

There are various conventional non-destructive techniques (NDT) for detection of leakages in processing vessels and plants. Some of them may be employed for off-line leak detection in heat exchangers during a maintenance shutdown. Normally, conventional NDT techniques are not suitable for on-line (without interrupting the process) leak detection in industrial heat exchangers.

Short descriptions of some conventional leak detection techniques are given below. To compare the sensitivity of various leak detection techniques the leak rate is used. The unit of leak rate unit is *mbar·L/s*; which is equivalent to $at.\ m^3.\ s^{-1}$.

Visual inspection is a technique carried out by NDT inspectors in almost all industrial plants, either looking for or accidentally discovering leaks of process fluids.

Chemical reagent tests: some process gases give chemical reactions with simple reagent, e.g. leaking ammonia gas may be detected by its reaction with hydrogen chloride producing dense white fumes of ammonium chloride. This test can be applied for leak detection in heat exchangers as well, but in off-line condition only.

Pressure change method is employed for leak detection in vacuum systems. The method employs pressure gauges which are ordinary used to monitor the system performance. Suspected leak sites can be squirted with a solvent (e.g. acetone or similar) while watching the gauge for a pressure rise that occurs when the solvent enters the leak. This method is not applicable for leak detection in heat exchangers.

Overpressure method (bubble test) is performed by filling the system to be tested with a fluid. Water is frequently used as the fluid. Observing the outside surface, the wetted areas reveal leaks. Testing with gas, the vessel is subjected to overpressure of some bars (depending on material and wall thickness) and immerged into water. At leaks, the gas bubbles begin to escape. In this manner, leaks up to 10^{-3} mbar·L/s can be detected. If the vessel is too large for immersion, the suspected points should be painted by soap solution and the bubbles can be seen if there is a leak. This technique enables leak detection up to 10^{-5} mbar·L/s. This method can be used for leak detection in heat exchangers, but in off-line condition only.

Dye penetrant method is an adaptation of a technique used to find cracks in metals and defects in welds. It uses a low viscosity fluid that exhibits a high rate of surface migration. This fluid is painted on one side of a suspected leak site, and after some time, it is detected on the other side of the wall. The test is simple, low cost, it leaves records, and the sensitivity can be as high as 10^{-6} mbar·L/s. It can be used for leak detection in heat exchangers, but in off-line condition only.

Acoustical leak detection uses the sonic or ultrasonic signal generated by gas as it expands through the leak orifice. The intensity and frequency of the signal are function of the differential pressure, the size and geometry of the hole. Acoustical leak detection technique requires a sensitive microphone; it is simple and fast, but is limited to about 10^{-3} mbar·L/s. This technique is not recommended for on-line leak detection in heat exchangers because of industrial noises and interferences.

Mass spectrometer as leak detector is used as very sensitive instrument for determining leak existence and pin-point the exact location of the leak in many industrial components. For units under pressure, the helium is added to the vessel under investigation at a suitable test pressure. Measurement at locations where helium may leak is then carried out using a helium portable mass spectrometer. The sensitivity of this method is up to 10^{-9} mbar·L/s. Helium leak detection technique is mainly used in off-line inspection for leaks in heat exchangers and other vessels (Fig. 5).

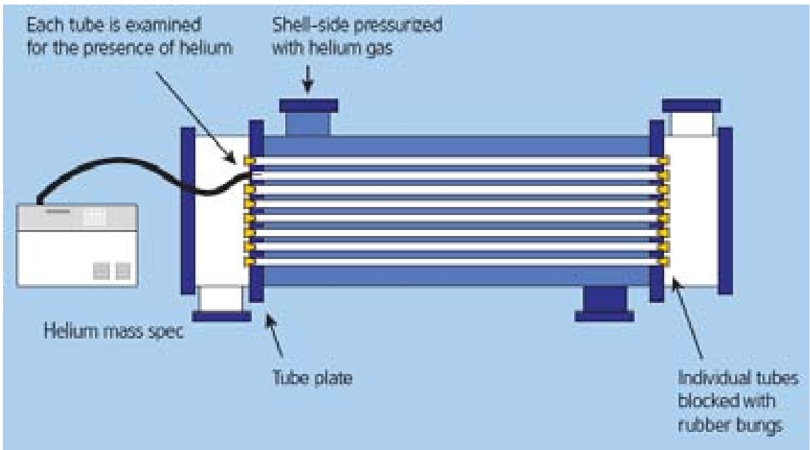


FIG. 5. Off-line leak detection in heat exchanger using the helium mass spectrometer technique

Thus, conventional NDT techniques are not employed for on-line leak detection in industrial heat exchangers. Using them for off-line leak detection, during a maintenance shutdown, does not bring expected benefits.

Only radiotracer offers possibility of on-line measurements, providing information in the shortest possible time. Gamma radiation the radiotracers emit penetrates the heat exchangers walls and provides information about very small leaks even when direct access to the heat exchanger is not possible due to envelopes or other barriers. The emission of radiation is a specific property of the radioisotope, not affected by interference from other materials in the system; thus radiotracers have strong resistance against severe process conditions of heat exchangers. Because the characteristics of the radiations differ from one radioisotope to another, multiple radiotracers may be employed and measured simultaneously if needed to locate the leaks.

Radiotracers are the most sensitive and competitive tools largely used for on-line leak detection in heat exchangers. The success of radiotracer applications for leak detection rests upon their extremely high detection sensitivity for extremely small concentrations; for instance, some radiotracers may be detected in quantities as small as 10^{-17} grams. The amounts of radiotracer used are virtually insignificant. For example, 1 Ci (37 GBq) of ^{131}I weighs 8 µg, while 1 Ci of ^{82}Br weighs only 0.9 µg. That is why, when injected, they do not disturb at all the fluid dynamics inside the heat exchanger under investigation, as well as they do not spoil the product quality. Normally, in heat exchangers it is not allowed to introduce other substances even in very low quantities because they spoil the final product and may destroy the exchanger itself. Radiotracer method is very sensitive; it enables the measurement of leak flows up to 10^{-10} mbar·L/s.

1.3. RADIOTRACER METHODS FOR LEAK DETECTION IN HEAT EXCHANGERS

1.3.1. Principle of radiotracer method

Fig. 6 gives the principle of radiotracer method for leak detection in shell and tube type heat exchanger, which is the most common type of heat exchangers in industry. A very small amount of a compatible radioisotope is injected as a sharp pulse into the higher pressure process stream entering the heat exchanger. Normally, a minimum of two radiation detectors are monitoring radiotracer movement through the heat exchangers.

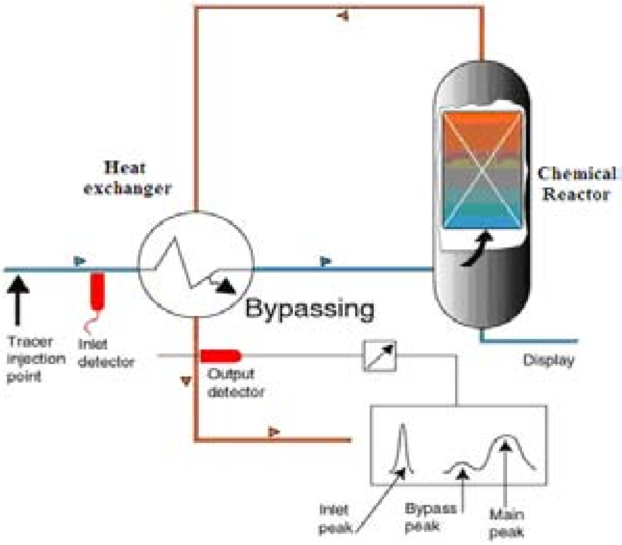


FIG. 6. Principle of radiotracer method for leak detection in heat exchanger using two detectors

The injection detector (inlet detector, Fig. 6) mounted at the tube side inlet (high pressure) monitors the injection peak and time. The leak detector (output detector, Fig. 6) mounted at the shell outlet (low pressure) detects radiotracer infiltrated into the lower pressure side from the higher pressure side showing the presence of a leak (if any). Any leakage throughout the high pressure tube side could be indicated by a subsidiary peak (so called bypass peak) preceding the main peak. The main peak represents the flow pattern of the fluid flowing from inlet to outlet in normal way, while the subsidiary peak represents the leak because it goes in abnormal way bypassing the normal flow. The outlet detector monitors the total activity injected. The leakage rate is the percentage of the area of the leakage peak to the sum of the areas of the leakage and main peaks.

Other detectors can be mounted at the tube side outlet and shell side inlet of the heat exchanger to monitor the radiotracer movement into the whole processing line. The records of the additional detectors help to identify better the presence of the leak peak. Fig. 7 shows an experimental setup where four radiation detectors are positioned to monitor radiotracer passage through the whole processing line, which consists of the heat exchanger and a converter.

Detector 1 shows the tube inlet injection pulse, while detectors 2 and 4 show the outlet responses from the tube and converter respectively. The subsidiary peak preceding the main peak (Fig. 7, detector 3) indicates the leak because appears in shell outlet before the main peak.

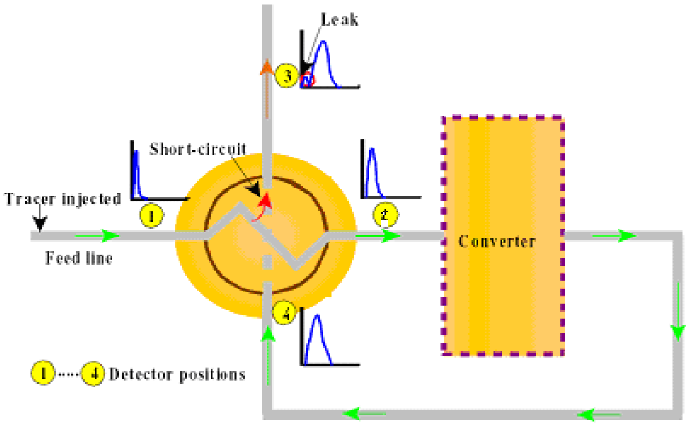


FIG. 7. Radiotracer method for leak detection in heat exchanger using four detectors

1.3.2. Confirmation of a leak using brick detector

Much care must be exercised when using radiotracer technique for detecting small leaks in heat exchangers, as confusion can be caused by erroneous responses (false peaks) of the leak detector coming from radiotracer at the injection moment or from adjunct pipes or vessels carrying the injected radiotracer. Fig. 8 illustrates this situation with a radiotracer test, which was performed at a shell-tube type heat exchanger in a refinery. Three characteristic detectors employed were:

- D1 (injection detector) at the inlet of the tube feed,
- D2 at the outlet of the tube side,
- D3 (leak detector) at the outlet of the shell side.

The experimental response curves recorded by three radiation detectors are presented in the Fig. 8. Detector 1 shows a typical instantaneous injection of radiotracer, detector 2 presents the residence time distribution (RTD) of the radiotracer in the tube system, and the detector 3 (leak detector) indicates a suspect for leak peak just before the mainstream dispersed peak. The identification whether it is a leak peak or false peak was impossible in this test.

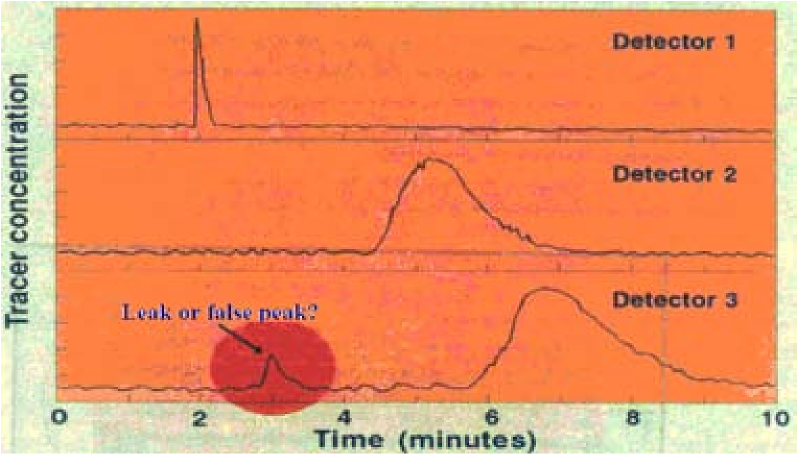


FIG. 8. Records of detectors

It is very important to shield and collimate the detectors in order to make it unresponsive to extraneous influences. Especially, the leak detector is heavily shielded from sides leaving a relatively small opening to the pipe. But sometimes this is not enough; false peaks still can be inducted from the surroundings and create confusion between true and false peaks. To avoid the confusion, a so called ‘brick detector’ is used in addition to the leak detector. Comparing records of the leak detector and brick detector facilitates the interpretation of radiotracer test and ensures very reliable identification of the real leak peak.

Fig. 9 shows a typical shell and tube type heat exchanger. Two identical radiation detectors are mounted at the suspected leak side near to each other, one is the ‘leak detector’ (shielded and open-collimated from leak side) and the other is ‘brick detector’ (shielded from all sides). The brick detector monitors background radiation and detect radiation influences from surroundings that are not leak related. If the leak exists, some part of the tracer will pass into the lower pressure stream and the leak detector will record a leak peak. If the brick detector records a smaller peak (in comparison to leak detector) or only the background, it confirms the radiotracer is passing in front of both detectors and the peak is originated from a leak. If sizes of the peaks recorded by the two detectors are nearly the same, this confirms that they are originated from unwanted influences outside the measuring point (from surroundings).

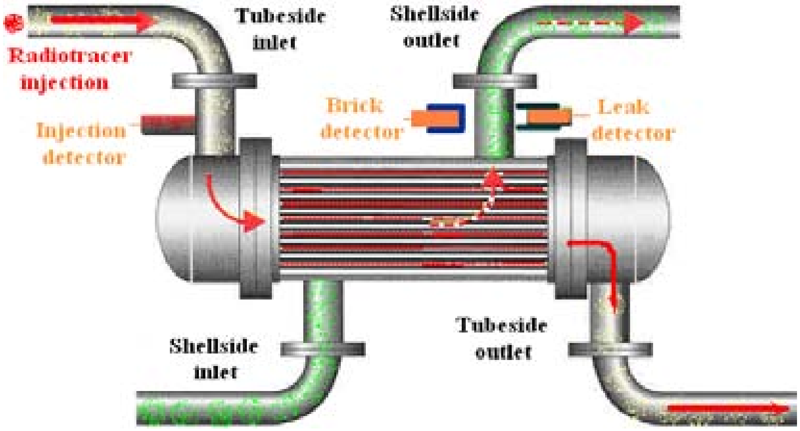


FIG. 9. *Radiotracer leak test in a heat exchanger employing a brick detector*

The data from leak and brick detectors are compared to ensure the presence of the leak peak (if any) by differentiating between false and true leaks (Fig. 10).

Fig. 10 illustrates the role of the brick detector in identifying the true peak (leak) from false one. The clear peak recorded by leak detector indicates a real leak, because the brick detector (located in the same place with leak detector) that monitored the background radiation and radiation influences from surroundings did not show any peak. In this case the leak flow rate was estimated nearly 0.5% of feed flow rate, as ratio of the peak areas of leak curve (right y-scale) to injection curve left y-scale).

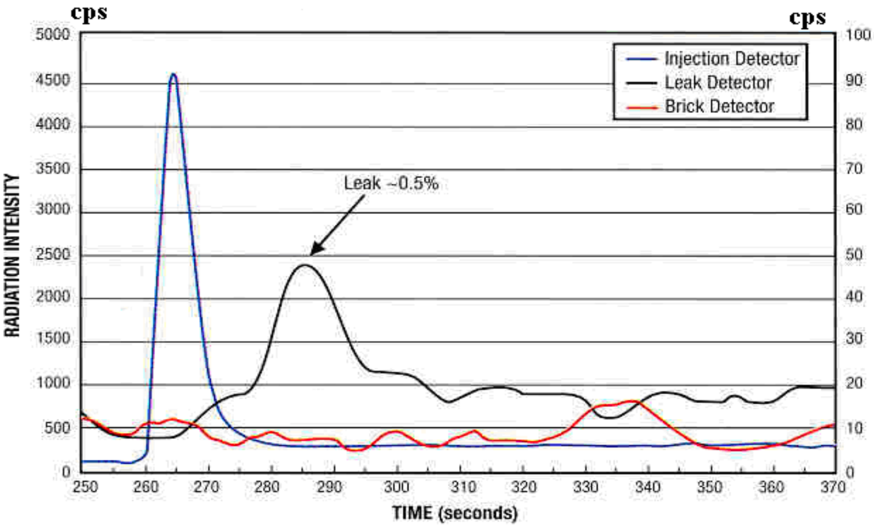


FIG. 10. *Results of radiotracer leak test comparing records of leak and brick detectors*

1.4. RADIOTRACER EXPERIMENTAL DESIGN AND EXECUTION

1.4.1. Selection of radiotracers

Selection of a suitable radiotracer is very important for the success of the leak detection test. Most of the radiotracers used in industrial tracer experiments are gamma emitting tracers. The energy of the gamma radiation should be sufficiently high to penetrate through the wall of the pipes or vessels. In addition, following parameters should be considered in the selection of a radiotracer:

- The physico-chemical behavior of the tracer should be the same as the fluid being traced,
- The half life of the radioisotope should be comparable to the duration of the experiment,

The behavior of tracer and labeling compounds under conditions of the processing line is very important. One must know, before injecting a tracer, how it will behave in the process. In certain circumstances, the injected tracer may undergo decomposition, phase changes, undesirable absorption and adsorption, chemical interaction with system constituents, etc., leading to incorrect results. For example, paradibromobenzene when used at high temperature in some heat exchangers may be decomposed and adsorbed on wall surfaces, and does not follow faithfully with the liquid phase.

^{82}Br is the most frequently used gamma emitter, in particular in countries that have nuclear reactor. ^{82}Br has a very convenient half-life ($T_{1/2} = 36$ h), that is long enough to use it for as long as one week after irradiation, but not so long as to cause radiation safety problems. The other advantages of ^{82}Br are:

- It is relatively easy to be produced in nuclear reactor in high specific activities,
- Various chemical compounds are available for gas, aqueous or organic phase tracing.

Inorganic bromides (NH_4Br, KBr), inorganic bromates ($NaBrO_3$, $KBrO_3C$) or organic bromine ($C_6H_4Br_2$) can be used as target materials for the production of ^{82}Br. The most convenient target in terms of radioactive purity is ammonium bromide (NH_4Br). However, its irradiation at high neutron fluxes causes evolution of gas due to the decomposition of bromide. It is obvious that low flux reactors with associated low temperatures at irradiated sites may be used to avoid this problem. Potassium bromide (KBr), which is less chemically active and more resilient to radiolysis, is quite satisfactory as well. The advantage of employing the KBr target is that it can be irradiated to significantly higher specific activities. To avoid labeling work with ^{82}Br, in particular preparing organic tracers, organic phase soluble ^{82}Br compounds are produced by direct irradiation of organic bromine compounds. Dibromobenzene has been chosen as a target, as it is comparatively resistant to radiolysis, and gives high specific activity. The commonly used radiotracer compounds for leak detection in heat exchangers are listed in Table 1. Table 2 presents the boiling points of the common radiotracer for tracing organic phases.

TABLE 1. RADIOTRACERS COMMONLY USED FOR LEAK DETECTION IN HEAT EXCHANGERS

Radioisotope	Half-life	Gamma Energy, MeV (Abundance %)	Chemical Form	Tracing Phase
Sodium 24	15 h	1.37 (100%); 2.75 (100%)	Sodium carbonate	Aqueous
Bromine 82	36 h	0.55 (70%) 1.32 (27%)	Ammonium bromide, Methylbromide, Dibromobenzene	Aqueous Gases Organic
Iodine 131	8.04 d	0.36 (80%) 0.64 (9%)	Potassium or sodium iodide, Iodobenzene, Hippuran	Aqueous Organic
Technetium 99m	6 h	0.14 (90%)	Pertechnetate	Aqueous
Indium 113m	100 min	0.392 (65%)	EDTA complex	Aqueous
Krypton 85	10.6 y	0.51(0.7%)	Krypton	Gases
Krypton 79	35 h	0.51 (15%)	Krypton	Gases
Xenon 133	5.27 d	0.081 (37%)	Xenon	Gases
Argon 41	110 min	1.29 (99%)	Argon	Gases

TABLE 2. COMMON RADIOTRACERS FOR ORGANIC PHASES

Radiotracer	Labelled compound and its chemical form	Boiling point (^oC)
^{82}Br	Paradibromobenzene, $C_6H_4{}^{82}Br_2$	219
^{82}Br	Bromododocane, $C_{12}H_{25}{}^{82}Br$	240
^{131}I	Ammonium iodide, $NH_4{}^{131}I$	220
^{82}Br	Ammonium bromide, $NH_4{}^{82}Br$	235
^{82}Br	Bromonaphthol, $^{82}BrC_{10}H_6OH$	130
^{131}I	Iodobenzene, $C_6H_5{}^{131}I$	188

Radionuclide generators are very important in radiotracer work in developing countries without nuclear reactors. There are three radionuclide generators useful for remote tracer leak detection mostly in liquid phase: $^{99}Mo/^{99m}Tc$, $^{113}Sn/^{113m}In$ and $^{137}Cs/^{137m}Ba$.

Commercially available generators are generally eluted using aqueous solution of NaCl or HCl, so that the eluates are compatible with the water or water-like flows. For producing an organic-compatible tracer, chemical treatment of the eluate from the generator is needed, in order that the radioisotope is incorporated into an organic complex.

$^{99}Mo/^{99m}Tc$ generator, which is largely used in nuclear medicine, is available in the market with reasonable price. However, it has rather limited applications in leak detection in heat exchangers due to low gamma energy of ^{99m}Tc.

$^{113}Sn/^{113m}In$ generator can be found from a few suppliers. The gamma-ray energy of 390 keV together with the useful half-life makes this generator suitable for leak detection in some water cooling type heat exchangers. Using the $^{113}Sn/^{113m}In$ generator to produce tracers that are compatible with organic flows is generally more difficult. $^{137}Cs/^{137m}Ba$ generator is normally used for leak detection in valves.

1.4.2. Estimation of the activity of radiotracer

After selecting a radiotracer suitable for a particular application, the estimation of the amount of activity of the radiotracer required to be used is another important step in designing a radiotracer experiment. The lower limit of activity of the radiotracer is estimated according to, accuracy desired, dilution between injection and detection points as well as the background radiation level. However, the upper limit is set by radiological safety considerations.

The background radiation level is required to be known prior to the tracer test for the estimation of the activity required. In general the maximum count rate coming from the radiotracer should be several times the background radiation level. The loss due to splitting of radiotracer stream through the leak should be taken into consideration while estimating the activity. For example, if the suspected leak is estimated 1% of the main flow, then 99% is lost and only 1% of the injected activity will be measured by the leak detector.

The activity of radiotracer required for a leak detection test for a given heat exchanger depends on following factors:

- Volume flow rates of tube side and shell side [Q_t and Q_s, $m^3 \cdot s^{-1}$]
- Volumes of tube side and shell side [V_t and V_s, m^3]

- Detection efficiency of the leak detector at the outlet pipe [k, counts·s^{-1}·Bq^{-1}·m^{-3}]
- Minimum leak rate need to be detected [$L_m = Q_l/Q_s$], Q_l is leak flow rate
- Mixing characteristics of tube side and shell side
- Accuracy (reliability) of measurement.

The detection efficiency k, is defined as the response (counts·s^{-1}) of the detector to the unit specific activity (Bq/m^3) of the fluid inside the outlet pipe at a given detection geometry. The detection efficiency can be measured experimentally by simulating the field experimental arrangement in the laboratory using a piece of pipe of the same diameter and wall thickness. The pipe is plugged at both ends and an injection port is installed on the pipe. The background count rate (R_b counts·s^{-1}) is measured at the beginning. The radiotracer with known specific activity (a Bq·m^{-3}) is injected and the count rate (R_t counts·s^{-1}) is measured. Then, the detection efficiency is:

$$k = (R_t - R_b)/a \text{ [counts·s}^{-1}\text{·Bq}^{-1}\text{·m}^{3}\text{]}$$

The detector efficiency can be calculated theoretically using software based on Monte Carlo method. The ECRIN2 software can be used for this purpose. The software was developed by CEA in France and has been using in many radiotracer laboratories.

Fig. 11 shows the pipe detector configuration used in the ECRIN2 software. It is assumed that the pipe is filled up with the fluid containing a certain concentration of a radiotracer, and a collimated detector is located close to the pipe.

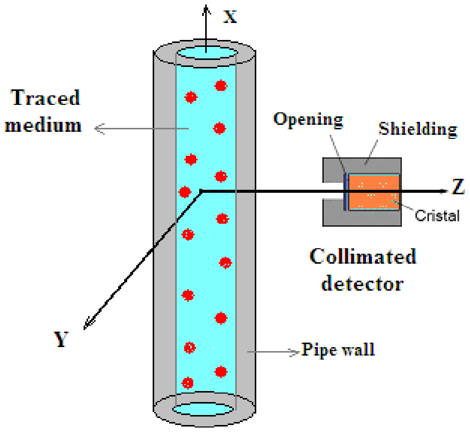


FIG. 11. Pipe-detector configuration used in ECRIN2 software

As an example of using the software, it is assumed that:

- The fluid is water,
- The pipe is a stainless steel pipe with 30 cm inner diameter and 1 cm wall thickness,
- The detector is 2”×2” NaI with a collimator having 2.5 cm diameter opening,
- The distance between detector and pipe wall is 2 cm,
- The radiotracer is an ^{82}Br compound.

Using these parameters, the detection efficiency calculated by the software is $k = 8.7 \times 10^{-5}$ cps/(Bq/m^3).

The leak in a shell and tube type heat exchanger can be presented schematically as shown in Fig. 12. For the calculation of the activity for leak test, it needs to know the volume from the inlet of tube side (high pressure) to the leak point, and the volume from the leak point to the outlet of shell side (low pressure) as well as the mixing characteristics of the flows inside of the two volumes.

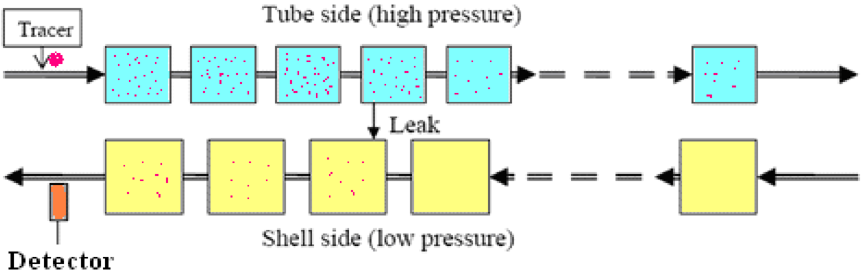


FIG. 12. Compartment model of a shell and tube type heat exchanger

As it is practically not possible to obtain these parameters, it is necessary to simplify the flows to make the calculation of the radiotracer activity possible. Two assumptions for the simplification are:

- No mixing (plug flow) in tube side and perfect mixing in shell side flow. This is reasonable assumption because the tube side is very narrow in comparison to shell side.
- The leak point is located at the inlet of shell side flow. This is the extreme case when the radiotracer is more diluted in the whole shell side volume.

Assuming an activity A Bq of radiotracer is injected at the inlet of the tube side, and the leak rate is L_m (fraction of the main flow). This situation is equivalent with injection of the activity $L_m \cdot A$ Bq to the inlet of the shell side. Fig. 13 illustrates this case.

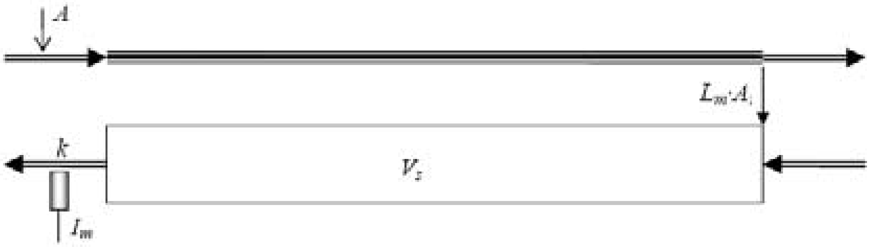


FIG. 13. Simplified compartment model of a heat exchange with a leakage

As the shell side is assumed as a perfect mixer, the leaked radiotracer will be immediately mixed in the whole volume of the shell side. Therefore, the specific activity just after the leaking will be $L_m \cdot A / V_s$ Bq·m^{-3}, and after will decrease exponentially with time. Then, the highest count rate recorded by the leak detector is:

$$I_m = k \cdot L_m \cdot A / V_s \text{ [counts·s}^{-1}]$$

With a counting time of Δt, the maximum count (C_m) is:

$$C_m = I_m \cdot \Delta t = k \cdot L_m \cdot A \cdot \Delta t / V_s$$

The minimum detectable radiotracer signal is accepted to be three times higher than standard deviation of the average background level (<1% error):

$$C_m \geq 3\sigma_b$$

Since background count: $C_b = R_b \cdot \Delta t$ and $\sigma_b = (R_b \cdot \Delta t)^{1/2}$, the minimum activity is:

$$A_m = 3\ (R_b / \Delta t)^{1/2} \cdot V_s / (k \cdot L_m) \text{ [Bq]}$$

Basically, the counting time (Δt) is a matter of choice. Normally, in a RTD test the data collection is continued until nearly 3 folds of the mean residence time (*MRT*), and around 100 data points are sufficient for an experimental curve. It means that nearly 36 data points for one *MRT* are sufficient. Thus, the counting time can be estimated as:

$$\Delta t = MRT/36 = V_s/(36 \cdot Q_s)$$

Then, the minimum activity required for detection of a leak test in a shell and tube side type heat exchanger is:

$$A_m = 18\,(R_b \cdot \mathrm{V}_s \cdot \mathrm{Q}_s)^{1/2}/(k \cdot L_m)\ [\mathrm{Bq}]$$

The volume (V_s) and flow rate (Q_s) of shell side are known from the exchanger design, while the minimum leak rate (L_m) can be provided by engineers as expected leak estimation. The background count rate (R_b) is measured at the site, while the detection efficiency (k) is obtained in laboratory or calculated by software simulation as described above. Knowing these parameters, the minimum activity required for detecting a leak can be easily calculated using the above equation.

The above equation gives an estimation of the minimal detectable activity required for detecting a leak of a particular size.

In practice the recommended activity is higher for better accuracy, especially in calculation of the flow rate of the leak. Nevertheless, a validation of this approach is recommended before the real radiotracer test in a plant. As seen by the above equation, following efforts are important to detect a given leak rate using smaller amount of radioactivity:

- Reduction of the background count rate (R_b) using a proper shielding and collimator,
- Increase of detection efficiency (k) by employing large size and high efficiency radiation detector, and the installation of the detector as close as possible to the surface of the pipe,
- Decrease the shell side flow rate (Q_s) when it is possible.

Example: The estimation of the activity needed for detecting leak in a shell and tube type heat exchanger, which has the following parameters:

Shell volume V_s=10 m^3, Q_s = 0.1 m^3/s, Leak size is supposed to be 1% of the main flow rate. Detection efficiency (calculated using ECRIN2 software imitating the real condition) $k = 8.7 \times 10^{-5}$ cps/(Bq/m^3) (^{82}Br is used as radiotracer). The background count rate R_b =100 cps.

In this case: $A_m = 18 \times (100 \times 10 \times 0.1)^{1/2}/(8.7 \times 10^{-5} \times 0.01) = (180/8.7) \times 10^7$ Bq = 5. 6 mCi. In fact, this is the minimum activity of the radiotracer. In practice, an activity of several timer of this value is applied for obtaining higher accuracy.

1.4.3. Injection of radiotracer

Heat exchangers normally operate in relatively high pressures, thus injecting radiotracer it is not so easy. If possible injection has to be carried out in the low pressure side of the pumping systems. The injection equipment depends on the physical nature of the stream such as, pressure, temperature and toxicity of the fluid. For the liquid injection, a hand -operating hydraulic pump can be used; for the gas stream a radioactive gas is injected with an inert backing gas, such as nitrogen, from a cylinder of pressure exceeding that in the line. For high-pressure liquid and gas systems, special injection systems are needed. Figs. 14 and 15 show typical injectors for gas and liquid radiotracer injection into heat exchangers under low and medium pressure.

1.4.4. Radiation detection

A. Radiation detectors

The most commonly used for on-line leak detection using radiotracers is NaI(Tl) scintillation detector. It is very sensitive sensor for gamma radiation. Fig. 16 shows the location of NaI detection probes at the outlet of heat exchangers. It is important that detection probes are well shielded. Lead is used mostly as shield material. Lead shielding thickness can vary from 2-3 cm for ^{99m}Tc and ^{133}Xe (low energy gamma), to 3-4 cm for ^{131}I and ^{113m}In (medium energy gamma) till 5-6 cm for ^{82}Br and ^{41}Ar (high energy gamma).

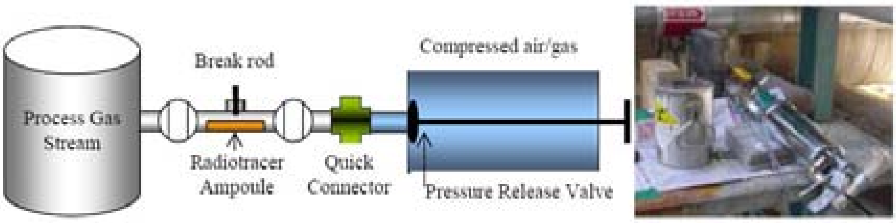


FIG. 14. An example of gaseous radiotracer injector

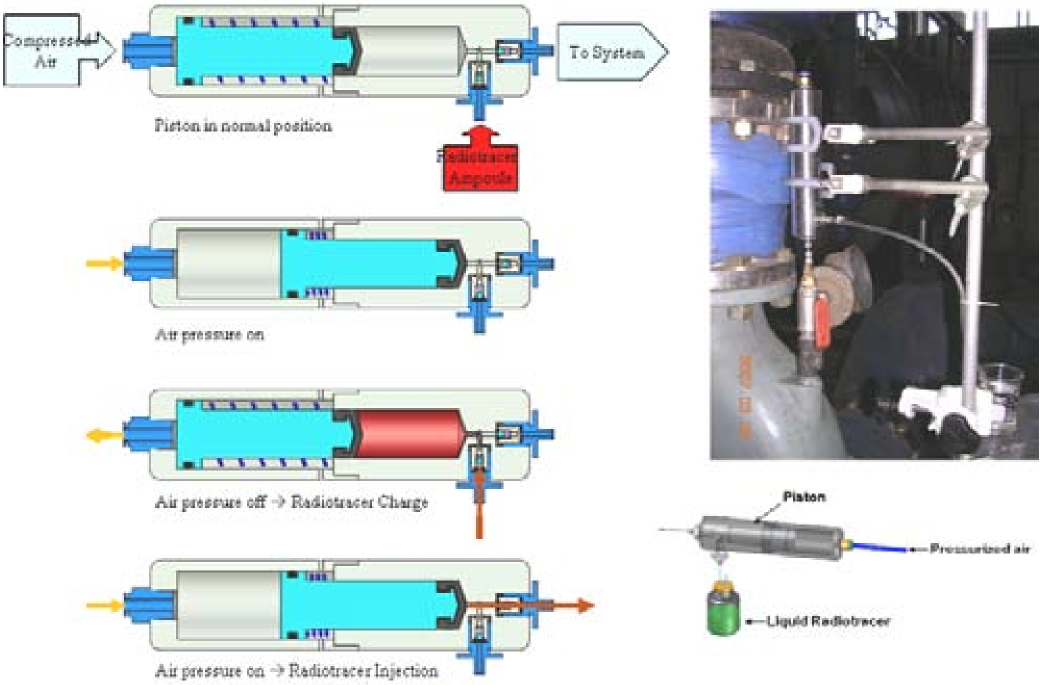


FIG. 15. Remote control liquid radiotracer injector

FIG. 16. NaI probes with lead collimator mounted at the outlet of a heat exchangers

For any detector, there are two important parameters that affect the overall efficiency of the system, geometric and intrinsic efficiencies. By multiplying these values, one can calculate the total efficiency.

In radiation measurements, the geometric efficiency is the ratio of the number of radiation photons that hit the detector divided by the total number of radiation photons emitted from the point source in all directions. Geometric efficiency is the solid angle subtended by the detector's active area divided by the area of a sphere whose radius is the distance from the radiation source to the detector. For example, if 10000 gamma rays are emitted from a source and 100 hit the detector then the geometric efficiency ε_g is 1%. The geometric efficiency follows a $1/r^2$ relationship and it decreases as distance increases.

The intrinsic efficiency is the ratio of counts detected to the number of photons or particles incident on the detector and is a measure of how many photons or particles result in a gross count. The intrinsic efficiency of NaI detectors are typically around 10 to 50%. The intrinsic efficiency of a 1"×1" NaI(Tl) crystal size detector for 500 keV and 1 MeV energy photon is about 26% and 10% respectively. For NaI (Tl) 2"×2" detector, which are commonly used in radiotracer experiments, its intrinsic efficiency is at least four times higher than for 1"×1".

Several factors can affect the calculation of the leak size and corrections should be made for the following, if necessary:

- *Different detector efficiencies*: it is not always possible to have all the detectors with the same efficiency and each detector must be calibrated prior to the experiment so that the areas under the peak can be corrected appropriately.
- *Detector geometry*: if the lines carrying the fluid under investigation are of different size and wall thickness, then the volume of material producing the response at the detector may be different or reduced by the extra metal of the wall. An appropriate correction must be made.
- *Difference in fluid flow rate*: the detector response is dependent on the time the radioactive tracer is passing in front of it and is consequently dependent on the flow velocity. The count rate is inversely proportional to the velocity of the fluid passing in front of the detector.

B. Data acquisition system

Radiotracer once injected in the system is monitored on-line continuously. Two or three radiation detectors are used for the leak detection in a heat exchanger. More detectors are employed for leak inspection of a bank of heat exchangers. The data acquisition system, which collects signals from the radiation detectors, is the basic equipment for on-line radiotracer leak inspection in heat exchangers. It ensures collection, treatment and visualization of the data in real time. Fig. 17 shows some commercial and home made data acquisition systems.

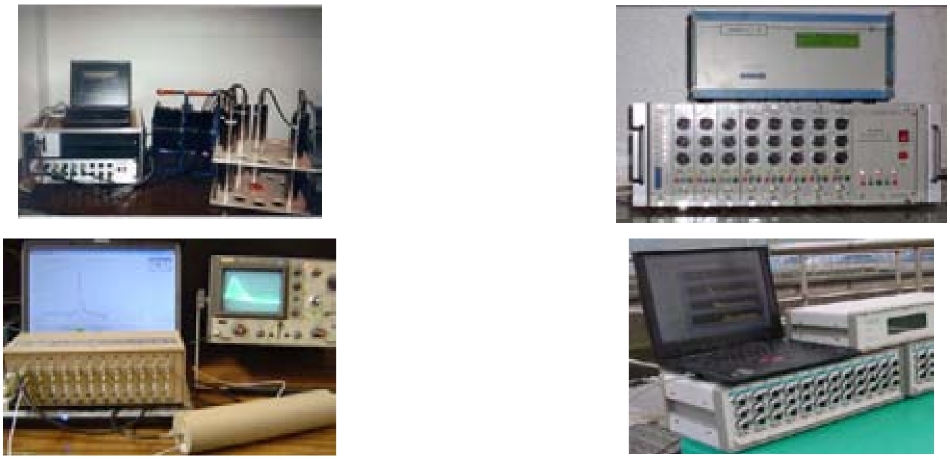


FIG. 17. Data acquisition systems for on-line radiotracer test

1.5. CASE STUDIES: LEAK DETECTION IN HEAT EXCHANGERS USING RADIOTRACERS

As mentioned above the heat exchangers are the most important hermetically closed processing vessels in petrochemical and chemical plants. Leak inspection in heat exchangers is crucial for the performance of processing lines and the quality of final products. Thus most of the described case studies are dealing with applications of radiotracers for leak detection in heat exchangers.

1.5.1. Leak detection in a heat exchanger

A heat exchanger in a refinery experienced a leak suspecting. The radiotracer method was employed to search for potential leak. Fig. 18 shows the experimental setup of a radiotracer test.

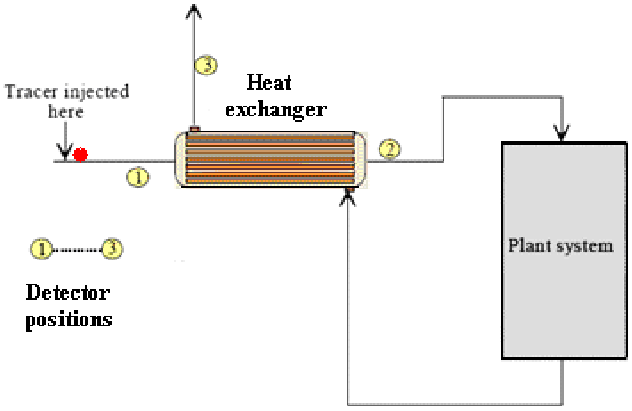


FIG. 18. Experimental setup for radiotracer leak inspection in a heat exchanger in a refinery

Three radiation detectors employed were:

- D1 (injection detector) at the inlet of the tube side feed,
- D2 at the outlet of the tube side,
- D3 (leak detector) at the outlet of the shell side.

The experimental response curves recorded by three radiation detectors are presented in the Fig.19 (D1-brown, D2- blue and D3-red).

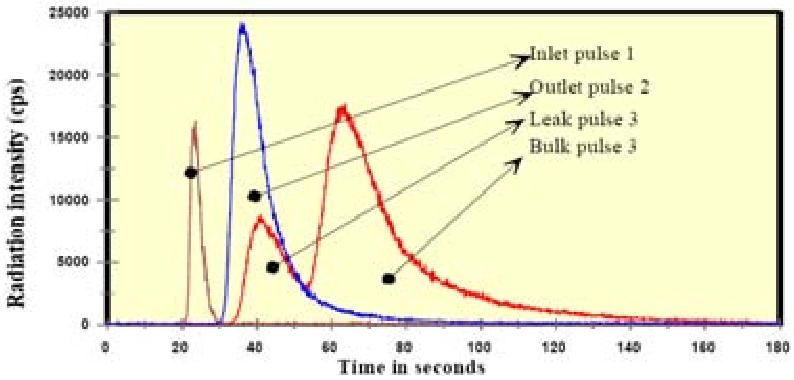
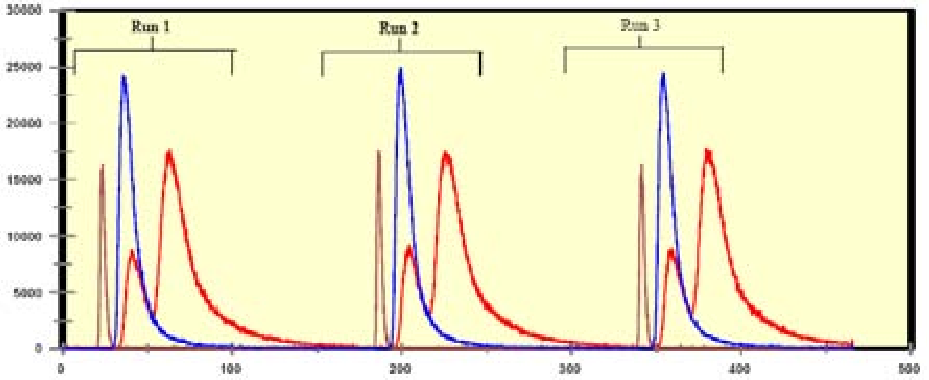


FIG. 19. Experimental response curves recorded by three radiation detectors

The experimental response curve of D3 clearly indicates the existence of two peaks. The first peak of the curve attributed to the leak has a relative area of nearly 25%. This means that the estimation of the leak rate was nearly 25% of the inlet flow, which is considered a large leak.

The radiotracer test was repeated three times for reliability of results. Fig. 20 shows the results of the three runs. As can be seen the repeatability is very good.



Note: The experimental response curves are measured with three different radiation detection probes (NaI), this is the reason of apparent confusion in their amplitudes. Normally, the injection detectors gives the highest peak as tracer is more concentrate in short interval injection. But, as the Fig.20 shows, this is not granted, and the case above confirmed that the peak amplitudes can be without any logic order; they follow experimental orders, that means the geometrical efficiency of injection detector(and its size) was apparently smaller than those of detectors 2 and 3.

FIG. 20. Three runs of radiotracer test for leak inspection

1.5.2. Leak detection in a crude oil pre-heater

a. Problem description

The crude oil is pre-heated using the high temperature refined product. The refined product, at a temperature of 470^{0}C, enters the top of heat exchanger, flows through shell-side and leaves the heat exchanger bottom at a temperature of 115^{0}C. The crude oil, at a temperature of 68^{0}C, enters the bottom of heat exchanger, flows through tube side and leaves the heat exchanger top at a temperature of 420^{0}C. The quality control department found contamination in refined product, which led to suspicion of leakage in heat exchanger. As there was a difference of opinion between plant engineers and quality control department, the plant engineers decided to perform a radiotracer leak test before taking any further action.

The unit under investigation is shell and tube type heat exchanger. It is a vertical heat exchanger with 25 m height, 1.194 m internal diameter and 48 mm wall thickness. It is a single pass heat exchanger with a fluid capacity of 25.5 m^3 (shell = 19.5 m^3, tube = 6 m^3).

b. Radiotracer test

The tracer group conducted radiotracer test using ^{82}Br in the form of dibromobenzene. Although, dibromobenzene is not an ideal tracer in given high temperature conditions, it had to be used because there was no other more suitable tracer available. A brief feasibility of experimental set up was carried out and necessary arrangements were made in cooperation with plant engineers before test conduction. Radiotracer injection was made through a by-pass arrangement.

Radiotracer ^{82}Br in the form of dibromobenzene with an activity of 130 mCi was injected at 14: 32 hours. The relative positions of various detectors are shown in Fig. 21.

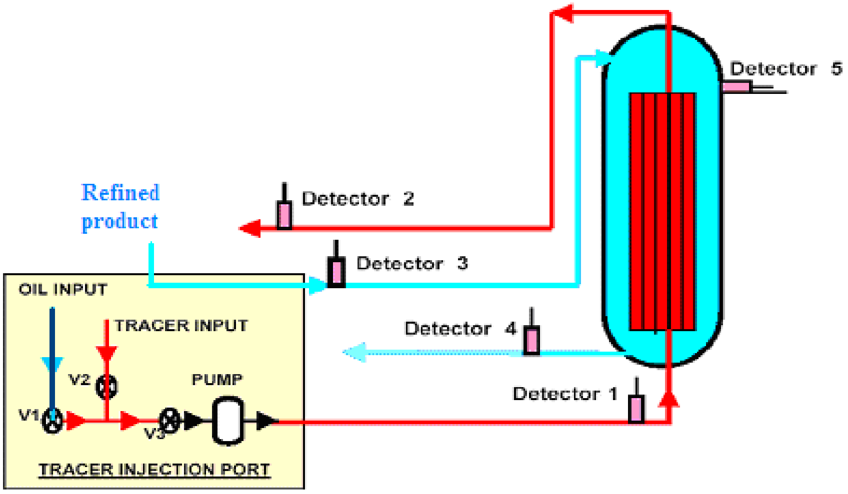


FIG. 21. Schematics of experimental set-up showing tracer injection port and position of various detectors

- Detector 1: At the tube side inlet, just before the tube inlet pipe enters the exchanger
- Detector 2: At the tube side outlet, away from the exchanger
- Detector 3: At the shell side inlet, away from the exchanger
- Detector 4 (leak detector): At the shell side outlet, just after the shell outlet pipe goes away from the exchanger
- Detector 5: At the shell top, against the shell wall at the level of tube bundle (for leak double check and comparison with D4).

Data of detector 4 was recorded every 5 seconds while data for other detectors was recorded for every 10 seconds. Records of the detectors 1, 2, 3 and 5 are not strictly related with leak detection, but their data help to identify the real leak peak form any false peak by comparative time analysis of their signals.

Valves V1 and V3 of the injection port (Fig. 21) were closed. The flange at the top of valve V2 was removed and the valve V2 was opened. The oil level in the horizontal pipe between valve V1 and V3 was maintained such that 3/4 of pipe diameter was filled with oil. Specially designed device to crush the silica glass ampoule was inserted vertically in the pipe through valve V2.

Two glass ampoules containing radiotracer ^{82}Br (in the form of dibromobenzene powder) were inserted in the crushing device. Ampoules were crushed and tracer was mixed in oil in the pipe. The valve V2 was closed and valves V3 and V1 were opened. The radiotracer was injected into the system by starting the pump. The injection was made at 14:32 hours in the tube inlet pipe through injection port. The data was recorded from 14:23 to 16:00 hours (i.e. for 1 hour, 37 minutes).

c. Results and discussion

The data obtained from detector 1,2,4 and 5 are plotted in Fig. 22. The experimental curves obtained by detector 2 (at the tube outlet) and detector 5 (at the shell top) represent the residence time distributions (RTD) of the fluid (crude oil) in the tube system. Both curves registered by D2 and D5 detectors do not indicate any thing about the existence of leaks.

The records of detector 1, monitoring the injection of tracer into the tub inlet, and detector 4 (monitoring leakage, if any, in shell outlet) have to be analyzed carefully (Fig. 23).

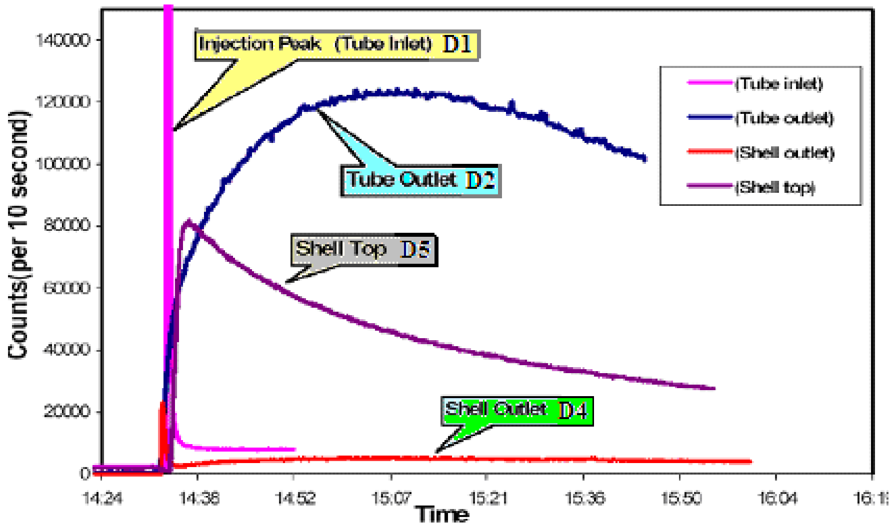


FIG. 22. Response of detectors 1, 2, 4 and 5

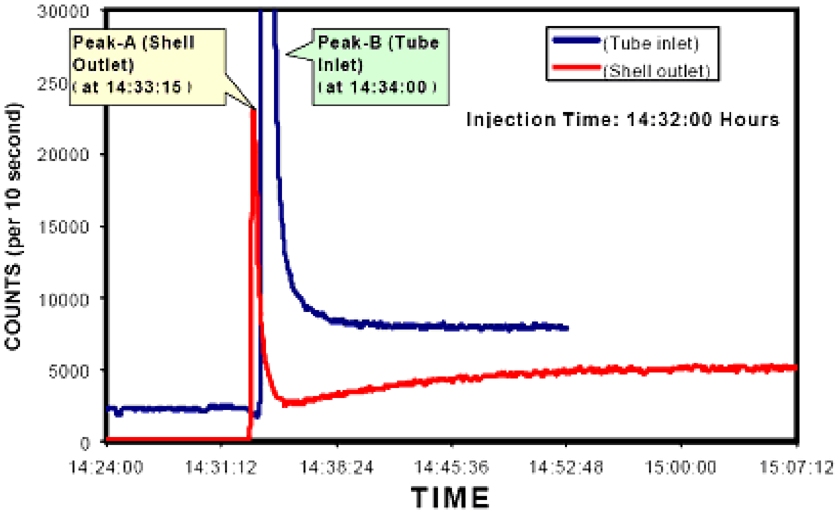


FIG. 23. Responses of detector 1(Injection) and detector 4 (Leak detector)

Radiotracer injection was made away from detector 1 at 14:32:00 hours (as very sharp Dirac pulse). The tracer plume reached detector 1 at 14:33:50 hours and passed detector 1 at 14:34:50 with duration of 60 seconds.

The maximum of injection peak was recorded at 14:34:00 hours (peak B, Fig. 23). A peak was also recorded by detector 4 placed at shell outlet. The tracer peak arrived at detector 4 at 14:33:05 hours and passed away at 14:34:05 hours with 60-second duration. The maximum of the peak was recorded at 14:33:15 hours (peak A, Fig. 23).

The detector 1 and detector 4 recorded the peak for the same duration i.e., for 60 seconds and the peak maxima reached within 10 seconds of the arrival of tracer peaks on both detectors. However, detector 4 recorded the tracer peak 45 seconds earlier than detector 1.

That means detector 4 recorded tracer peak before the tracer entered the exchanger. This indicates that the peak recorded by detector 4 at 14:33:05 hours was not related to any leakage in the exchanger but this peak is due the fact that detector 4 has seen activity of injection plume while tracer passed through the tube inlet pipe in the near vicinity. This is a typical false peak that could have been avoided with a heavier shielding of the detection probe D4. Using high gamma energy ^{82}Br as radiotracer the lead collimator should have a thickness of more than 5 cm around the detector, while using low gamma energy ^{131}I collimator walls around the detector have to be around 2-3 cm thick.

d. Conclusion

The radiotracer test reveals that there is no leakage in the exchanger.

1.5.3. Radiotracer leak test of a heat exchanger tower

a. Problem

The heat exchanger of a tower (Fig. 24), a tube and shell type heat exchanger, was suspected for leaks from tube side into shell side as indicate by contaminants found from laboratory analysis. To identify the problem, radiotracer technique has been applied by injecting a gamma radiotracer into the tube side inlet and monitoring gamma radiation at the tube side and shell side outlets.

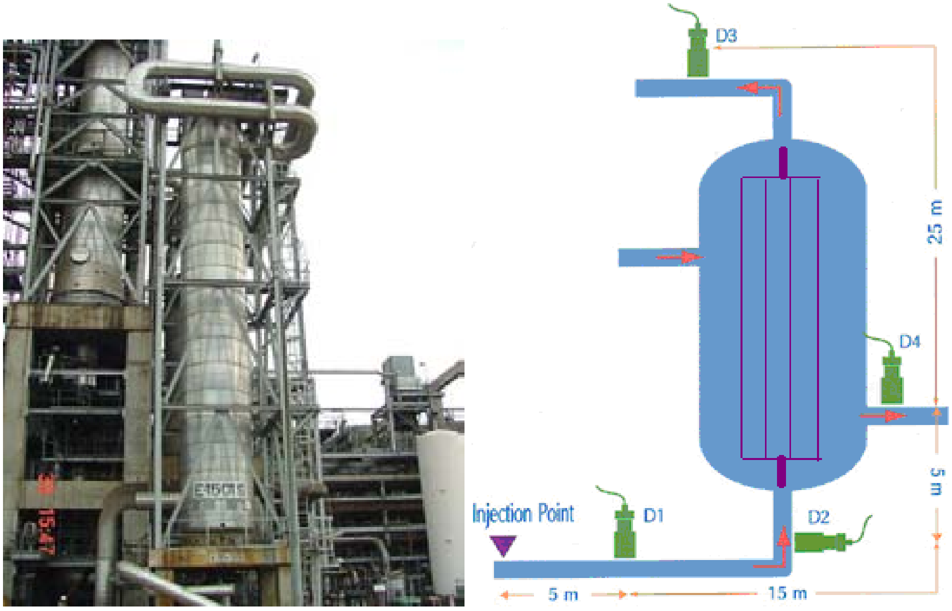


FIG. 24. A tower tested for leaks and experimental setup

b. Radiotracer test

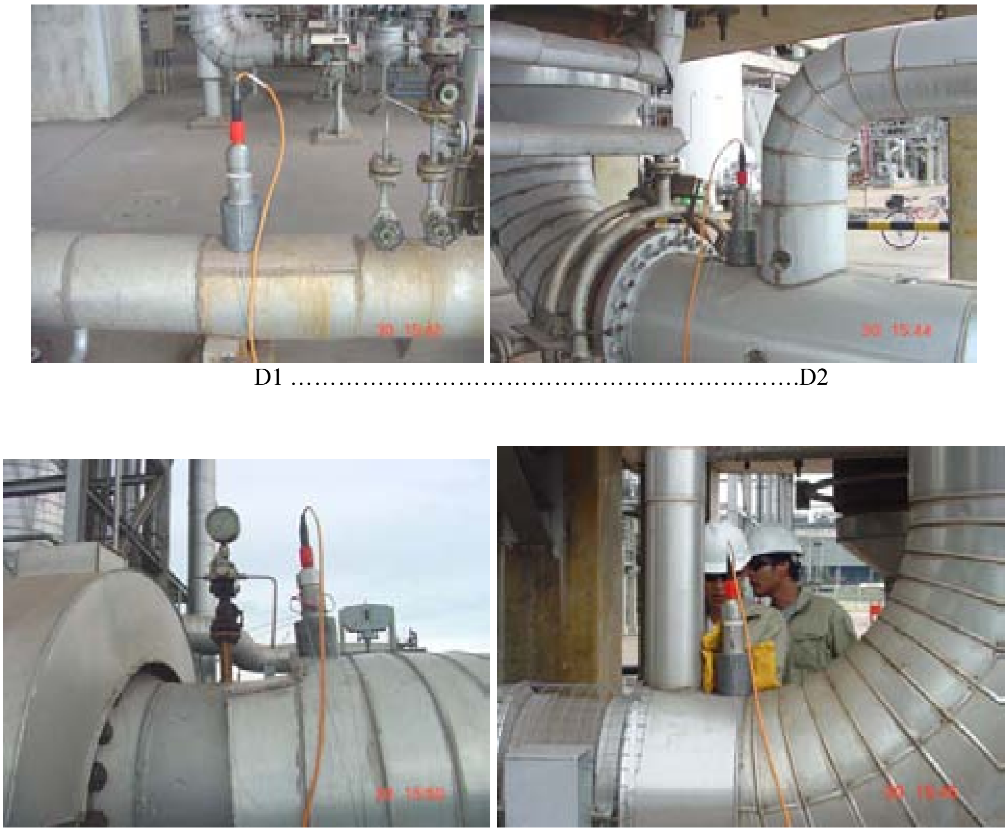
The experimental setup is shown in Fig. 24; four collimated detectors were installed at inlets and outlets of tub and shell sides. Radiotracer (dibromobenzene labeled with ^{82}Br in liquid form) was injected into the process line through tube side inlet.

Detectors were located as follows:

- Detector 1 about 5 meter after the injection point (before entry of naphtha feed line)
- Detector 2 at tube side inlet (naphtha inlet line)
- Detector 3 at tube side outlet (naphtha outlet line)
- Detector 4 (leak detector) at shell side outlet (reformate outlet line).

Fig. 25 shows the photos of the four detectors installed for the radiotracer experimental work.

Detectors were connected to data acquisition system with 0.05 s measuring time (Fig. 26). The activity of injected radiotracer was approximately 15 mCi. The injection was performed at 15 bars into the process stream of 8 bars. Transmitted gamma ray intensities at each position were recorded.



D1 ……………………………………………………….D2

D3……………………………………………D4

FIG. 25. Installed radiation detectors

FIG. 26. Injection facility(left) and data acquisition system (right)

c. Results

Fig. 27 shows the experimental curves obtained from the four detectors during the radiotracer test. The record obtained from ‘leak detector’ D4 is analyzed separately in a larger y-scale for better interpretation of the data (Fig.28).

Table 2 presents the results of the radiotracer test.

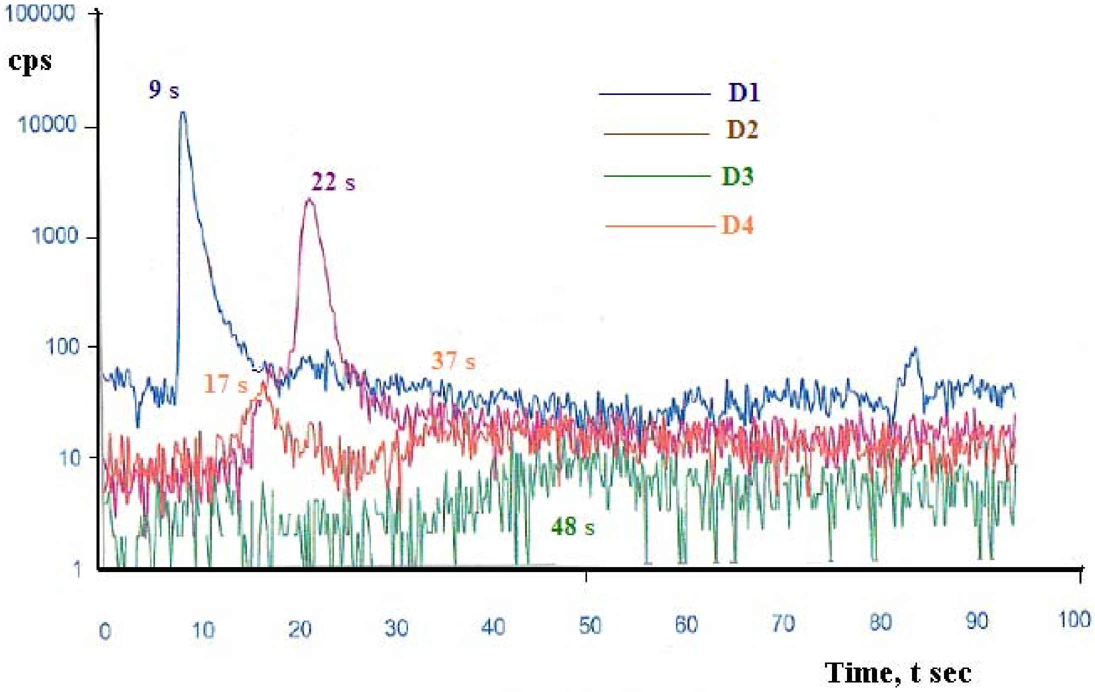


FIG. 27. Radioactive detection curves

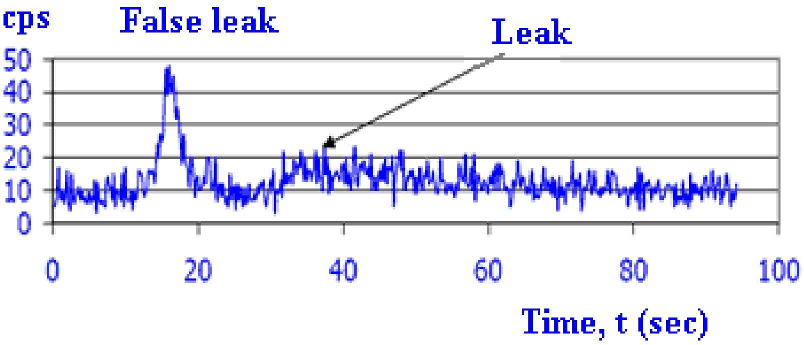


FIG. 28. Experimental curve of 'leak detector' D4

TABLE 2. ARRIVAL TIMES AFTER INJECTION (SECONDS):

Detector	Peak location (s)	Peak center (s)	Peak area (counts)
D1	7- 17	9	
D2	17-27	22	26000
D3	42-60	48	
D4	11- 25 & 30-60	17 &37	1300 (for second peak)

d. Discussion

Experimental curve obtained by D4 (leak detector) shows two peaks (Fig. 28); the first (higher) peak at 17 s and the second (smaller) peak at 37 s after injection, respectively. The first peak at 17 s after injection at the shell outlet is from pickup of the injection of radiotracer in the tube side, because it arrives before the radiotracer enters the tube side (D2 peak at tube inlet is recorded at 22 s).

Thus, the first peak is interference from radiotracer injection because apparently the detector was not well and enough shielded. The second peak represents the leak. The ratio of peak areas D4/D2 (after correction for the background) gives the approximate size of the leak e.g. 5% of the inlet fluid is leaking:

Ratio of sum peaks D4/D2 = 1300/26000 = 5 %

To confirm the result of on-line radiotracer test, reformate samples were taken from the shell side outlet to analyze their radioactivity in the laboratory. Trace of ^{82}Br was detected that confirmed the on-line radiotracer test conclusion.

The radiotracer test finding was confirmed later also by visual inspection after heat exchanger shut down, where the leak point was small but quite visible (Fig. 29).

FIG. 29. Visual inspection after shut-down shows leak point

1.5.4. Radiotracer leak test on a heat exchanger at an ammonia plant

a. Problem

Plant engineers suspected a leak on a heat exchanger serving a converter at an ammonia plant (Fig. 30) because the pressure drop across the line was decreased significantly since start-up after a maintenance shutdown. Radiotracer leak test was carried out in the heat exchanger to identify the leak problem.

FIG. 30. Ammonia plant, left, and injection of gas radiotracer ^{41}Ar, right

b. Radiotracer test

100 mCi ^{41}Ar radiotracer gas was injected as a pulse into the feed line to the heat exchanger. Progress of the radiotracer was followed by means of NaI (Tl) scintillation detectors placed at appropriate positions. Fig. 31 shows radiotracer injection and detection positions.

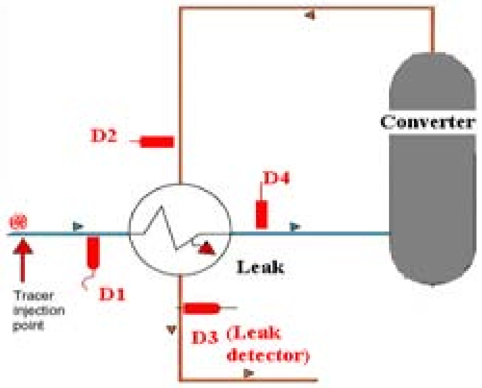


FIG. 31. Experimental setup: Injection and detection positions

Four radiation detectors were placed as follows:

- Detector 1: At the tube inlet, just before the tube inlet pipe enters the exchanger
- Detector 2: At the shell inlet from converter
- Detector 3 (leak detector): At the shell outlet, just the pipe goes away from the exchanger
- Detector 4: At the tube outlet, away from the exchanger (indication of this detector is not significant for leak detection, so the corresponding experimental curve is not presented in Fig.32).

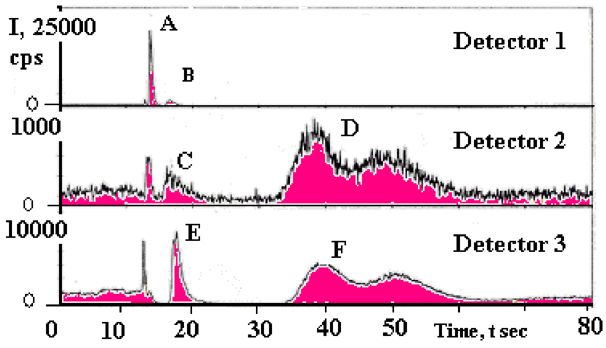


FIG. 32. Experimental response curves of radiation detectors

The table below summarizes the mean residence times of radiotracer recorded from all detectors.

Pulse	Mean residence time (s)
A	0
B	3.1
C	3.9
D	30.4
E	4.1
F	31.8

c. Results and discussion

The recorded pulse A in Fig. 32 indicates the injection moment (t = 0). Radiation peaks recorded by other two detectors at that moment (t = 0) were due to external exposure to radiotracer when ^{41}Ar moved from the well-shielded injection equipment to the line inlet, thus these are 'false' peaks and should be ignored. The outlet pipe of the heat exchanger feeding the converter was fairly close to the injection point where detector 1 was placed, so radiotracer moving along this line on its way to the converter was 'seen' for a while by detector 1 providing the false peak B, which should be ignored as well.

Detector 2 was placed at the shell inlet, which by construction was very near to the feeding pipe to the converter where the radiotracer enters. The recorded peak C is considered as false similar to the peak B. Signal D recorded by detector 2 after the converter provides the residence time distribution (RTD) of the radiotracer inside the converter. The RTD form provides information about the process development inside the converter. It could be interpreted as two parallel flow model or axial dispersion model with back mixing, but is not related with leak detection test.

Detector 3 placed at the shell outlet records leaks if any, so this curve should be analyzed very carefully comparing with detectors 1 and 2. Signal F is similar to the signal D of detector 2, which is normal because in this part of the line tracer is moving according to the model of the converter. Detector 3 recorded peak E much before bulk of the tracer (pulse F) passed in front of it. This peak E indicates a potential leak in the exchanger (i.e. feed short-circuiting to outlet).

Let analyze the reasons for this quite important peak (much higher than peaks B and C occurred at nearly the same moment). One possibility for this peak is being caused by the exposure to radiotracer moving from heat exchanger to the converter (like other two detectors 1and2 that have indicated false peaks B and C). Detector 3 was approximately at the same distance from feeding pipe as other detectors 1 and 2, so the peak E should have been much smaller if was a false peak. Peak E is obviously much higher than false peaks B and C, thus it indicates the presence of the leak as well. In fact the peak E overlaps the leak peak and false peak together.

Since the possibility that radiotracer radiation from the converter feed line affected the response of detector 3 could not be ruled out, the accurate leak size was difficult to be determinate in this test. Moreover a brick detector (that could have estimated the false peak) was not used in this case. The simple approach used to solve this problem was to consider the false peak (part of peak E) similar with false peak B recorded by detector 1 (according to the experimental set up the detector 1 and 3 had the same distance from the feeding line).

The area under pulse E was corrected for false peak B and the size of the leak was estimated from the ratio of the corrected area under pulse E to the total area under E and F. The leak size of 14 % was obtained (17 % is the estimation without correction of the false peak). The leak was confirmed by visual inspection of the heat exchanger performed after the shutdown.

d. Conclusion

The results of radiotracer test on heat exchanger showed conclusively that nearly 14% of the feed gas entering exchanger short-circuited directly via a leak to its outlet. Despite its large size. the identification of the leak was very difficult due to the overlap of false peak interfering from external sources. The comparative interpretation of all detector records helped in this case. Heavier shielding of detectors, better positioning of detectors (as far as possible from other processing lines), and repetition of the radiotracer test placing another brick detector near the leak detector is suggested in similar leak test situations to obtain more accurate and reliable results as well as to identify relatively small leaks.

Radiotracer leak detection in heat exchanger of an Alkylation's production unit

The objective of the radiotracer test was to inspect the heat exchanger of the Alkylation's production unit for possible leaks. A potential leak in the heat exchanger will result in a portion of the feed gas short-circuiting directly to the effluent line, and thus adversely affecting the performance of the process. Fig. 33 shows the heat exchanger and location of one of the detection probes.

FIG. 33. The shell and tube type heat type exchanger and shielded detector

The schematic layout of the Alkylation's process is presented in Fig.34 with the position of radiation detectors and the injection point. ^{41}Ar gas radiotracer was used with activity of 100 mCi. Six detectors were installed in the alkylation's production line, including heat exchanger and treaters A and B. Detectors D1, D2 and D5, D6 are significant for leak detection in heat exchanger, the others are for investigating any potential leak in the block valve. Detector D1 was installed at the tube inlet so it indicates the injection time, which is reference for other records and helps in interpretation of results. Detector D2 measures radiotracer going through tube outlet. Detectors D5 and D6 located at the shell outlet (effluent line) record leak signals; there were installed two detectors in the same position for double check.

Detector responses are shown in Fig. 35.

Detector D1 (black line) marks the time when the radioactive gas tracer enters the tube side of the heat exchanger system. Other experimental RTD curves are regularly shifted without showing any sign of any 'leak peak'. Under normal conditions, the traced fluid flow after crossing tube side of heat exchanger goes to the treater B, from where it entries treater A and from treater A is moving towards the shell side of heat exchanger. If there is a leak in the heat exchanger a portion of the injected activity should have short-circuited directly into the shell side and with effluent flow out of exchanger from shell output where detectors D5 and D6 were installed. Thus, if leak was present the detectors D5 and D6 should have indicated a signal before tracer signal comes to detector D2 (D5 and D6 are located nearer than D2 from heat exchanger). Apparently, this was not the case. Fig. 36 shows the responses of all detectors in a larger y-scale.

In fact, in Fig. 36 it appears that detectors D5 and D6 have recorded a small signal in nearly the same time the tracer was moving from D3 to D4 (passing in front of the detector D4). This small peak apparently was caused by radiotracer leaking through the block valve situated at the position of detector D3, which normally was kept close. The valve in this case was suspected leaking (not well closed). In order to clarify this suspecting, comparison of the experimental RTD curves provided by all detectors was performed in a larger y- scale (0-5000 cps).

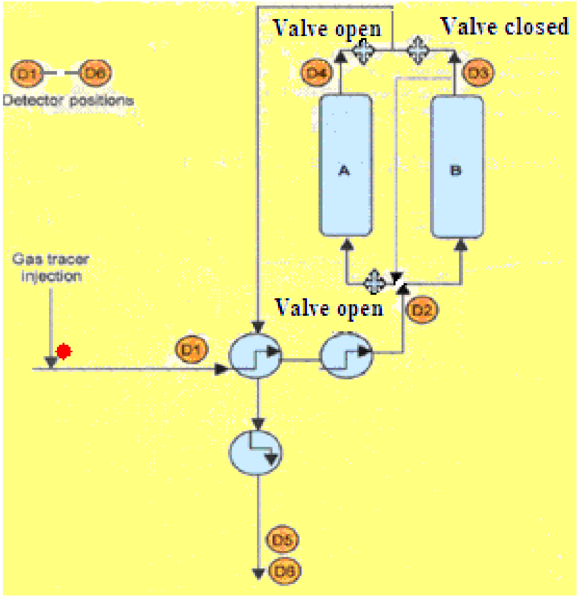


FIG. 34. Schematic layout of Alkylation's process

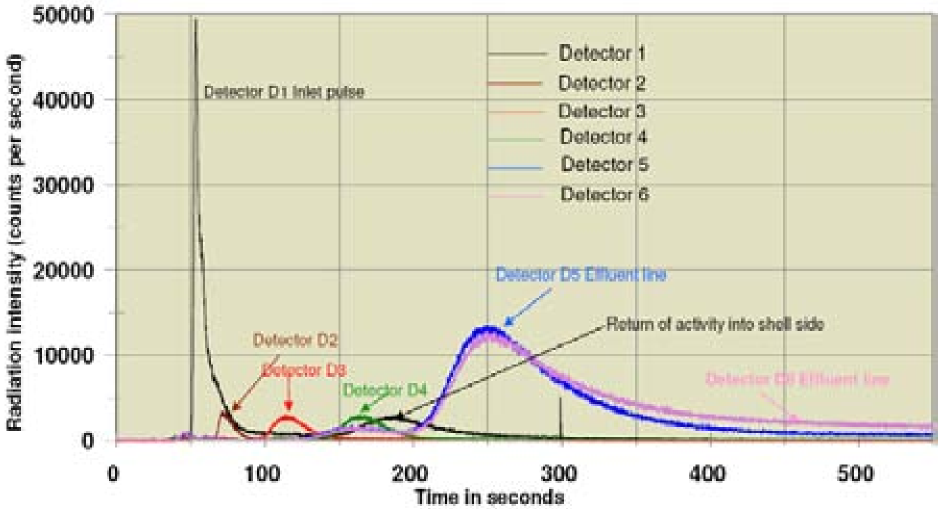


FIG. 35. Detector responses

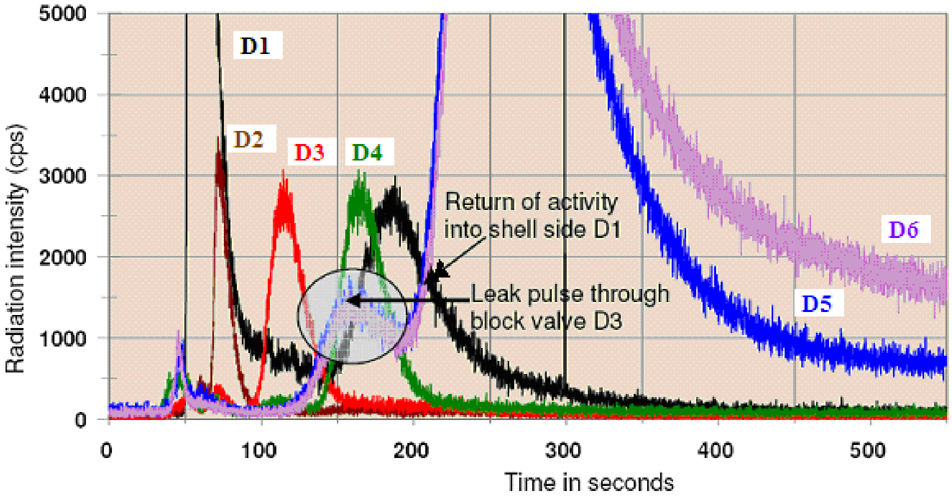


FIG. 36. Detector responses in a larger y-scale

Small pulses recorded at the beginning (just after radiotracer injection) by all detectors are coming from the radiotracer manipulation during injection. Detectors D4 and D5 show nearly the same peak after 150 -160 s. This peak is coming much after the peak shown by D2, that means is not related with any peak in the heat exchanger. Following the tracing fluid flow map, the most convenient explanation of this peak is a leak through the valve situated at the position of D3, that means at the exit of the treater B the stream is split in two parts, one following the normal run to the entry of the treated A and the other bypassing through a valve leak directly to the shell side of heat exchanger. After the record of the peak by D4, another peak is recorded by D1 (unexpected peak). This is an induction peak coming from the radiotracer flowing through the shell side of the heat exchanger after crossing treater A. It seems that D1 is very near the heat exchanger and not well collimated.

As conclusion, because detectors D5 and D6 did not measured any tracer signal before detector D2, it was concluded that there was no leak in the heat exchanger during the time of investigation. The pulses recorded by D5 and D6, at time app. 160 s, are caused by activity leaking through the block valve situated near the position of the D3. Possibly, the block valve was not 100% blocked and the radiotracer leaking through it enters the heat exchanger shell side.

1.5.5. A pre-shutdown diagnostic assessment of ammonia synthesis line

As part of investigation to assist in pre-shutdown planning, plant engineers wanted to establish why the ammonia synthesis line was not performing as efficiently as expected. The reasons could either be poor catalyst performance, internal bypassing (leakage) of the catalyst bed, or leakage through a faulty bypass valve that should have been closed. A series of radiotracer tests were carried out for troubleshooting of different processing loops of ammonia synthesis and converter line. A pre-shutdown diagnostic assessment of main reactors of ammonia production plant was performed, mostly related with detection of suspected leaks in different processing loops. Fig. 37 shows the diagramme of the ammonia synthesis loop.

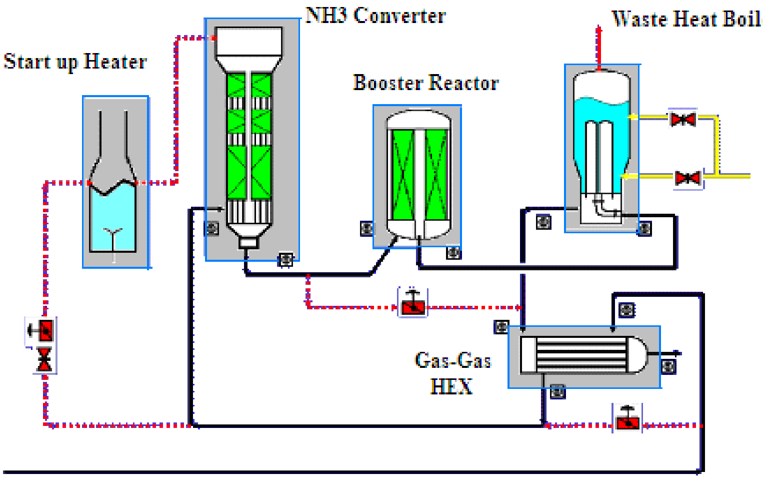


FIG. 37. Ammonia synthesis loop diagram

The objective of the diagnostic work was:

- To determine and identify potential areas or locations of leakage within the loop, where the process gas is bypassing the equipment, either internally or externally,
- To finalize inspection work requirements on high pressure equipment,
- To assess the need to open high pressure equipment and catalyst vessels

Four tests were performed, the first test in the gas-gas heat exchanger (HEX), the second in the ammonia converter, the third in the booster reactor and the fourth in the waste heat boiler.

A. Test 1 - Internal leakage through gas- gas heat exchanger and leak in bypass valve

Radiotracer method was used to search for leak detection in the heat exchanger and in bypass valve. Experimental setup is shown in the Fig.38. Gas radiotracer, 50 mCi of ^{41}Ar, was used as radiotracer. Four radiation detectors were active in this test: injection detector (D1, black) at shell inlet; D2 (red) at shell outlet; heat exchanger leak detectors (D3, blue and D4, green for double check). Between inlet and outlet pipes of the shell side was a bypass valve, which in normal condition is closed not to allow the outlet gas to entry to the inlet. The experimental response curves of four radiation detectors employed in this test are given in Fig. 38.

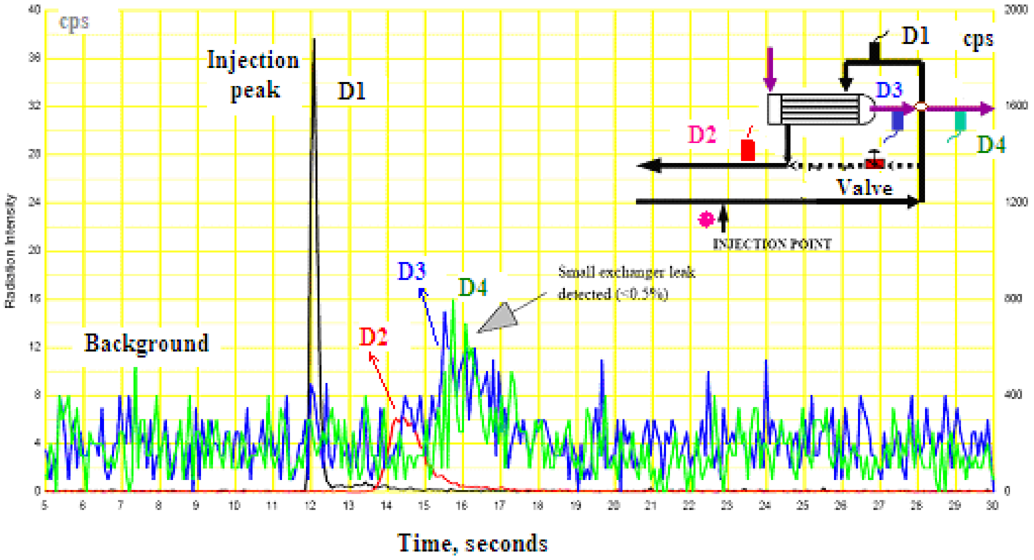


FIG. 38. Experimental response curves of four detectors employed in this test

The black curve indicates the injection peak (t = 0); the red curve represents the tracer RTD in the shell outlet. The y-scale for these two detectors is on the right side of the graph. The blue (D3) and green (D4) curves represent the leak peak because if no leak both curves would remain in the background level. This is not false peak because both peaks were recorded 3~4 s after injection, they were very heavy shielded and collimated, and they have more or less the same amplitude (≈ 15 cps) despite the fact they were several meters from each other and quite far from injection point and shell outlet. The area of leak peak shown by D3 was found smaller than 0.5% of the area of the entry peak recorded by D1.

The regular experimental RTD curve obtained by the D2 located at the outlet pipe of shell side shows that there was not any leak through the valve. If the bypass valve between inlet and outlet pipes of the shell side was not closed then a bypass peak has to be seen at the beginning of D2 curve, that it was not the case. As conclusions of test 1: small shell to tube leak in the heat exchanger was detected (<0.5%), which does not exercise major effect on loop performance, as well as there was no bypass valve leak.

B. Test 2 - Internal leakage through ammonia converter

Experimental setup shown in Fig. 39 was very simple in this case.

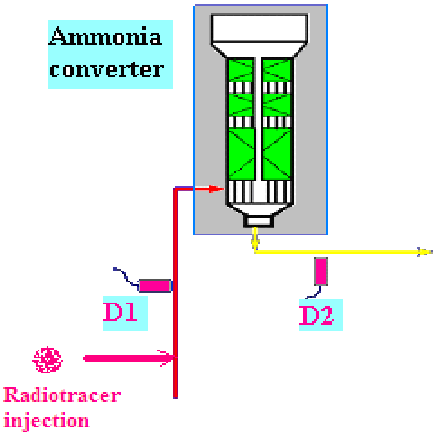


FIG. 39. Experimental setup for radiotracer inspection of internal leak through ammonia converter

30 mCi ^{41}Ar radiotracer gas was injected by means of high-pressure helium gas, in order to overcome the plant pressure. There were two detection detectors only, the injection detector (at the converter inlet) and leak detector (at converter outlet). The leak detector installed at the converter outlet did not record any radiotracer signal but remained in the background level, this simply means that no leak in the ammonia converter. All internal interchangers were found in good conditions.

C. Test 3.- Internal leakage through ammonia booster converter and leak in bypass valve

The leak inspection of booster converter bypass was performed as the third test. 10 mCi of ^{41}Ar gas radiotracer was injected before the bypass valves, and four detectors were placed as shown in Fig. 40.

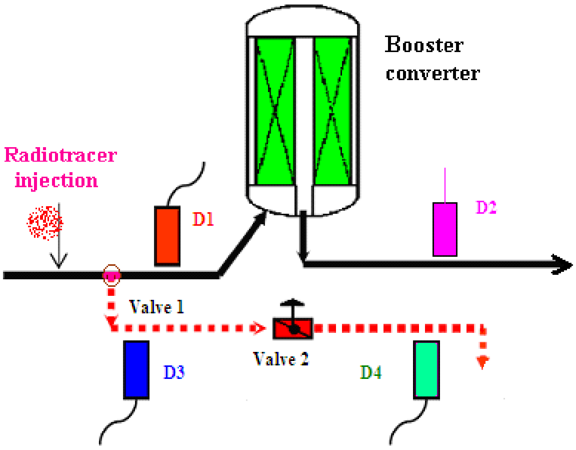


FIG. 40. Leak inspection through the booster converter bypass

Detector D1 installed at the booster entry records the injection peak, while the detector D2 at the converter outlet registers the residence time distribution (RTD) of the radiotracer within the booster – converter system. Detectors D3 and D4 were installed after two bypass valves V1 (D3) and V2 (D4). They will response to the leaks though these valves if any.

The experimental response curves of the radiation detectors are shown in Fig. 41.

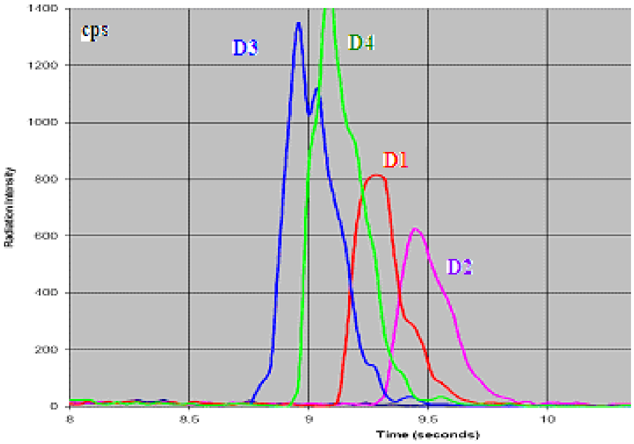


FIG. 41. Experimental response curves in booster converter bypass test

Both detectors D3 (blue) and D4 (green) installed at the bypass valves recorded significant peaks that indicate the presence of the leaks through the bypass valves V1 and V2 that means these valves were not completely closed. It seems that D3 and D4 were not calibrated and corrected for different radiation detection geometries; this explains the higher amplitude of the D4 compared to D3.

Detectors 1 and 2 recorded normal RTD curves. The RTD curve registered by D2 at the outlet of the booster – converter system indicates that no internal bypassing in the system. Any internal leakage could be indicated by a subsidiary peak (so called bypass peak) preceding the main peak, that is not the case in Fig. 41.

The radiotracer test for leak inspection in booster-converter system and in valves in bypass lines around converter, which are expected to be closed, arrived in the conclusions a large bypassing was discovered in the ammonia booster-converter loop, which was caused by ssignificant failure of the bypass valve. Valve bypassing was ssignificant contributor to poor overall loop efficiency.

D. Test 4: Internal leakage through the waste heat boiler.

The waste heat boiler (WHB) is independent part of the ammonia production line; that means its operation is not strictly related with the performance of the ammonia synthesis loop. Nevertheless, a radiotracer test was carried out in the waste heat boiler as well because it was not operating efficiently, with the exit temperature of the process gas much higher than expected. There was a suspicion that this may be due to internal bypassing of some of the gas at an inlet flanged bellows arrangement, and as a planned plant shut down was imminent, a radiotracer test was requested to confirm this theory.

50 mCi ^{41}Ar radiotracer gas was injected and detectors were installed on the gas exit line to analyze the exit pulse. The arrangement and subsequent detector responses are shown in Fig. 42. Two leak detectors (red and yellow) were installed at the gas exit line to confirm the existence of the leak (if any). Besides the leak double-check role, the yellow detector can be used to measure the leak flow rate (using peak to peak method). An additional detector (green) was installed at the exit of heat exchanger following the boiler for obtaining additional information about the heat exchanger performance. In fact the utilization of this detector has no significance for the detection of the leak in the WHB and is not justified; the performance of the gas-gas heat exchanger was already investigated during the test 1.

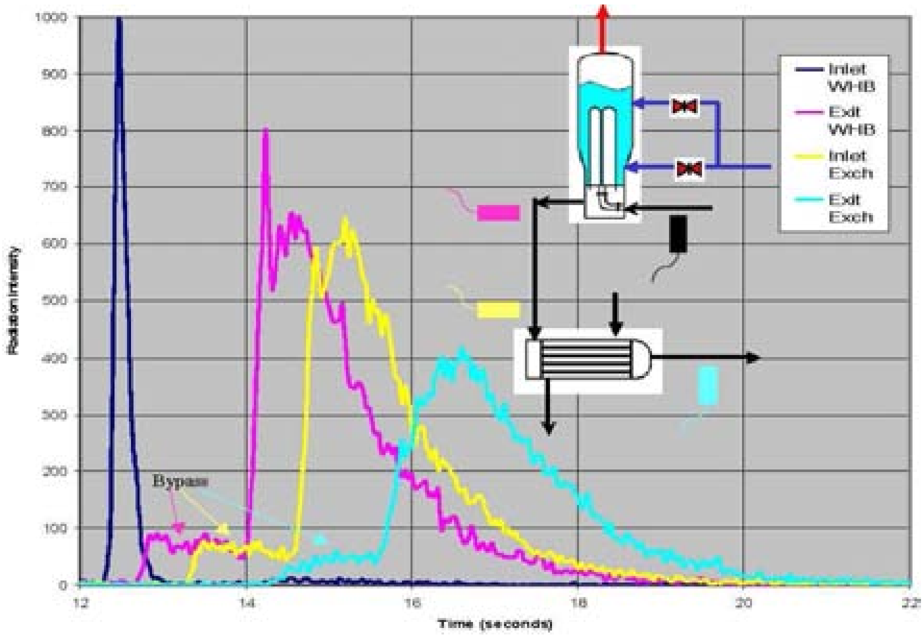


FIG. 42. Detection of vessel internal bypassing

The black curve indicates the injection peak (time = 0). The experimental RTD curve obtained at the exit of the WHB (red line) shows the initial bypass peak, which is characteristic of leakage (internal bypassing). As can be seen from the graph, next detector (yellow) has shown the same initial bypass peaks, which confirms the existence of the leak.

The same characteristic of the experimental RTD curve was provided by the additional detector (green), which was installed at the exit of heat exchanger for obtaining additional information about the heat exchanger performance. It seems that HEX has not any evident problem, because the experimental RTD curves at inlet (yellow) and outlet (green) have the same shape.

As conclusion, initial bypass peaks were recorded by every detector, prior to the main pulse of radiotracer being observed (in regular sequences). This conclusively proved that internal bypassing was occurring in the waste heat boiler, and a replacement bellows inlet device was ordered to be installed in the forthcoming shutdown. The internal bypassing observed in waste heat boiler might have a minor negative role in the overall performance of the ammonia production line.

E. Conclusion of the pre-shutdown diagnostic assessment of ammonia synthesis line.

The pre-shutdown diagnostic assessment of the ammonia production line using radiotracer techniques was completed successfully. All logistic issues have been addressed and overcome. Leak inspection using radiotracers has allowed a better understanding of the performance of critical equipment. Maintenance work has been re-scheduled to avoid unnecessary inspection.

1.5.6. Leak detection in bank of heat exchangers in a refinery

A hydrocracker plant in a refinery in India was designed for conversion of fresh feed i.e. vacuum oil gas to diesel. The hydrocracker plant mainly consists of a packed bed reactor (hydrocracker) and a battery of high-pressure heat exchangers connected in series. A photograph of the battery of heat exchangers is shown in Fig. 43.

FIG. 43. Bank of heat exchangers in refinery where radiotracer test was carried out to search for leaks

Refinery engineers suspected leak(s) in the heat exchangers because of high level of sulphur content in the final product. Radiotracer investigations were carried out for leak detection in the battery of five heat exchangers. ^{82}Br as dibromobiphenyl was used as a radiotracer. 50 mCi was injected in the feed inlet to the exchanger. Seven identical NaI (Tl) radiation detectors (D1-D7) properly collimated were installed in different position of the system.

The schematic diagram of heat exchanger system and radiation detector location is shown in Fig. 44. Detector 1 is so called injection detector that means records the injection peak at time zero. Detector D7 is in the feed outlet; its experimental response curve is not related with the existence of peaks only shows the residence time distribution (RTD) of radiotracer inside the system of five heat exchangers. Detectors D2-D6 (so called leak detectors) are all installed at the shell outlets of respective five heat exchanger units of the battery; if no leak they should measure only the background.

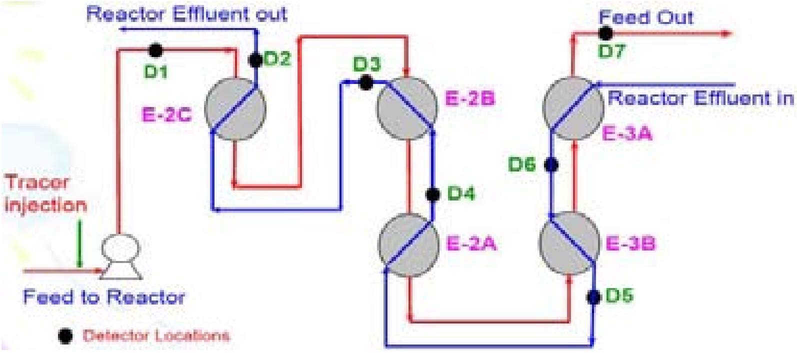


FIG. 44. Schematic diagram of heat exchanger system and radiotracer monitoring location

Fig. 45 shows the experimental response curves obtained during the first test. Peaks recorded by leak detectors D2-D6 indicate the presence of important leaks in the system of battery of five heat exchangers. To identify the leaks in five individual units of the battery of heat exchangers the comparison of time and amplitude characteristics of five response curves of detectors D2-D6 is performed.

Fig. 45 shows that peaks recorded from detector D2 (blue) are coming few seconds latter in comparison with detector D3; this fact indicates that the heat exchanger unit E-2C is not leaking, because if there was leak in this exchanger the peak response recorded by D2 would have been appeared before the peak recorded by D3.

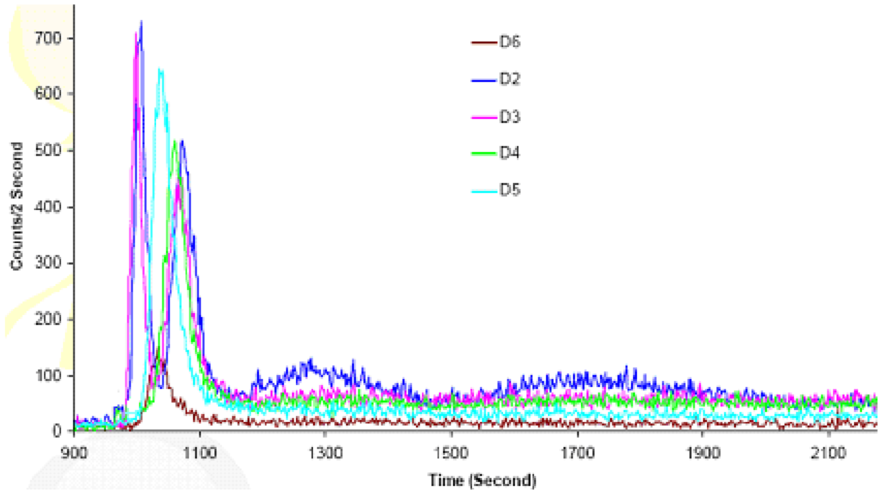


FIG. 45. Radiotracer response curves recorded by different detectors (Test 1)

Detector D6 has recorded a relatively small peak (~ 130 counts/ 2s) at ~ 1030 s. This peak reflects the leak in the heat exchanger unit E-3A. Detector D5 shows a relatively high peak (~640 counts/2s) at nearly the same time (few second after) as D6. This higher peak (in comparison with D6) indicates that unit E-3B was also leaking. Comparing the two peaks of D6 and D5 it results that leaking flow rate in the unit E-3B was higher than in E-3A (detection efficiencies were nearly the same for all 7 detectors).

Detector D4 recorded a relatively medium peak (compared with D6 and D5) at ~ 1070 s. This peak reflects leaks coming from units E-3A and E-3B. If the unit E-2A was leaking then another peak should have appeared before the recorded one. Thus, the unit E-2A was not leaking.

Detector D3 shows two peaks, one relatively high peak (~ 700 counts/2s) at ~ 980 s and after the second medium peak (~ 430 counts/2s) at ~ 1080 s. The fist peak indicates the bypass of the influent fluid in the unit E-2B that means the leak in this unit. It seems that the leak in the unit E-2B is the largest in the heat exchanger battery. The second peak reflects the leaks in units E-3A and E-3B.

The radiotracer test showed that three out five units of the battery of heat exchanger were leaking. A second test was performed in the same conditions to confirm the results of first test and to quantify the leak rates. In order to quantify the leak rates, the area of peak recorded by inlet detector, i.e. detector D1 and the area of peaks recorded by leak detectors were compared and the leak rates were estimated using the following relation:

$$\text{Leak rate }(\%) = \frac{\text{Area of leak peak}}{\text{Area of input peak}} \times 100$$

The total leak rate was found nearly 25% of the reactor effluent flow rate.

Fig. 46 shows the experimental response curves obtained during the second test.

The records of seven detectors, including very high peaks of feed injection (D1) and exit (D7) are analyzed carefully. Leak detectors D2-D6 showed more or less the same results of the first test. The peaks registered by detectors D2-D6 reflect leaks; if no leaks in the whole bank of heat exchangers then five detectors (D2-D6) should have registered only background. In order to obtain quantitative results on leak location and size, more detailed comparative analysis of experimental response curves was required.

Fig. 47 gives the experimental response curves of detector D5 and D6.

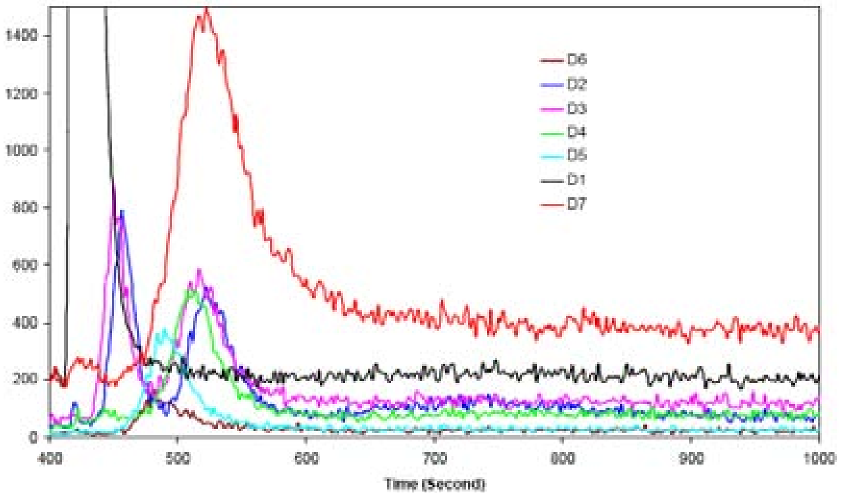


FIG. 46. Radiotracer response curves recorded by all seven detectors (Test 2)

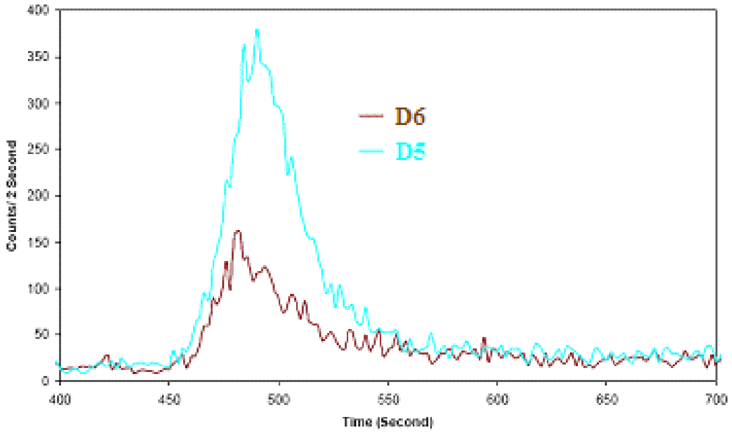


FIG. 47. Radiotracer responses recorded at tube outlets of heat exchangers E-3A, E-3B (Test 2)

D6 indicates the peak coming from leak of the unit E-3A, while D5 reflects peaks coming from leaks in both heat exchangers units E-3A and E-3B.

Fig. 48 shows the experimental response curves of detectors D2, D3 and D4.

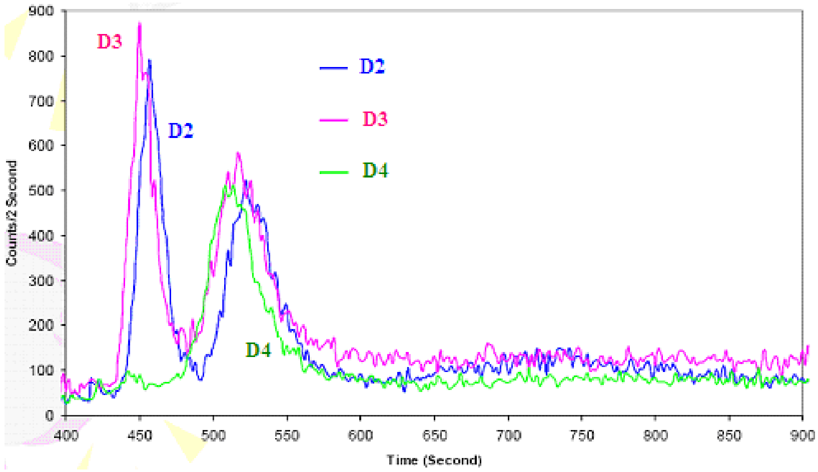


FIG. 48. Radiotracer responses recorded at tube outlets of heat exchangers E-2A, E-2B, E-2C (Test 2)

The first peak recorded by detector D2 come after the first peak registered by D3 that confirms the results of the first test that unit E-2C was not leaking. Two first peaks of detectors D2 and D3 are results of the leak in the unit E-2B only.

Comparing second peaks recorded by detectors D2, D3 and D4 with peaks recorded by detectors D6 and D5 (Fig. 47) it seems that leak peak recorded by D5 is crossing the detectors D4 with nearly the same amplitude indicating no additional leak in the unit E-2A. The second peaks recorded by D3 and D2 are consequences of the same leak peak coming from E-3A and E-3B, in addition D3 records also leak coming from E-2B.

The careful time and peak analysis of experimental response curves concluded that three high-pressure heat exchanger units of the bank of five were found leaking. The leak rates in individual heat exchangers were found to be ranging from 5-10%, however the total leak rate was found to be about 25 %. Leaks were visually confirmed during shutdown.

Based on the results of the radiotracer investigations, the shutdown of the plant was planned for remedial action.

After a normal operation of about fifteen months, the sulphur content in the product was found again abnormally high (> 400 ppm). Ruling out other possibilities, again leaks in some units of heat exchanger battery were suspected. Therefore, another radiotracer investigation was carried out in the same heat exchanger system. Similar experimental procedure and scheme (Fig. 44), as adopted in first investigation was used. 25 mCi of ^{82}Br as dibromobiphenyl was injected in the feed inlet to the exchanger.

Fig. 49 shows the radiotracer experimental response curves.

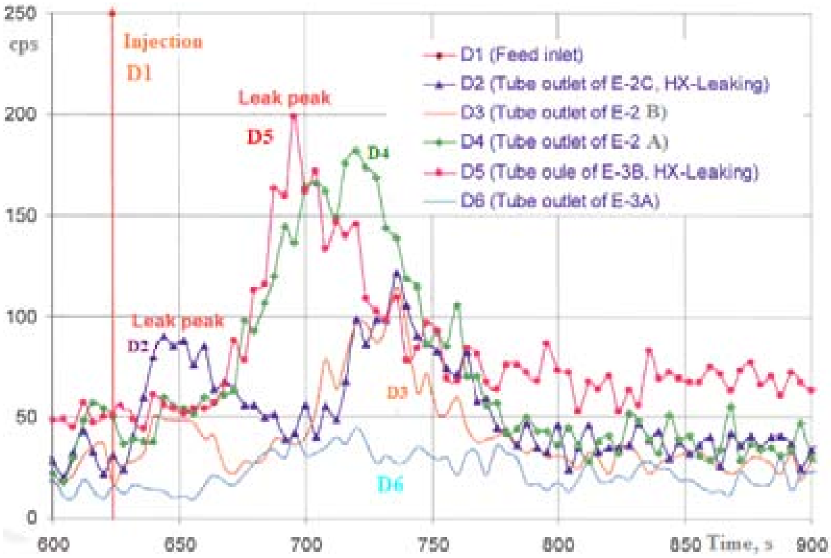


FIG. 49. Experimental response curves recorded by detectors D2-D6

Detector D6 does not show any significant peak that means E-3A unit was not leaking. D5 recorded a peak that indicates that unit E-3B was leaking. D4 and D3 show the peaks coming from the leak in the unit E-3B; thus units E-2A and E-2B were not leaking. D2 shows a peak at the beginning, before the peak of D5; this means that unit E-2C was leaking.

The radiotracer test clearly showed that two out of five units of the battery of heat exchangers were leaking. The intensity of the recorded peaks indicated that the leak rate could be higher in the heat exchanger unit E-3B than in the unit E-2C.

The identification of the leaking heat exchanger units reduced the plant down time by a total of 20-25 days. After plugging the leaks, the operating temperature of downstream hydrotreating reactors could be lowered by about 40 ^{0}C, thus extending the life of the catalyst by two years. These two factors resulted in substantial economic benefits to the refinery.

The frequent occurrence of leaks in the heat exchanger system indicated that the bridge-lock type heat exchangers are more susceptible to the leaks in high temperature and high pressure refining operations. Thus plant engineers contemplated to replace the bridge-lock type heat exchangers with some other suitable heat exchangers in near future.

1.5.7. Radiotracer leak test in a bank of heat exchangers

Leaks on a heat exchanger usually result in off-spec material being produced. If the system has a bank of exchangers then it is very difficult to identify which one (or pair) is leaking using laboratory sampling alone. A client had a problem with a feed-effluent exchanger system consisting of five exchangers in series (Fig. 50).

A diagram showing detector positions is presented in Fig. 51. ^{82}Br (50 mCi) in the form of the ammonium bromide ($NH_4{}^{82}Br$) was used as radiotracer for liquid organic phase. A sharp pulse of liquid tracer was injected into the feed. The passage through the system was monitored by four detectors, with D4 on the final product line being the 'leak detector'.

FIG. 50. Bank of heat exchangers

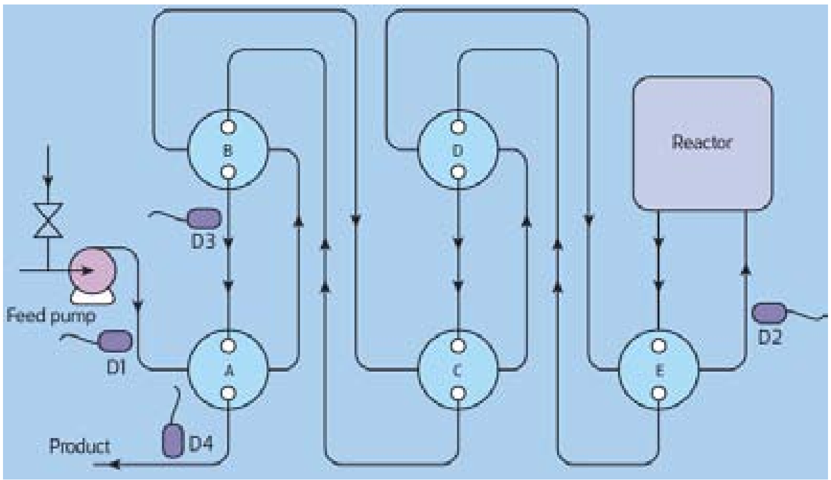


FIG. 51. Radiotracer test for leak detection in a bank of heat exchangers

D4 indicated that a leak of feed to product of approximately 2.5% was present in the system. By using the other detectors and residence time calculations it was possible to determine that exchanger 'A' was leaking. Therefore only one exchanger needed to be removed from duty and repaired. This minimized loss of production and eliminated unnecessary down time for inspections.

1.5.8. Gamma absorption technique for leak detection in intercooler exchangers

A customer has requested to perform a leak test on six intercooler exchangers because one or more of them were suspected of leaking cracked process gas into the cooling water. When asked to perform a leak test of exchangers, the common sense almost invariably is to use a radiotracer technique. The traditional way to carry out a leakage test on this type of system would be to inject gaseous radiotracer into the high pressure process gas side and to deploy sensitive radiation detectors at strategic positions on the low pressure cooling water side.

In planning the use of a radiotracer, consideration must be given to its acquisition and transportation, and obtaining permission from regulatory authorities. This can lead to significant delays, resulting in operational and financial burdens on the customer, particularly if the facility is located in a remote area. Since this plant was in a remote area this would have involved the importation of the radiotracer into the country following the slow process of obtaining the necessary legislative approval to carry out an unsealed radioactive tracer study. The customer needed to know quickly which of their exchangers was leaking.

Although the use of radioactive tracers for carrying out leak tests on heat exchangers is a valuable, well used and successful technique there are times when equally valuable results can be obtained using a sealed source technique. A situation where this applies is when a significant density change occurs because of the leak.

The system shown schematically in Fig. 52 was one of six intercoolers in a cracked process gas compressor train. The process gas pressure was higher than the closed circuit cooling water. In the cooling water circuit there was a buffer drum at the suction of the recirculation pumps. The drum had a nitrogen blanket and was fitted with a relief valve. The relief valve was found to be opening to atmosphere. Analysis of this vented gas showed it to contain cracked gas. To minimize maintenance effort and shutdown time, the customer needed to know which of the six intercoolers was leaking.

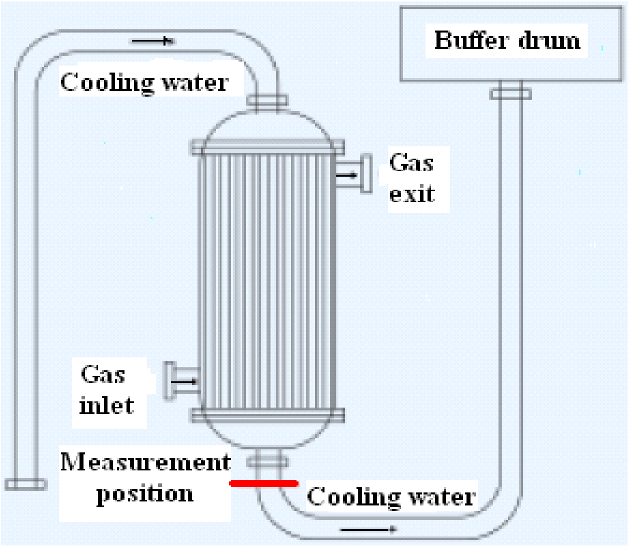


FIG. 52. A schematic illustrating one of six intercoolers in a cracked process gas compressor train

The innovative solution was to use the hypothesis that if cracked process gas was leaking into cooling water, then it would have the effect of reducing the density of the water immediately downstream of the leaking intercooler. If the density in the cooling water line from each exchanger could be measured non-intrusively then the leaking exchanger could be identified.

Gamma transmission (absorption) technique using a sealed source of ^{137}Cs (10 mCi) was employed to measure the density of the material in the cooling water exit line of each intercooler and determine which one was leaking. Measurement of radiation intensity passing through the cooling water inlet and exit pipes was measured at the indicated location for each exchanger (red line in Fig. 52).

After careful calibration in laboratory with the same pipe and detector for various gas cooling in water, the registration of detectors were converted to the amount of aeration in the cooling water exit lines.

The sensitivity of this type of test depends upon a number of factors such as the radioisotope gamma energy and activity as well as the path length through which the radiation beam passes. In laboratory, it was realized that in ideal situations this technique is capable of detecting changes in the density of the water caused by a leak as low as 1% of the gas in liquid. In the field practice, the variations within the pipes reduced the sensitivity to a leak rate limit of detection of 2% of the gas in liquid. The volume percentage of gas for the six exchangers is shown below:

Exchanger	***% Gas in cooling water exit line***	***Conclusion***
A	0 (< 2)	Not Leaking
B	9	Leaking
C	0 (< 2)	Not Leaking
D	0 (< 2)	Not Leaking
E	0 (< 2)	Not Leaking
F	5	Leaking

Conclusion

The test showed that exchangers B and F were leaking. This work was carried out in a matter of a few days, instead of the weeks of planning and preparation that would have been required for a traditional radiotracer leak test in this particular country, significantly reducing the customer's operational and financial burden.

2. RADIOTRACER METHODS FOR LEAK DETECTION IN UNDERGROUND PIPELINES

2.1. PRINCIPLE OF RADIOTRACER METHODS FOR LEAK DETECTION IN UNDERGROUND PIPELINES

Some conventional NDT techniques such as gas detection, acoustic emission, and infrared waves are developed for underground pipeline leakage detection. Leak location of a long underground pipeline is an extremely difficult task, as their sensitivity and ability for on-line leak location are not as satisfactory as required.

Radiotracer techniques are very useful in the detection of leaks on underground pipes because of their high sensitivity and accuracy in comparison with the conventional NDT techniques. An appropriate radiotracer is injected into a pipeline and a certain pressure is applied to the pipeline to allow the radiotracer to leak out (if any). The leaked tracer may migrate towards the ground surface in case of gaseous radiotracer or adsorbed on the soil or thermal insulation around the lea point in case of liquid radiotracer. The location of a leak is discovered by surveying the radioactivity from the leaked radiotracer.

The detection of the leaked radiotracer is performed from the ground surface, when the thickness of the soil above the pipeline is small enough (the gamma radiation of the radiotracer or the gaseous radiotracer itself can penetrate to the ground surface). In case of deeply buried pipelines the detection of leaked radiotracer is performed from the inside of the pipeline using a pipeline pig (pipeline inspection gauge) equipped with one or more radiation detectors and a data logging system. Three methods are used generally to detect and locate leaks in buried pipelines: tracer patch migration method, velocity drop method, and radiotracer – detector pig method.

2.1.1. Radiotracer patch migration method

This technique is known also as the radiotracer pulse migration method. The section of a pipeline to be inspected is filled with a fluid and is isolated by closing the valves. A small amount of radiotracer is introduced as single pulse at an injection point located in the middle section of the pipeline. A preset pressure is applied to the pipeline through the injection point using a pressure pump. The movement of the radiotracer is monitored by two radiation detectors installed at a few meters away from the injection point to both sides as shown in Fig. 53.

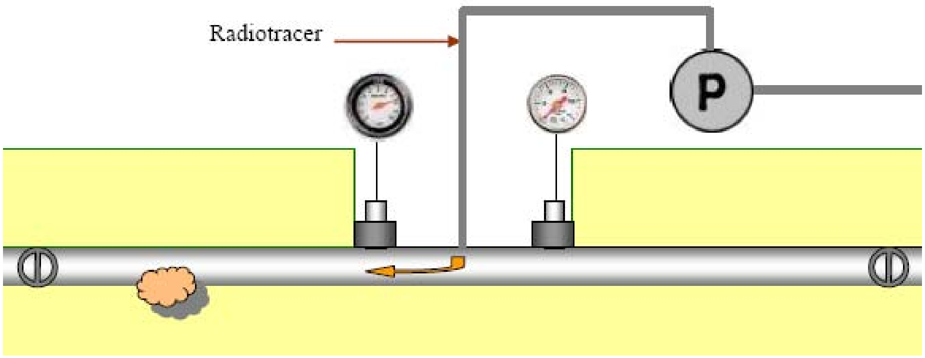


FIG. 53. Radiotracer patch migration method

Radiotracer patch moves along with the fluid and migrates towards the direction where the leak is. Rough estimation of the leak flow rate is also possible by measuring the velocity of the tracer patch movement. The search for localization of leak can continue only at that side where the radiotracer is moving.

A modification of this method is to inject a radiotracer from one end and monitor its migration towards the leak using many detectors installed along the pipe. The pipeline dimensions affect the velocity of the radiotracer movement along its way from the injection point to the leak point. The chance to find small leaks in large diameter pipelines is rather scarce because the radiotracer concentration decreasing under the influence of diffusion and dilution with respect to time. However, for larger leaks this technique works quite well.

The radiotracer patch migration technique can be employed in some circumstances for both shallow and deeply buried pipelines. For shallow buried pipelines the detection is normally performed by moving a detector on the ground surface along the pipeline, while for deeply buried pipelines the radiotracer patch inside the pipeline is monitored using radiation detectors logged into pits dug at regular intervals along the ground surface projection of the pipeline (Fig. 54). Dug pits are few tens of centimeter depth to shelter the detection probe as much as possible near the pipeline.

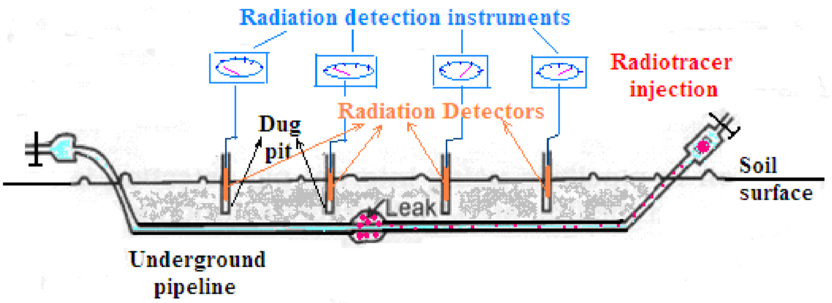


FIG. 54. Radiotracer patch migration method using dug pits for radiation detection

Radiation detector records show radiotracer cloud passing in front of each detector. Non-arrival of the tracer pulse in a dug pit within the stipulated time calculated by radiotracer travel velocity indicates that the leakage zone is located between the dug pit and previous one. Further investigation is needed in smaller scale to localize the leak place with proper accuracy.

The dug pit interval depends on the pipeline section length to be investigated. For some kilometer pipeline the dug pits could be drilled every few hundred meters. This method is usually not used for leak detection in long pipelines because it is very laborious and not accurate enough. Long pipelines should be searched for leak section by section, but it is not always possible to isolate a section and to keep it under the pressure.

2.1.2. Radiotracer pulse velocity drop method

This is an on-line method. Radiotracer is injected some where upstream flowing with the pipeline fluid. Two pairs of detectors are sheltered in dug pits located both sides of suspected leak point for measuring the fluid velocity using peak-to-peak technique (Fig. 55). The flow rate Q_1 is measured with detectors D1 and D2, while the flow rate Q_2 is measured with detectors D3 and D4.

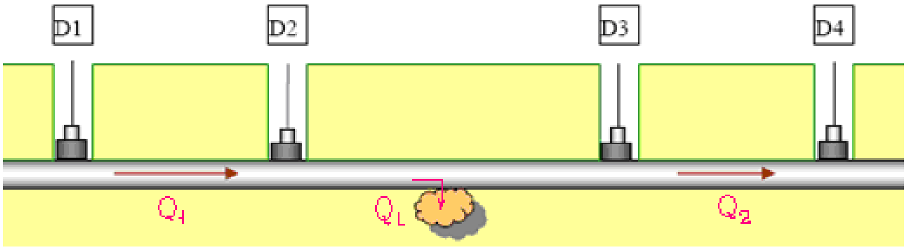


FIG. 55. Radiotracer pulse velocity drop method

The leak flow modifies the flow regime inside the pipeline. The upstream flow rate Q_1 is the sum of the downstream flow rate Q_2 plus the leak flow rate Q_L. Thus, leak flow rate is calculated: $Q_L = Q_1 - Q_2$. This method is applied for relatively large leak that can modify substantially the flow regime inside the pipeline.

2.1.3. Radiotracer detection pig method

Radiotracer detection pig is an inspection vehicle that moves inside a pipeline pushed along by the flowing fluid material. Radiotracer pig is a very competitive on-line technique for leak detection in deeply buried pipelines. The principle of leak detection in deeply buried pipelines using radiotracer is illustrated in Fig. 56.

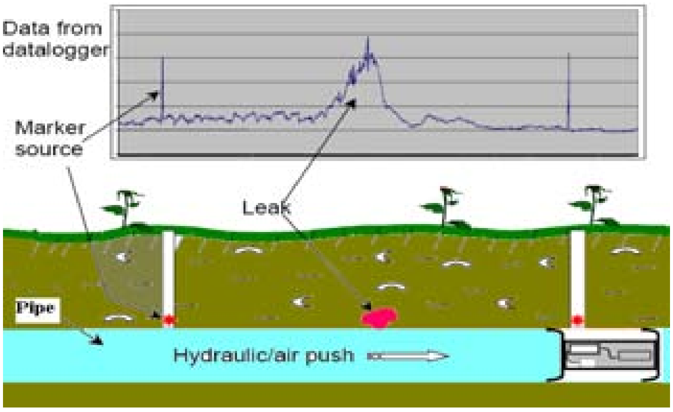


FIG. 56. Principle of radiotracer pig method for leak detection in deeply buried pipelines

The principle of the method consists in introducing a radiotracer to the underground pipe. The tracer travels towards the leak, where it is adsorbed on soil, sorbents and/or thermal insulation. The detection of the radioactivity is performed by a radiotracer detection pig, which records radiotracer signals measured from the inside of the pipeline. It has high sensitivity in leak detection due to its close contact with the leaked radiotracer.

Radiotracer detection pig method can be used on-line or off-line mode. For on-line mode, the inspection of the pipeline is carried out during its normal operation. Firstly, the radiotracer is injected into the pipeline as a tracer plug. Where the 'tracer plug' meets holes or fractures a certain amount of the tracer penetrates and remains outside the pipe.

The fluid (oil or other liquid) following the 'tracer plug' will clean out residues of the radiotracer. In the second step, the radiotracer detection pig is launched into the pipeline to detect leaked tracer. The pig has to be launched after long enough time interval after the radiotracer plug to secure the pipe's interior is free of the radiotracer.

For off-line mode, the suspected buried pipeline is filled with the fluid mixed with radiotracer. The pipeline is closed both side and is kept under a preset pressure for a certain time. After the radioactive fluid is removed, the detection is carried out by moving the pig along the pipeline.

2.1.4. Experimental design of the radiation detection pig method

Radiation detection pig technique is the most sensitive technique for leak detection in deeply buried pipelines. Basic advantages of the radiotracer pig detection method in locating leakage in pipelines are: very high sensitivity, short time of experiment and relatively low cost. The sensitivity of leak detection is around 0.1 L/h. Radiotracer detection pig consists of a gamma radiation detector and data logger assembled together with a battery inside a compact watertight container. Fig. 57 shows the pig inserting into a pipeline launcher.

FIG. 57. Inserting the pig into a pig launcher of a pipeline

Pig moves together with the medium through the pipeline at a constant speed by hydraulic or pneumatic push. After retrieving the pig at the other end, the recorded data is downloaded in a PC to see whether there are leaks and their locations.

Preparation of the pipeline for leak inspection is connected also with installation of distance markers placed in the pits dug at regular intervals on ground level. ^{60}Co sealed sources of some MBq (30-100 μCi) are installed in pits above the pipeline to mark the pig records. Fig. 58 shows a ^{60}Co marker installed in a control well above the pipeline. Calibration source is used to calibrate the pig detector converting the response in counts rate to the activity. Normally, radiotracer in a sealed source is used as calibration source.

FIG. 58. ^{60}Co markers installed in a pit (left) and on the pipeline(right)

Radiotracer inspection of the pipeline is being made in two pig runs. In the first run the natural background inside the pipeline as well as counting level of ^{60}Co markers are recorded. They are needed for calculating total activity of tracer, necessary for realization of assumed sensitivity control. In the second run (after radiotracer injected and pipeline washed up) the detection of leaks is being searched. The following types of radiation are recorded by the pig:

- distribution of natural radiation in the area surrounding the pipeline
- radiation intensity coming from the radioisotope distance markers
- radiation intensity coming from radioisotope calibration markers
- leak peaks if any.

2.1.5. Some pig prototypes

Radiotracer pig is a state of the art of hardware and software combination. It contains gamma radiation detector coupled to data logger; it operates by data acquisition software. It has special mechanical features combining anti shock protection and robustness. The type of pig to be used and its optimum configuration depends on a particular task and a particular pipeline. Each pipeline has its own set of characteristics which affect how pigging is used. Thus, there is not a pig prototype in the market for all kind of applications. Most of the radiotracer pigs used by radiotracer groups around the world are home made. Some of them demonstrated in regional training courses are described below.

A. Polish pig

The radiotracer pig is designed for measuring and recording radiation intensity of a radioactive tracer absorbed at the leak site. The detection system is adapted to operation inside the piping. It is shockproof and resistant to mechanical damage. A 3”×3” NaI scintillation detector is installed inside the pig. The detector operates in gas-tight housing. The power for the measuring and recording units is supplied from batteries, which can be used continuously for 100 hours. It can be used for leak inspection of pipes with diameter 200 – 600 mm. Fig. 59 shows the Polish pig, model DN 1.

FIG. 59. Polish DN 1 pig in housing (left) and ready for using (right)

The detection module of the DN 1 model has diameter 100 mm, length 660 mm and mass 8 kg. Hermetic case of the DN 1 has the total length including guides 970 mm, the external diameter of metallic cylindrical housing 167 mm and the total mass with guides 35 kg. The signal coming from the scintillation detector is supplied to the input of the amplifier. The amplifier gain can be varied in a way that amplitude of the output signal should not exceed 5V.

The detector –data logger module has the following performance characteristics:

- Measuring time can be set in range from 0.1 to 3276 s
- Maximum number of samples (channels) possible to record is 262144.
- Memory records are transferred to a computer with serial transmission interface RS-232 allowing data transmission with speed 19200 bits/s
- Maximum recording time 100 h.

B. Danish pig

FORCE Technology, Denmark has developed a very sensitive pig for on-line leak detection in underground pipelines. Pig has two sections composed of a 'Driving module' and a 'Detector module'.

The driving module houses power supply and odometer instrument for determination of travel distance. The detector module houses two highly sensitive radiation detectors and their data logger. Fig. 60 shows the Danish radiotracer pig for pipelines with diameter 400-500 mm.

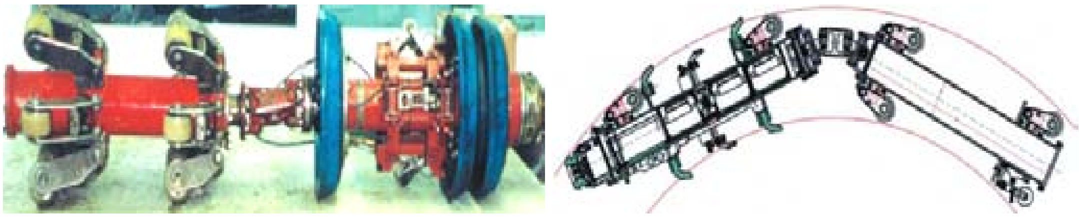


FIG. 60. Danish pig for leak detection: driving and detection parts

C. Indian pig

The radiotracer group of the Bhabha Atomic Research Center (BARC) in India has been developing another radiotracer pig. Fig. 61 shows a pig constructed at the BARC, India.

FIG. 61. Pig designed and constructed in India

After laboratory trials and some real industrial tests, the Indian tracer group at the BARC is developing further this pig to make it reliable in harsh field conditions. The radiotracer pig they are developing have the following features:

- Battery operated (Dry cell for 8 hours)
- 2”× 2” NaI(Tl), HV supply, pulse processing electronics, data acquisition and storage
- Flash card memory for data storage and retrieval
- Water tight stainless steel enclosure
- Counting time: Settable between 1 to 999 seconds
- Number of events: up to 100000
- HV Supply: up to 1000V - 100μ Amps

2.2. SELECTION AND PREPARATION OF THE RADIOTRACER FOR LEAK DETECTION IN UNDERGROUND PIPELINES

Both gas and liquid radiotracers are used depending on the phase of the fluid flowing inside the pipeline. In case of gas transporting pipelines, the gaseous methylbromide labeled with ^{82}Br is mostly employed; ^{41}Ar is used as well. In the case of liquid flow pipelines, the $NH_4{}^{82}Br$, $K^{82}Br$, and $Na^{131}I$ are used in case of water, while for organic phase the first choice is for paradibromobenzene (p-C_6H_4 ^{82}Br); dibromobenzene labeled with ^{82}Br (C_6H_4 ^{82}Br) and iodobenzene labelled with ^{131}I ($C_6H_5{}^{131}I$) are employed as well. ^{82}Br is high energy gamma radiation emitter. Its gamma rays can penetrate 1 m soil material. This radiotracer has optimal parameters from technical and radiation safety point of views. The main disadvantage of ^{82}Br is its short-life ($T_{1/2}$ = 36 hours) that makes it difficult to import.

Gaseous methylbromide labeled with ^{82}Br exhibits the best properties as radioactive tracer for leak proof control for both liquid and gas fluids. Methylbromide, CH_3Br is an organic halogen compound. It is a colorless gas at room temperature and a liquid below 4.6ºC or when compressed. It is usually shipped as a liquefied, compressed gas. Gaseous methylbromide is heavier than air; its specific gravity is 3.27 compared to 1 for air.

The gaseous methylbromide is synthesized from potassium bromide irradiated in nuclear reactor in the thermal neutron flux. Conversion of solid potassium bromide to gaseous methylbromide proceeds according to the following reaction:

$$2\ KBr + (CH_3)_2SO_4 \xrightarrow[70^{0}C]{H_2SO_4} 2\ CH_3Br + K_2SO_4$$

The transformation of the solid potassium bromide to gaseous methylbromide is carried out in a mobile chemical reactor, called methyl bromide generator, specially constructed for this purpose. Depending on the type of the generator amounts up to 10 Ci (370 GBq) can be handled and transported. Fig. 62 shows the methyl bromide generator system constructed in Poland.

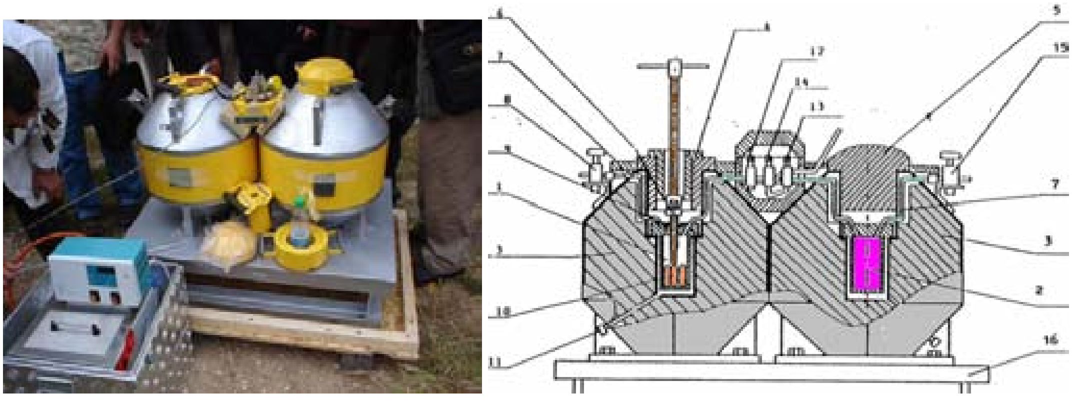


FIG. 62. *Methyl bromide gas generator: converting* $K^{82}Br$ *to gaseous* $CH_3{}^{82}Br$

The methylbromide generator consists of these parts (Fig. 62, right):

1. Reaction vessel, 2. Feeder, 3. Lead container; 4. Protective plug; 5. Protective plug; 6. Breakdown mill; 7. Steel pipe; 8. Valve; 9. Teflon seal; 10. Quartz ampoules with potassium bromide; 11. Pipe for carrying away water supplied by the thermostat; 12. Valve; 13. Valve; 14. Valve; 15. Valve; 16. Steel plate.

The methylbromide generator is transported to the radiotracer test site in two lead containers mounted on a steel plate, a reaction vessel, a dispenser, fittings and a thermostat. The overall weight of the generator is 900 kg.

2.3. RADIOTRACER INJECTION

The selection of injection equipment depends on the physical nature of the stream to be injected, the pressure and the temperature. In general, for the liquid radiotracer injection into liquid stream, a hand-operated hydraulic pump for stream pressures limit up to approximately 50 bar is used; for the gas stream the radiotracer gas is injected with inert gas, such as nitrogen, from a cylinder of pressure exceeding that in the pipeline. For high-pressure liquid and gas systems, special injection systems are needed.

Fig. 63 shows the process of injection of the gaseous methylbromide (10 Ci $CH_3{}^{82}Br$) directly from the generator to the pipeline. A manual air pump with manometer is connected through a flexible metallic tube to the gaseous methylbromide generator from one side (Fig. 63, left) and to the injection valve installed at the pipeline launcher at the other side (Fig. 63, right). Pushing the handle of the air pump the gaseous radiotracer was injected instantaneously directly from the generator to the pipeline.

FIG. 63. Injection of the radiotracer gas methylbromide from the generator to the pipeline using a manual air pump with manometer

2.4. CASE STUDIES: LEAK DETECTION IN UNDERGROUND PIPELINE USING RADIOTRACERS

2.4.1. Radiotracer leak inspection in an underground ethylene gas pipeline

A 10.4 km section of 76 km long underground 250 mm diameter pipeline carrying ethylene gas was suspected leaking since it was not holding the pressure. Conventional techniques failed to detect the leak. Radiotracer pulse migration method was used to locate the leak. Fig. 64 shows the experimental design and position of detectors.

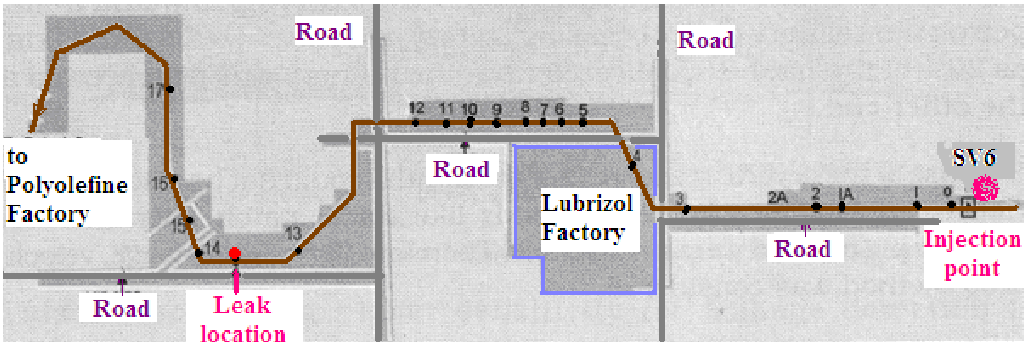


FIG. 64. Radiotracer pulse migration technique; top view showing dug pit locations

About 10 mCi of ^{82}Br in the form of methylbromide trapped in a stainless steel container was used as radiotracer. A sharp pulse of radiotracer was injected through the SV6 side of the pipeline after closing the other end (Polyolefine factory end). Pressure in the both side closed pipeline was maintained to about 3 kg/cm^2 with the help of compressed air. Passage of the radiotracer pulse was monitored with scintillation detectors introduced in the dug pits. Pits were dug along the pipeline projection on soil at approximately every half kilometer distance in non-equidistance manner depending on the accessibility of ground constructions. 17 pits were dug in all.

Radiotracer pulse moved consistently at a speed of about 2 km/h and was monitored up to the pit number 13 within predetermined time, but a detector placed in pit 14 did not show any rise in count rate. This indicated that the gas must have leaked out between the pits 13 and 14. Pressurization from the SV6 end was discontinued. Area between pit 13 and 14 was assayed with the help of hand held scintillation detector. Background count rate started increasing after about 200 meters from pit 13. Maximum count rate of the order of 55000 counts per minute was observed at 244 meters from pit 13. The area was excavated and a hole to the pipeline was visually observed.

2.4.2. Radiotracer leak inspection in an underground naphtha pipeline

Underground pipeline (200 mm diameter, 5 km long) carrying naphtha from a petroleum refinery to a processing factory was suspected leaking as 20% of the naphtha delivered from the refinery was not received at the other end. Because of the several reasons flow of naphtha could not be discontinued. Hence, application of other methods like radiotracer patch migration and pig method were not feasible. Primarily, this was an on-line application that means that the pipeline remained in service (it was not possible to shout it down) and the radiotracer injected from the inlet side. It is called the velocity drop method because monitors the radiotracer pulse intensity decrease with the time and distance from injection. This method is used for relatively large leaks mostly of the order of tens of liters per hour.

10 mCi of ^{82}Br in the form of paradibromobenzene dissolved in kerosene was used as a radiotracer. A sharp pulse of radiotracer was injected from the refinery end. Pits were dug after every 500 meters to reach up to the pipe surface (the underground pipeline was buried in average 1.5 m under soil surface). Scintillation detectors coupled to count ratemeters were placed in the dug pits. The passage of radiotracer pulse was monitored by successive ratemeters. Detectors have nearly the same efficiency and geometry for comparison of results (peak records). Knowing the distance between two successive pits and measuring the successive time between recorded peaks in each pit, the velocity of about 2 km/hour was found till the seventh pit. However, it took about double the time for the diminished peak to arrive at the eighth pit. This sharp drop in velocity prompted for existence of leak between seventh and eighth pit.

There was a railway track between seventh and eighth pit. A large water pond was also seen near the track. The area between seventh and eighth pit was surveyed with the help of handheld scintillation detector. The pond water started showing higher background. The soil near the railway track was excavated where naphtha was seen coming out from the vicinity of pipe which indicated that the pipe was leaking below the track.

2.4.3. Radiotracer leak detection in an underground cooling water pipeline at a thermal power station

a. Description of the problem

Cooling water was being pumped from the water pump to the condensers of a thermal power plant by a 400 meter long buried pipeline (Fig. 65).

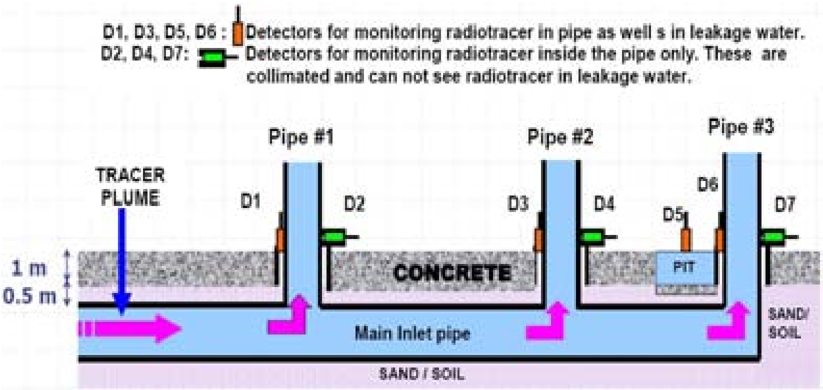


FIG. 65. *Layout of 'teeing-off' pipes and leakage monitoring plan*

Two pumps were feeding water to pipeline, which is made of mild steel having internal diameter of 2240 mm with 12 mm wall thickness. The total volumetric flow rate in the pipeline was 29043 m^3/hour. This pipeline was buried ~ 2 meters deep under the soil surface until it enters the plant building. Inside the plant building, the pipe was buried under one meter thick reinforced concrete floor. Under the concrete floor, there is further 0.5 to 1.0 meter soil cover over the pipeline.

At the distribution point, inside the building, three pipes (labeled as Pipe #1, Pipe #2 and Pipe #3 as shown in Fig. 65) were teeing-off vertically upwards from the main pipeline. Each teeing-off pipe has a metal sleeve around it separating the pipe from the concrete floor. There was a gap (3- 5 cm wide) between teeing-off pipe and metal sleeve.

Leakage water was flowing out from the gap between pipe and sleeve around all three teeing-off pipes. The first teeing-off pipe was supplying water to various services and has volume flow rate of 1543 m^3/hour. The second and third pipes were supplying water to condensers with a volume flow rate of 13750 m^3/hour each. Apparently, much more water was leaking from Pipe # 1 as compared to Pipe # 2 and 3. Further more, there is a pit (~ 5x 5 × 5 cm) between Pipe # 2 and 3 (just adjacent to Pipe #3 as shown in Fig. 65). A small amount of water was also leaking from the pit.

It may be mentioned that a number of plant installations are present in the near vicinity of leakage point and it is not easy/advisable to dig out the floor without knowing exact position of leakage. Apparently, leakage water is coming out around all three teeing-off pipes and in first instance it looks that the leakage is at teeing-off joints. But as mentioned earlier, there is one-meter thick reinforced concrete floor overlying the pipeline and all around inside the building area.

Therefore, any leakage in portion of the pipeline, which is inside the building, can only come out on the floor from these three metal sleeves around pipe # 1, 2, 3 and the pit dug in floor near pipe #3 (Fig. 65). Any leakage in the area outside the plant building has a little chance to appear inside the building because of soil nature and natural drainage conditions. Therefore, leakage may be anywhere in the pipeline after it enters the building. The objective of the radiotracer study is to identify the leakage point(s) so that the repair plan may be prepared accordingly.

b. Experimental procedure

Radiotracer pulse migration method was used to investigate this problem. An activity of ~50 mCi of ^{131}I in the form of NaI solution was injected at the pump inlet in the sump pit close to the suction point. A glass vial containing liquid radiotracer was crushed inside water using a specially designed vial crushing mechanism. Radiotracer injection was monitored at pump outlet using a collimated sodium iodide (NaI) detector of 2”× 2” crystal.

The volume flow rate of cooling water inside the pipeline was 29043 m^3/hour at a pressure of 2 kg/cm^2 and linear speed of around 2 m/s. Therefore, radiotracer flowing inside the pipeline will be traveling fast along with the cooling water. However, when water leaks out, its speed and pressure become lower.

Two radiation detectors were installed side by side at the exit point of leakage water at each teeing-off pipe to detect radiotracer flowing inside the pipeline and radiotracer present in leakage water. So there must be an appreciable time-lag between the arrival, at detectors, of radiotracer flowing inside the pipe and radiotracer present in leakage water. Logically, radiotracer flowing inside the pipeline should arrive the detection point earlier than the radiotracer present in leakage water. Similarly, radiotracer present in leakage water should appear earlier at those radiation detectors that are relatively closer to the leakage point.

Seven detectors (NaI, 2” × 2”) were installed around the suspected leakage points for monitoring of radiotracer present in water flowing inside the pipelines as well as in potential leakage water. Detectors D1, D3 and D6 were installed adjacent to pipe #1, pipe #2 and pipe #3 respectively. These detectors were not collimated and were dipping inside the leakage water coming out from the sleeves of the respective pipes. The purpose of these detectors was to monitor radiotracer present in the leakage water outside the pipes but these could also see the radiotracer passing inside the pipes because these are installed just near the pipes.

Fig. 66 shows the experimental response curves recorded by 7 detectors. Detectors D2, D4 and D7 were collimated with lead shielding and were installed horizontally against pipe #1, #2 and #3 respectively. The purpose of these detectors was to monitor radiotracer passing inside the pipes only, i.e., they were made blind to the tracer in leakage water.

Detector D5 was uncollimated and installed in the pit water. It could see radiotracer inside adjacent pipe #3 as well as radiotracer present in leakage water.

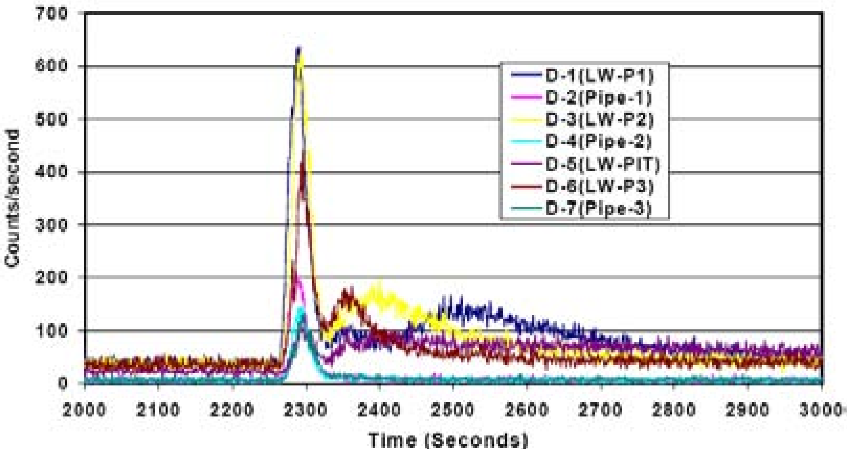


FIG. 66. Radiotracer responses registered by seven detectors

The leakage water from pipe #1, #2, #3 and pit was isolated, on the floor, from each other so that the leakage from one point must not mix with leakage from any other point until it goes away from radiation detectors and is discharged into the drain.

c. Results and discussion

The summary of radiotracer arrival and peak timings at seven detectors is given in Table 4. The comparison between the relative timings of leakage peaks helps determine the leakage points.

TABLE 4. RADIOTRACER ARRIVAL AND PEAK TIMINGS AT DIFFERENT DETECTORS

Detector	D-1 (LW-P1)	D-2 (P1)	D-3 (LW-P2)	D-4 (P2)	D-5 (Pit)	D-6 (LW-P3)	D-7 (P3)
Tracer arrival time (sec)	2266	2266	2269	2269	2272	2272	2272
Peak 1 (signal from pipe)	2291	2287	2292	2293	2292	2296	2298
Peak 2 (leakage)	2349	-	2399	-	2389	2362	-
Peak 3 (leakage)	2497	-	-	-	-	-	-

The arrival of radiotracer at detectors D1and D2 is recorded at the same time i.e., at 2266 seconds. Detector D1 has recorded three peaks; peak 1 is due to tracer flowing inside the pipe #1 while peak-2 and peak-3 are due to leakage. Detectors D2, D4 and D7 have recorded only one peak because they are seeing radiotracer flowing inside pipe #1 only and are blind to radiotracer present in leakage water. The arrival of radiotracer at detectors D3 and D4 is recorded at the same time i.e., at 2269 seconds (3 seconds after radiotracer arrival inside pipe #1). Detector D3 has recorded two peaks, peak-1 is due to tracer flowing inside pipe #2 and peak-2 is due to leakage.

Arrival of radiotracer at detector D5 is recorded at 2272 seconds. This detector has recorded two peaks. Peak 1 is recorded at 2292 seconds and it is due to radiotracer inside pipe #3, while peak 2 recorded at 2389 seconds is due to leakage.

The arrival of radiotracer at detectors D6 and D7 is recorded at the same time i.e., at 2272 seconds (3 seconds after radiotracer arrival at pipe #2). Detector D6 has recorded two peaks. Peak 1 is due to tracer flowing inside pipe #3 and peak 2 is due to leakage water.

Radiotracer responses of un-collimated detectors D1, D3, D5 and D6, which were monitoring radiotracer flowing inside the pipes as well as from leakage water, are presented in Fig. 67. Radiotracer arrival at detectors D1, D3 and D6 is recorded exactly at the same time as it is recorded at collimated detectors D2, D4 and D7 respectively. Detector D5 also recorded the same arrival time as that of Detector D6 and D7. Peak 1 of all the four detectors represents the radiotracer passing through the pipes while peak 2 of all detectors and peak 3 of detector D1 represent the leakage water.

d. Conclusions

- Leakage peak first appears at detector D1 (installed at pipe #1) at 2349 s which indicates leakage near pipe #1 and then it appears at detector D6 (installed at pipe #3) at 2362 s indicating leakage near pipe #3.
- The leakage water near pipe #3 travels backwards in the soil along the outer surface of the pipeline and reaches the detector D5 (installed in pit water) at 2389 s. The same leakage water travels further backwards and reaches detector D3 (installed at pipe #2) at 2399 s. This leakage water travels further more towards pipe #1 and reaches detector D1 (installed at pipe #1) at 2497 s.

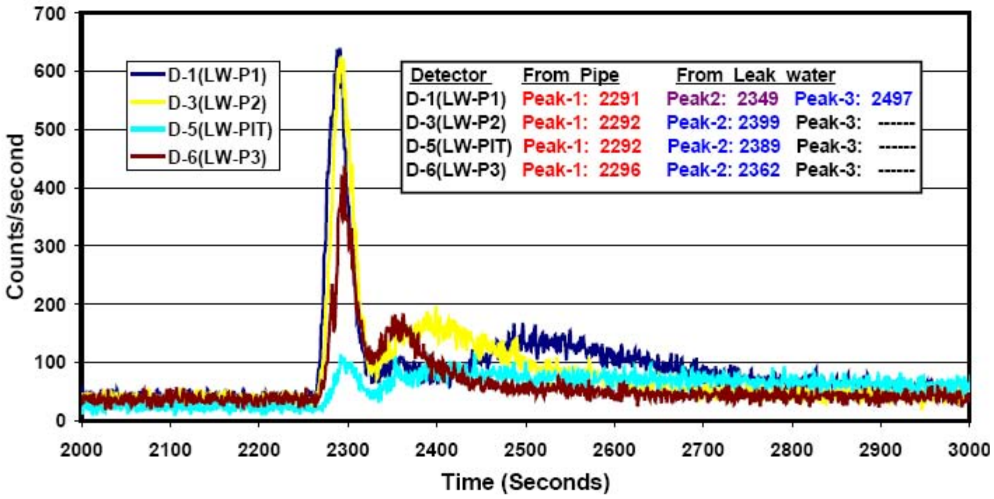


FIG. 67. Radiotracer responses of un-collimated detectors D1, D3, D5 and D6

- The leakage near pipe #1 is not recorded at any other detector except detector D1 installed at pipe #1. However, the leakage near pipe #3 is first recorded at pipe #3 (2362 s) then at water pit (2389 s), then at pipe #2 (2399 s) and later on at pipe #1 (2497 s).
- Leakage peak corresponding to pipe #1 contains maximum of 109 cps while the peak, corresponding to leakage water from pipe #3, arriving at pipe #1 (peak-3 of detector D1 installed at pipe #1) contains 165 cps at the same position. This higher count rate of 165 cps shows a higher leakage rate near pipe #3. This higher count rate is despite the fact that this leakage water is further diluted while traveling from pipe #3 to pipe #1 before reaching detector D1.
- This situation shows that the leakage near pipe #1 is small as compared to leakage near pipe #3. The higher rate of leakage near pipe #3 is maintaining hydrostatic pressure around leakage point and nearby surroundings and is not allowing the leakage water near pipe #1 (which is smaller in quantity hence at lower pressure) to flow towards pipe #2, water pit and pipe #3.
- Leakages were found near Pipe #1 and Pipe #3. Leakage near pipe #1 is small as compared to pipe #3. There is no leakage near pipe #2.

2.4.4. Radiotracer pig test for leak inspection in an underground gas pipeline.

The Polish radiotracer pig was demonstrated during an AFRA regional training course in Libya. 10 Ci of Br-82 methylbromide gas provided by a methylbromide generator was used as radiotracer. The on-line radiotracer test was performed in a 40 km gas pipeline (diameter of pipe 400 mm), which was buried 2-3 m under the soil surface. The radiotracer gas was injected in the operational pipeline under pressure with the aid of compressed nitrogen. After 2 hours the radiotracer pig was introduced to the pipeline through the cleaning chamber for leak detection run. Pig moved together with the transportation gas for around 6 hours. After retrieving the pig at the other end of the pipeline the data was downloaded to the PC to see whether leaks are. Fig. 68 shows the pig records developed in the PC after the pig recovery at the end of the pipeline.

Fig. 68 presents the detection data recorded by the pig during a time interval of one hour. The graph shows the background (red) and two sharp peaks that are coming from two ^{60}Co markers.

The conclusion was that no leak was found in this pipeline.

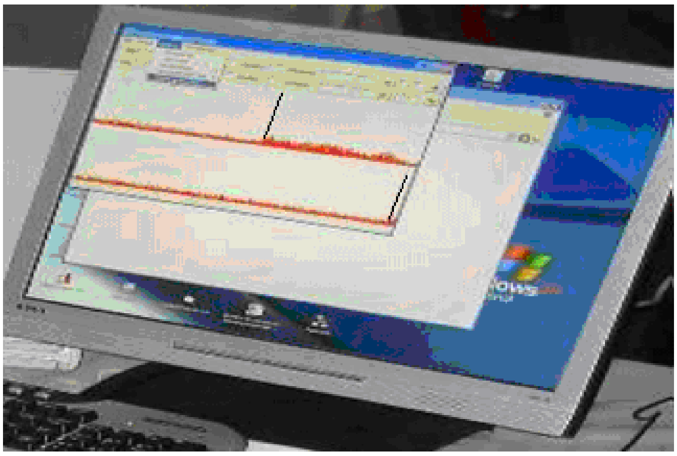


FIG. 68. PC screen showing the pig records; background (red line), markers and no leak

2.4.5. Radiotracer pig test for leak inspection of an underground oil pipeline

An underground oil pipeline in Denmark was inspected for leak using radiotracer. ^{82}Br (as bromobenzene) was used as radiotracer with an activity of some Ci. The pipeline was 106 km long with a diameter of 500 mm. Calibration of the radiotracer pig was performed before the test using various ground material simulators such a sand and ceramic, as well as natural radioactive materials like potassium chloride (which contains the radioisotope ^{40}K) and ^{226}Ra. Calibration provides data for calculation of the requested activity and the expected sensitivity.

Fig. 69 provides the calibration setup (left) and pig records for various standard natural materials (right) obtained during calibration in the test loop trial in the 500 mm diameter pipeline.

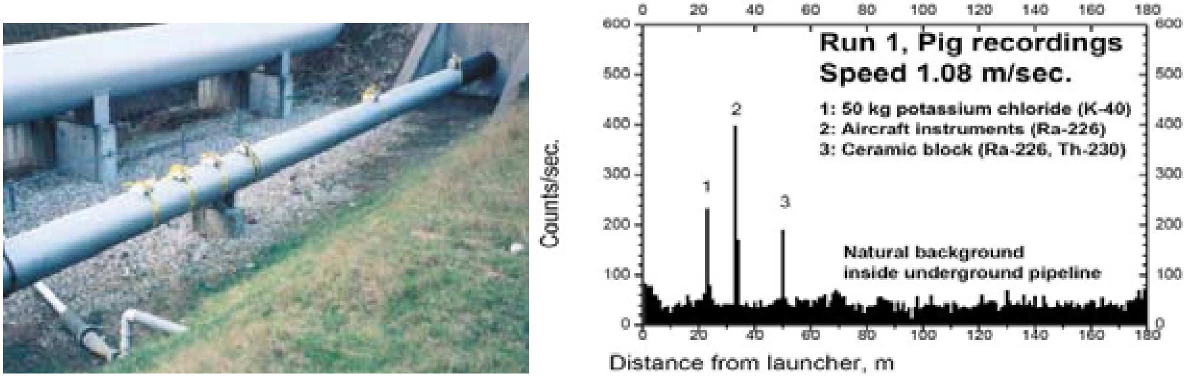


FIG. 69. Pig detection sensitivity calibration in test loop trial

The calibration of the pig has proven to be capable of identifying very small leaks; in oil pipelines carrying 1500 m^3/h, leakages down to 1 liter per hour can be detected. This sensitivity is much higher (10 times higher) than the sensitivity of an acoustic NDT pig. Leakages can be positioned with a precision of less than 1 meter.

A real test of the on-line pig method was conducted in the oil pipeline under the normal operation of the line. The underground pipeline was 106 km long and had 13 valve stations. The oil flow rate was 1500 m^3/h. After recovering and opening the pig, the signal recorded during the test was developed in the PC (Fig. 70). The results indicate no leak peak; the signal is coming only from background from surroundings that have different values along pipeline.

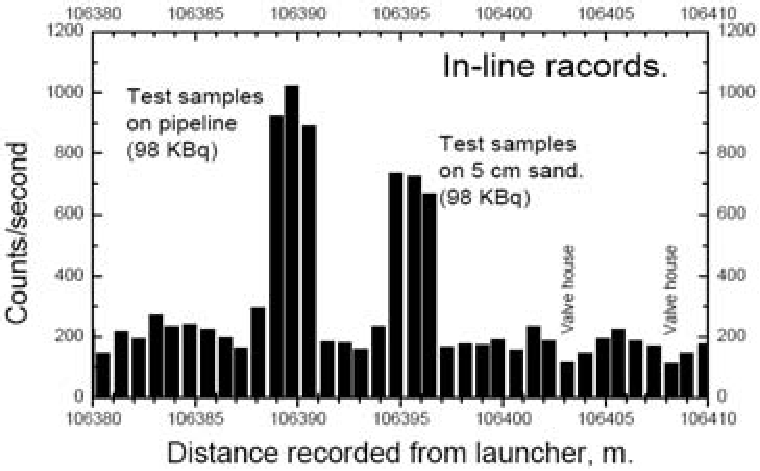


FIG. 70. Pig record

2.4.6. Radiotracer pig test for leak inspection in an underground pipeline

The Indian pig was used for leak inspection in an oil pipeline, which was found leaking. The pipeline was 62 km length (diameter of 300 mm) and buried 1-1.5 m below the ground surface. The pipeline was cut into different sections by maintenance engineers, and each section was individually hydro tested. Out of 62 km length of the pipeline, 59 km was successfully hydro tested and could hold the pressure of 108 kg/cm^2. The section of length 3 km was asked to be tested by radiotracer pig method for localizing leaks. This was an off-line version of the radiotracer pig method.

About 1 Ci of ^{82}Br in the form of aqueous solution of ammonium bromide was used as radiotracer. Diluted radiotracer was filled in the pipe section and was pressurized to 108 kg/cm^2. Since the leak rate suspected was about 40 liters per minute, the pipeline was kept under pressure for about four hours. The pipe section was then thoroughly washed with water. The marker sources (50 µCi ^{60}Co sealed source) were placed in dug pits at an interval of 400 m.

The radiotracer pig was made to move inside the pipeline with uniform velocity using water pressure. After about 4 hours inspection the pig was received at the other end. Data records from the pig data logger were downloaded in a PC and analyzed (Fig. 71).

The obtained experimental results are presented in the Fig. 72. A leak peak was observed between starting point and first marker source signal. Another one was observed between second and third marker signals. These two peaks, other than marker source signals, correspond to two leaks.

FIG. 71. Radiotracer pig data downloaded to a PC

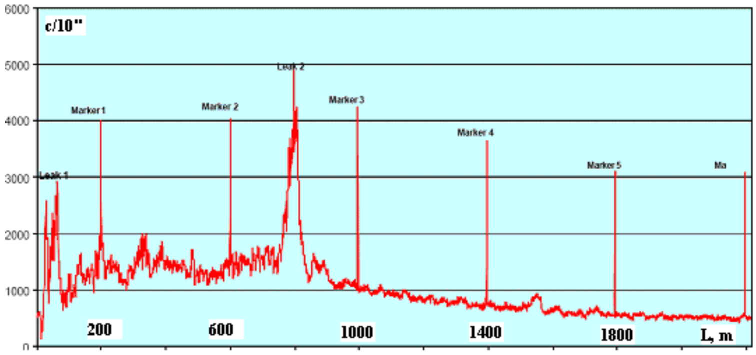


FIG. 72. Radiotracer pig record

Areas around detected leaks were surveyed with a radiation detector to confirm the position of leaks. Background count rate was increased in two places. Excavating the soil, black oil spots were seen (accumulated during the operation of the pipeline), and the background was increasing till saturation of the ratemeter. The holes to the pipeline were visually observed.

2.4.7. Radiotracer pig test for leak location in underground JVPL pipeline

a. Problem

Finished hydrocarbons like diesel and gasoline produced by a refinery in India were loaded in storage tanks of a port terminal before shipping further to other destinations.

The transport from the refinery to the storage tanks was carried out through underground 26 km long 25 cm diameter pipeline, which is known as JVPL pipeline. Drop in pressure was observed in the pipeline during November 2008. It was suspected that the pipeline was leaking, and from the pressure drop per unit time the leak rate of few tens of liters per hour was estimated. Several attempts were made to locate the leak using conventional techniques. Idling of the pipeline was resulting in loss of million of US$. Hence, the radiotracer method was requested to help in locating the leak from this pipeline in a short time.

b. Experiment

Since the pipeline was piggable, the radiotracer detector pig method was used to locate the leak. At distance intervals of nearly 500 m (with some exemptions) pits were dug where the marked ^{60}Co sealed sources (~100 μCi) were placed near the pipeline surface. The suspected section with volume of about 850 kiloliters was isolated (off-line test). About 2 kg of ammonium bromide (NH_4Br) was dissolved in 20 liter of water and was poured in a 1000 kiloliters tank to serve as carrier. 1 Ci of ^{82} Br radiotracer (as ammonium bromide) was introduced to the tank as well (Fig. 73, left).

FIG. 73. Radiotracer introduction (left) and pig launcher (right)

The tank was filled with 1000 kiloliters of water. The mixer was homogenized for about 2 hours using a pump. The homogenized radiotracer from the tank was introduced in to the pipeline. The isolated pipeline section was pressurized to the operating pressure and kept for 6 hours. Then the valves were opened and fresh water was introduced to flush the pipeline to remove the radiotracer. The pipeline was thoroughly washed with water for a few hours until the water radioactivity showed only background reading. The radiotracer detector pig of Fig. 61 was launched to the pipeline through a pipe launcher (Fig. 73, right). The pig was received at the other end of the pipeline after about eight hours.

c. Results

The datalogger of the pig was connected to a PC and the recorded data was dumped in excel (Fig. 74). From the Fig. 74 it was observed that all marker source signals were recorded. Only an additional peak was observed between marker sources 21 and 22 (The distance between markers was 2100 m). The distance between the suspected peak and both the marker sources was calculated based on relative position of the leak peak from the two marker peaks. Location of leak was about 1084 m from marker source 21 and about 1016 m from marker source 22. Based on the results, soil was excavated above the pipe in this location, and water was seen oozing out from the pipe through a very small crack of about 3 mm length (Fig. 75).

d. Conclusion

The radiotracer detector pig method was successfully used to exactly pinpoint location of the leakage from the underground JVPL pipeline.

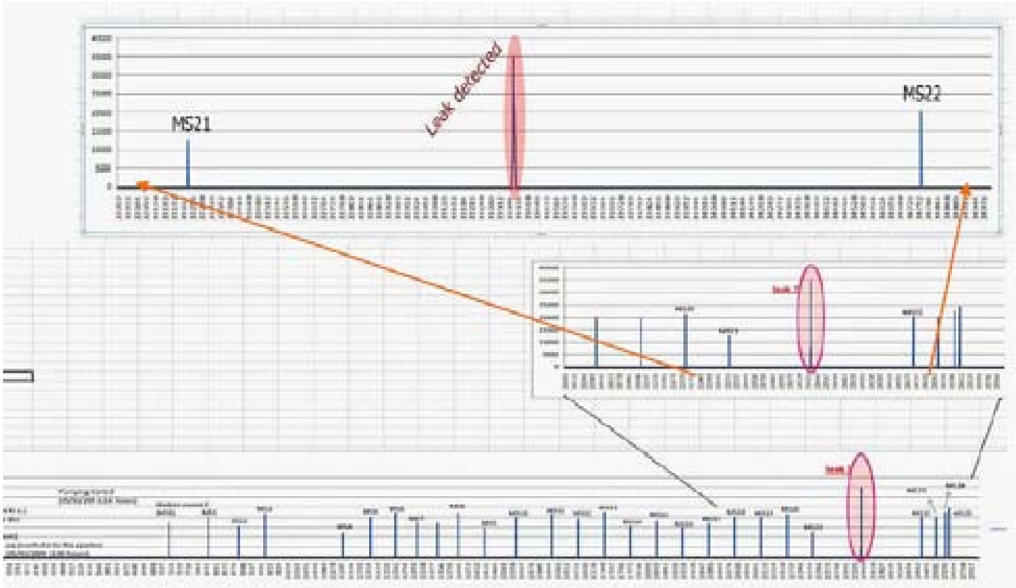


FIG. 74. Excel plots showing marker sources and the peak corresponding to the leak

FIG. 75. Leak visually confirmed

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Annex

GUIDELINES FOR TESTING FEED/EFFLUENT HEAT EXCHANGER SYSTEMS USING RADIOACTIVE TRACERS

GUIDELINES FOR TESTING FEED/EFFLUENT HEAT EXCHANGER SYSTEMS USING RADIOACTIVE TRACERS	C. No.	
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CONTENTS

1. OBJECTIVE

Radioactive tracer techniques are widely used in the oil, gas and chemical industry for detecting leakage in banks of feed /effluent heat exchangers. These guidelines are written to show the steps that should be taken to enable the leakage tests to be carried out in a systematic manner. It is also intended that the guidelines can be incorporated into the service providers own quality system, whilst at the same time giving sufficient latitude to enable the supplier to vary the procedure to meet specific test requirements.

2. SCOPE

The guidelines shall be applicable to leakage testing in banks of feed/effluent type heat exchangers using radioactive tracer techniques.

3. METHOD STATEMENT

A sharp pulse of suitable radioactive material is injected into the process material, upstream of the exchanger bank on the high pressure side. Any leakage within the system will be from the high pressure side to the low pressure side. Because the radioactive tracer mixes thoroughly with the inlet fluid, if there is a leakage within the system some of the radioactive tracer will enter the low pressure side. Suitable deployment of sensitive radiation detectors will confirm the presence of a leak and indicate which one of the exchangers is leaking. Detailed analysis of the data will enable the size of the leak to be quantified.

4. RESPONSIBILITIES

To enable leakage tests to be carried out efficiently, responsibilities should be clearly defined prior to any work taking place. They usually take the following format:-

Client – Responsible for supplying the service provider with sufficient information to enable the work to be carried out, safely, and efficiently in an agreed manner. It is expected that he will provide such help and assistance as could reasonably be expected between contractor and client, be responsible for providing safe access and issuing an appropriate work permit.

Projects Manager - Person ultimately responsibility for the planning and execution of entire job. This includes defining the work scope, allocation of sufficient trained and competent manpower and resources to conduct the work. He is responsible for ensuring compliance with any statutory legislation to ensure protection of the workforce, members of the public and the environment. He is ultimately responsible for interpretation of the obtained data and supplying a suitable report to the customer within an agreed time period.

Senior Field Technician – The person on-site responsible for carrying out the instructions of the Projects Manager. He shall be responsible for ensuring that the site work is carried out safely and in accordance with the agreed workscope. He will ensure that suitable barriers and warning signs are deployed so as not to compromise the safety of the site workforce and members of the public.

Junior Field Technician – Depending upon the complexity of the proposed work there will be one or more junior field technicians. They will be responsible for safely and efficiently carrying out the instructions of the Senior Field Technician.

5. WORKSCOPE PLANNING

Prior to carrying out any work the Projects Manager should agree with the client the objectives of the work. He will need to ascertain the composition of fluids within the system, the temperature and pressure inlet and exit each exchanger and also the phase composition. He must ascertain the flowrate through the system and agree the sensitivity of the test.

6. EQUIPMENT REQUIREMENTS

Equipment required for on-line feed effluent heat exchanger leakage testing will depend upon the precise nature of the agreed work. It will comprise the following:

- Suitable radioactive tracer
- Suitable injection equipment
- Suitable detecting system
- Suitable data acquisition system
- Appropriate ‘tools of trade’ such as radiation and contamination monitors, barriers, warning notices, activity handling tools, protective equipment

It is recommended that a check list is prepared and items checked off before shipment

7. EXECUTION OF WORK AT WORK SITE

Upon arrival at the work site the Senior Field Technician will ensure that a suitable permit to work is obtained.

- He will inspect the work site and ensure that there is safe access.
- He will visually inspect the type A container to ensure that it is not damaged and confirm by monitoring that the radioactive material is still present.
- He will immediately report any abnormalities and after consultations with the Project Manager take such remedial action as is required.

- He will carry out the leakage tests in the agreed manner.

Any deviation to the agreed leakage test procedure must be approved by the Project Manager after due consultation with the client.

8. DATA PROCESSING AND REPORTING

After carrying out the tests the data will be processed, and the findings relayed to the client. These will be confirmed in a written report to the customer within 14 days or in such time as agreed between the two parties. If no leakage is detected the report must show the minimum detectable limit for the tests.

APPENDIX 1- SELECTION OF RADIOTRACER

When carrying out leakage tests it is essential that the radioactive tracer that is used can physically get to the leakage location on the high pressure stream in order to pass from the high pressure stream to the low pressure stream. Liquid organic, liquid aqueous, gaseous or a mixture of these phases can be encountered. It may be necessary to inject more than one type of radiotracer in order to be certain that the radiotracer will reach the leakage location. This is particularly so when phase changes occurring within the system. It may for example to inject a liquid radiotracer and a gaseous radiotracer.

Among the parameters that should be considered for the selection of a radiotracer are:

- the physico-chemical behaviour, the half life, the specific activity, the type and energy of radiation.
- the physico-chemical behaviour should usually be the same as the material being traced.
- the half life of the radiotracer should be comparable to the duration of the experiment; if the half life is short we can inject a high activity.
- the type and energy of radiation should be sufficiently high to penetrate through the material(s) between the process stream and the detectors. The wall thickness will have a significant effect upon the amount of radiotracer that is required.
- The availability of the radioactive tracer

The specific activity after test is an important factor to be considered from the safety point of view.

Before finally selecting a particular radiotracer a safety assessment should be carried out.

APPENDIX 2- CALCULATION OF QUANTITY OF RADIOTRACER REQUIRED.

Several factors can affect the calculation of the amount of radiotracer that is required. These include the following:-

Sensitivity of the test – As a general rule the more radioactivity that is injected, then the more sensitive the test becomes and the minimum detectable leakage rate becomes smaller. There are however limits on the amount of radioactivity that it is acceptable to use on a particular test. The use of radioactive material must be justified so that the advantages outweigh the disadvantages. Beyond a certain amount the test can no longer be justified. This quantity must be calculated on each occasion using data supplied by the ICRP.

Detector efficiency – Usually sodium iodide crystal detectors are used. The efficiency of detection will vary depending upon the physical dimensions of the crystal and its physical condition. The most efficient detectors should be used to maximise the sensitivity of the test. It is not always possible to have all the detectors with the same efficiency and each detector must be calibrated prior to the experiment so that the areas under the peak can be corrected appropriately.

Flow rate within the system - the detector response is dependent on the time that the radioactive tracer is passing in front of it, consequently for higher flows we need more radiotracer.

Wall thickness – The detector response will get smaller as the wall thickness is increased.

APPENDIX 3 – INJECTION EQUIPMENT

The injection equipment depends on the physical nature, the pressure, the temperature and the toxicity of the stream into which the radiotracer is to be injected.

A variety of pumps can be used, but each must be appropriate for the duty that it has to perform. Such pumps may include hand-operated hydraulic pumps, or air operated pumps for stream pressures of up to about 35 bars, for liquid injection into liquid streams. For injection of radioactive gases a system using inert backing gas, such as nitrogen, from a cylinder having a higher pressure than the line pressure may be used.

For high-pressure liquid and gas systems, special injection systems are needed.

It is important to ensure that the injection rig has a higher rating than the duty that it is required to perform.

APPENDIX 4 – CALCULATION OF LEAK SIZE

When calculating the leakage size consideration should be given to the following:-

Detector geometry: if the lines carrying the medium under investigation are of different size and wall thickness, then the volume of material producing the response at the detector may be different or reduced by the extra metal of the wall. An appropriate correction must be made.

Difference in pipe diameters: the detector response is dependent on the time the radioactive tracer is passing in front of it and it is inversely proportional to the velocity.

After all of the relevant factors have been taken into consideration the leakage size can be calculated by comparing the size of the leakage peak with the size of the inlet peak.

It is normal to consider that leakages of approximately 0.1% of the total flow rate can be measured using this technique. However, each case must be calculated individually taking into account the physical features of the equipment under test. Great care must be exercised when using this method, as confusion can be caused by erroneous responses of the leak detector from adjacent pips or vessels carrying the injected radiotracer. In closely-confined congested areas on modern plants, it is generally desirable to surround the leak detector with thick lead shielding so that it is unresponsive to possible extraneous influences.

APPENDIX 5 – EXAMPLE OF TECHNIQUE

The following Fig. A-1 gives an indication. This technique is probably the most common and involves the injection of a suitable radiotracer into the process stream, which is suspected of leaking, and seeking the presence of that tracer in the outlet. This can be done by using sensitive radiation detectors mounted externally on the outlet pipes. The system shows one exchanger only. The principle is the same for multiple exchangers.

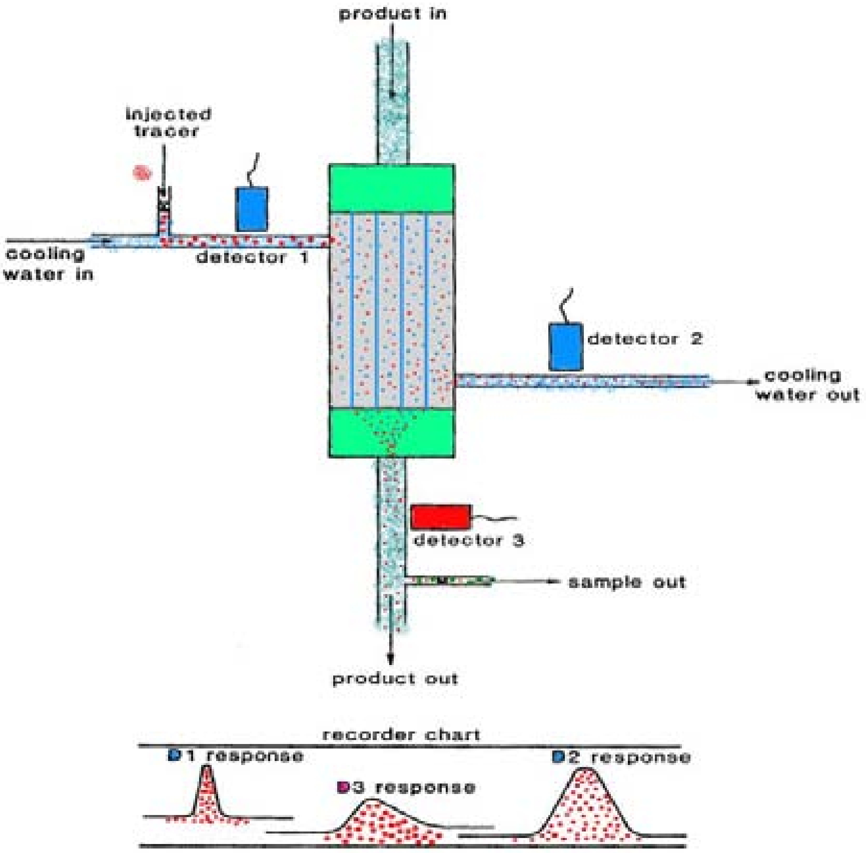

Fig. A-1: Leakage detection using external detectors

The sharp pulse of activity is injected into the inlet on the high pressure side and detectors 1, 2 and 3 are positioned as shown to monitor its passage through the exchanger. Typical detector responses are shown in the Fig. A-1. Detectors 1 and 2 show the inlet and outlet responses, whilst detector 3 will only respond if there is any leakage from the shell side to the tube side of the exchanger. Calculation of the amount of leakage is made by comparison of the respective areas under the main inlet peak and the leak peak.

Several factors can affect the calculation of the leak size and corrections should be made for the following, if necessary:

- ***Different detector efficiencies:*** it is not always possible to have all the detectors with the same efficiency and each detector must be calibrated prior to the experiment so that the areas under the peak can be corrected appropriately.
- ***Detector geometry***: if the lines carrying the medium under investigation are of different size and wall thickness.

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