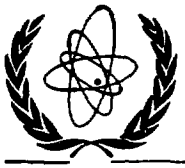


International Atomic Energy Agency

INTERNATIONAL ATOMIC ENERGY AGENCY

REPORT
of the
Consultants' Meeting
on
"Real-time Nondestructive Monitoring of Wear and Corrosion using the Thin Layer Activation Technique"

IAEA Headquarters, Vienna
15-18 May 1990

Introduction

The Consultants' Meeting of the International Atomic Energy Agency on "Real-time nondestructive monitoring of wear and corrosion using the thin layer activation technique" was held at the Agency Headquarters from 15 to 18 May 1990.

The Consultants' Meeting (CM) brought together experts in the field of thin layer activation and the industrial applications of charged particle accelerators. The main purposes of the meeting were:

- to discuss the present state-of-the-art of the thin layer activation technique and its application for the real-time nondestructive monitoring of wear and corrosion;
- to assess the possibilities and potential limitations in introducing this activity in developing countries;
- to identify and define concrete future lines of activity, if any, where the Agency's efforts would have the greatest impact and significance.

It was underlined by all the participants of the CM that the accelerator-based methods as a whole, including thin layer activation technique (TLA), should be considered as a prospective field for the fruitful co-operation between countries with different levels of industrial development.

C O N T E N T S

Thin Layer Activation Techniques in Research and Industry

T W Conlon
Accelerator Applications Department, MMTD
AEA Technology, UK

1 Introduction

Thin Layer Activation is one of a general class of methods depending for its application on the radiative properties of accelerated ions in materials.

Many such accelerator based methods rely on the inherent atomic and nuclear properties of fast ion beams and their interaction with materials. By selecting beams of species and energy the depth of interaction can be precisely controlled over a very wide range from at least nanometres to centimetres. This covers the range of depth important for material surface properties such as friction, wear, corrosion, catalysis, oxidation etc. - phenomena of great importance for both the nuclear and many nonnuclear industries. Hence, the increasing deployment of such techniques both within and outside of the nuclear industry (from which they largely evolved) where the importance of surface properties can justify the attendant costs involved.

An understanding of fundamental processes occurring in the slowing down and stopping of slow ions in matter has contributed to the widespread use of ion implantation (II) for the modification of materials. In general, at higher energies the ion-materials interaction becomes more benign and can be used to probe nondestructively materials characteristics by so-called ion beam analysis (IBA). At still higher energies nuclear reactions occur which increase the scope of IBA, e.g. resonant and nonresonant reaction analysis and allow techniques based on activation such as thin layer activation (TLA) to be developed.

2 Thin Layer Activation

Nuclear reactions of light and heavy ions at medium energies can be tailored to generate trace quantities (typically 1 in 10^{10}) of radioisotopes with a well defined depth distribution in the near surface of materials. Such thin layer activation techniques, the principle of which is shown in fig. 1(a) were virtually unknown a decade ago, yet are now extensively used to provide radioisotope-labelled surfaces for a wide variety of uses. The surface label can range in depth from microns to millimetres, thus providing a scale against which microscopic changes in the surface (caused by material loss, change in morphology or porosity) can be determined in the operating environment of the material. The basic thin layer activation technique was initially limited to certain materials, particularly metals, capable of providing radioisotopes by direct activation. The method has undergone extensive development to the stage where it can now be used to label any material and particularly nonmetals with a wide choice of radioisotope and depth distribution. These developments and case studies of uses have been reviewed (see, for example, refs. 1, 2 and bibliography therein); current developments and future trends are noted below. Typical uses include the accurate measurement of wear, erosion and corrosion losses: these can be done on-line to the process stream and with sensitivity ranging from atomic layers to micrometres. The method is used as a research tool to aid the design of a wide range of automotive components and machine tools, for the improvement of oil formulation, and in determining flow and solute conditions needed to control and minimise corrosion. An example of on-line work to determine corrosion rate is given in figs. 1(b) and (c).

The relatively new area of corrosion monitoring is now beginning to grow very significantly as illustrated below. This growth largely reflects the enormous economic benefit to be achieved. For example, in the power industry corrosion failure can lead to plant being unexpectedly taken out of duty at a cost to tens of millions of dollars per day. Reliable techniques that can forewarn of plant failure are thus at a premium.

Conventional corrosion monitoring techniques are either on-line of off-line. Small samples of the containment material are inserted into pipe lines and periodically removed for weight loss measurements (off-line). On-line

electrical resistance probes can be inserted and the change of resistance measured. The TLA method can be applied both on- and off-line and has a number of advantages over competing methods; i.e. it is not prone to the edge-corrosion complications of weight-loss coupons and allows flush-mounting of probes to experience actual conditions at the containment wall - a feature difficult to engineer into resistance probes. Another advantage is that it allows the performance of actual components to be assessed under operating conditions (such as illustrated in figs. 1(b) and (c)). A corrosion monitor based on flush-mounted TLA probes has recently been developed [3], built and licensed under patent. The system has the potential for widespread use in the oil and petrochemical industries where access fittings are extensively deployed.

In this design an activated coupon fig. 1(d) is installed through a conventional access fitting (of which there are typically hundreds in modern petrochemical plant) on the end of a hollow plug. A detector can be inserted periodically into the hollow plug to measure the change in activity and therefore the metal loss from the coupon. A self-contained control box gives a direct display of the metal loss. The system is sensitive to submicron loss and incorporates a high degree of reliability with built in calibration, design for intrinsic safety, rugged construction, operating up to 100° C and portability. Future developments will extend to permanently wired in systems for multiplexing to the process control room.

As noted above various techniques are available 'off-the-shelf' to monitor corrosion of oilfield production plant in topside locations, using access fitting technology, for example. In contrast there is little technology to monitor corrosion directly in sub-sea pipework systems. Within the last year or so [4], a new non-intrusive diver-operated instrument system for sub-sea corrosion monitoring of oil production pipework has been developed and is currently undergoing trials.

Another advantage of TLA over other monitoring techniques is the considerable potential that it offers for future development. For example:-

(i) advanced methods using at least two radioisotopes with different depth distributions have been shown to give information on the

evolving morphology and porosity under operating conditions. (See Section 4.2 below.)

(ii) the availability of fast recoil techniques made possible by use of energetic heavy ion beams is enabling a universal activation method (not limited to metals) to be developed. This could allow all of the methods formerly developed for metals (or more precisely conducting media) to be applied to materials such as plastic and ceramics which are increasingly replacing metals in many technological applications. This recoil technique recently played a crucial rôle together with ion implantation in a programme to aid the development of improved hip-joint prostheses (ref. 2 and Section 3.2 below) and is likely to contribute to the assessment of the usefulness and durability of ceramics in a number of areas.

(iii) solid state processes operating at high temperature (diffusion) and under very active chemical conditions (leaching) are proving amenable to study by the use of radioactive tracers injected by recoil techniques. The production and injection of suitable radioisotopes traces to follow the behaviour of individual isotope species often taxes the current state of knowledge of nuclear physics reaction mechanisms, as well as the solid state chemistry of fast recoil ions in materials, and provided an impetus for future basic work in both areas.

3 Applications of TLA in Research and Industry

Table 1 lists a number of key applications of TLA in research and industry. The major applications in the power industries were discussed briefly above. Case studies in fusion, medical research and in the transport industry are given below.

3.1 Ion - Erosion in Fusion Tokamaks

Electrical plasmas in controlled thermonuclear fusion devices cause erosion of the containing wall by sputtering with consequent contamination of the plasma and enhanced radiation (energy) loss. An important criterion to

determine container lifetime and plasma temperature is the rate of erosion of the containing wall. DITE (Divertor Injector Tokamak Experiment) is one of the UKAEA's major fusion devices and a forerunner of the large European project JET. One of the main features of the device is the divertor which deflects heavy metal impurities out of the main torus and focusses them onto a Mo collector plate (fig. 2). The erosion of potential main wall materials can be simulated by looking at the erosion of samples which can be placed for test purposes on the Mo collector plate. Titanium is one such material.

A titanium strip was activated by the $^{48}Ti(p,n)$ reaction to ^{48}V(half-life 16 days) to a depth of 25μm and placed on the divertor plate as shown in fig. 2 (ref. 5). The activity was detected by a NaI crystal in air outside the main magnetic coils of DITE and monitored while plasma pulses of hydrogen ions are an equivalent temperature of 10^7K were fired. The technique proved sensitive enough to detect an erosion rate of 0.2μm after 60 such pulses as shown in fig. 3. The slope of the solid line corresponds to a loss of 3.54±7 nm/pulse (the broken lines show the average standard deviation due to counting statistics); this value is between ten and a hundred times higher than expected from sputtering erosion alone and evidence for other predominant loss mechanisms, such as arcing, in the plasma device.

The extension of such studies to the much larger JET machine and its successors is an intriguing possibility.

3.2 Bio-engineering Technology

The use of radioisotope labels has made possible many key advances in medicine and biology by allowing, for example, normal physiological functions to be followed in situ. A recent example which continues this tradition and demonstrates the diversity of current uses of thin layer activation techniques in conjunction with ion implantation in a programme of development of bio-engineering materials (ref. 2).

The use of ion implantation to induce hardening in many alloys including those of titanium, as well as the ability of TLA to monitor submicron changes in both metallic and non-metallic substrates, were noted above. The

advantages of both were recently brought together in a successful programme to identify ways of improving the durability of hip joint prostheses - a programme which made use of no less than four major ion accelerators; a Cockcroft Walton machine for ion implantation, an AVF cyclotron and tandem for activation and a Van de Graaff for element analysis.

Prosthetic hip joints (fig. 4) comprise a metal femoral component, for which titanium is a favoured material, and an acetabular cup made of ultra-high molecular weight polyethylene. During use the joints can wear, which results in the production of wear debris which after many years may cause inflammation and other clinical problems. This has prompted the study of a variety of surface treatments - ion implantation, ion beam mixing, and sputter ion plating - which might improve the wear resistance of titanium alloys against polyethylene.

The most successful treatment has been ion implantation, which has been developed for improving the wear resistance of tools and components. In the hip joint programme nitrogen was introduced into a titanium alloy (IMI 318) to improve its wear qualities.

A special wear tester was devised for the study enabling pin-on-disc tests (titanium alloy pins on revolving polyethelene discs) to be carried out under liquid. Bovine serum was used as the medium for the tests to simulate, as far as possible, wear processes in body fluids. Wear measurements were obtained by means of thin layer activation techniques. The titanium was directly activated to produce ~5μCi of ^{48}V over a depth of 100μm by the reaction $^{48}Ti(p,n)^{48}V$. The acetabular cup was activated by recoil implantation of ^{7}Be generated in the reaction $Li+H \rightarrow {}^{7}Be+n$ from a sacrificial target of polyethylene.

Sensitive measurements of components surface loss were made, without interrupting the test cycle, by measuring the accumulation of radioactivity in the wear debris. Moreover, since both titanium and polyethylene components were activated, a further important process, the transfer of material from one surface to another, could be investigated.

The dramatic reduction in wear rates (by a factor exceeding 400) achieved using nitrogen implanted titanium suggests that hip joints made of this material would operate for over 30 years without pronounced wear. As a result, wear debris would be minimal and the possibility of adverse reactions with body tissues would be reduced.

3.3 Automobiles: "Greener" Emissions

Demands for a cleaner environment have led to the use of catalytic converters and the trend to reduce all forms of exhaust emissions. This in turn requires methods of lowering oil consumption and wear rates particularly in automobile engines.

For wear studies components which have been activated include cam followers, cylinder liners, valve seats, fuel injection equipment, steel tubes and bushes and a variety of machine tools. A major use of the technique is in engine testing of lubricants and fuels. A typical example is given in ref. 6.

Other participants (ref. 7) cover this area of application in more detail so no further discussion is provided here.

4 Future Developments

The growing experience of the successful (and cost effective) applications of (conventional) TLA in the study and quantification of surface loss in mechanical, chemical and electrical systems strongly suggest an eventual market for lesser known variants of the technique, such as fission fragment TLA, multi-layer TLA and recoil implantation, the latter has already been dealt with in principle and in a biomedical application above. The other two are described below.

4.1 Fission fragment implantation of TLA isotopes

Fission fragment implantation utilizes a portable long-lived fission fragment source, for example ^{252}Cf, to generate fission fragments with suitable half-lives and gamma-ray signatures to serve as TLA indicators.

Figure 5 shows the profile for implantation into iron of radioactive ^{140}Ba and ^{103}RH (half-lives 13 days and 39 days respectively) produced following beta-gamma decay from primary fragments from a ^{252}Cf source. The source strength used is typically 100 μCi allowing usable products to be laid down in a few days. The average depth of implantation is limited owing to energy distribution of fragments from the source. The width of the distribution is controlled by the angular acceptance of the substrate (which was restricted for the data in fig. 5). Up to now the shallow activation depths achieved and long implantation times required have restricted the applications of this process. However, the advantage of a portable 'activation' source may be overriding in some applications.

4.2 Multiple activation profiles

There are some mechanisms for surface removal for which material loss is substantially non-uniform: for example, certain well recognized conditions of corrosion progress by local attack, with the formation of deep pits in which rapid chemical activity occurs in preference to the rest of the surface. The depth of such pits can dramatically exceed the average corrosion depth determined, for example, by weight-loss measurements or single-layer activation, and the detection of such local attack my be crucially important. A method of detecting the occurrence of such local attack has been devised and developed (ref. 1). The method is based on the introduction to the surface of two (or more) layers of radioactivity with different depth profiles and different gamma-ray signatures. This double layer activation provides the first stage of improvement over the standard one-layer method. Two different active layers can be produced by activating the substrate separately with two different ion beams. However, by means of a deuteron beam two suitable layers can be produced for iron and steels in a single beam exposure (ref. 2), as shown in fig. 6(a). The active species in this case is ^{56}Co produced in a relatively shallow layer near the surface, and ^{57}Co produced to a depth of about 200 μm. The detection of non-uniform surface loss is achieved by comparing the loss of ^{56}Co from the shallow layer with the loss of ^{57}Co from the deep layer by monitoring the active area directly (alternatively the increase in activity of the corrosion medium could be monitored). If uniform loss of surface occurs, as is often the case in conventional wear situations, then the locus of points for ^{56}Co

loss versus ^{57}Co is shown in fig. 6(b). If local attack occurs then the loss of ^{56}Co from the shallow layer will be lower than that expected for uniform loss, so under local attack the shallow layer loss will be smaller than that indicated in fig. 6(b) for a given deep layer loss, and indeed the locus of points generated in that case depends upon the shape of the pits thus formed. For example, fig. 6(c) shows typical results for conical shaped pits, while fig. 6(d) shows the results for deep spherical or bottle-shaped pits formed by material removed by undercutting the surface. Thus by monitoring the change in activity of the two layers, it is possible to detect not only the occurrence of non-uniform surface loss but also to obtain information on the surface morphology. Moreover this can be done non-destructively and non-invasively. It is clear that more extensive information on pit size distribution and progression could be obtained with the use of more than two layers.

5 Conclusions

TLA is one of a number of accelerator based methods that are finding extensive use in research and industry; another area of note is the micro-analysis of materials with MeV ion beams.

In materials technology a major trend is the gradual replacement of metals and their alloys with new materials, such as polymers and ceramics, for a wide variety of uses. It would be surprising if accelerator-based methods such as those noted above were not to play a major rôle in providing rapid and economic methods of assessment in both laboratory and plant for these materials too. However, in contrast to metals many of the new materials are electrical insulators whose response to MeV ion energy deposition is quite unlike that in metals with their high electronic mobility. For insulators this leads to a wide (at present often bewildering) variety of observed effects including ion induced adhesion or stitching of polymers to metals (already being examined as the basis of new coating technology), the formation of ion tracks and latent porosity in solids which can be developed on etching to macroscopic dimensions, the modification of interface reflectivity, the enhancement of surface erosion, etc. These and other as yet poorly understood effects promise great scope for increasing interplay and synergy in the nuclear and materials applications of accelerators.

References

1 T W Conlon, Contemporary Physics 23 (1982) 353.

2 T W Conlon, Contemporary Physics 26 (1985) 521.

3 J Asher, T W Conlon, B C Tofield, S Sugden and P F Lawrence, Paper No 131 NACE Corrosion '86, Houston, TX, USA (March 1986).

4 P H Schwabe, J Asher, S Sugden, N Nash, UK Corrosion '89 (to be published).

5 D H J Goodall, T W Conlon, C J Sofield and G M McCracken J Nucl Mat 76/77 (1978) 492.

6 R Evans, Wear 65 (1980) 311.

7 B Jeanneau, A I Leonov, I Mahunka, H Schweickert current proceedings.

Table 1

TLA in Research and Industry

Application	Topic		
Research	1	Ion-Erosion in Fusion Tokamaks	
Power	2	Erosion-Corrosion in power stations	{ nuclear, conventional }
	3	Corrosion off-shore	{ top-side and sub-sea
Medical	4	Bio-prostheses eg Hip joints	
Transport/ Environmental	5	Automobile: 'Greener' emissions	

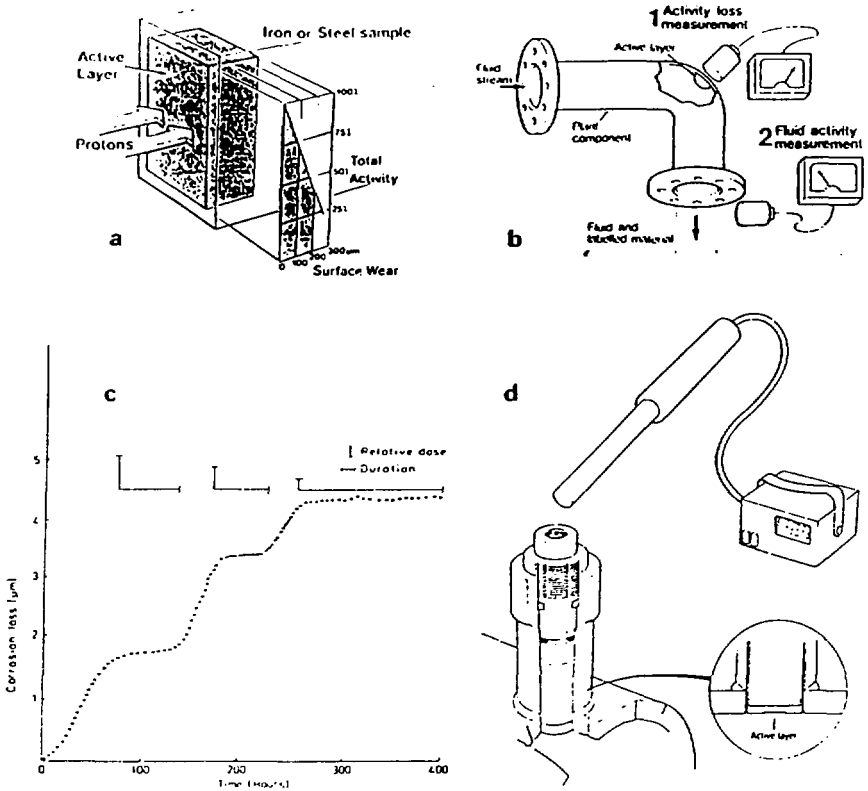


Fig. 1 (a) Thin layer activation of a metal (e.g. iron or steel) by a high energy ion (proton) beam. (b) TLA measurements of an activated layer within the pipework of an operating plant. Two methods are available as shown. The most widely used is method 1. (c) TLA is extensively used to monitor, on line the effects of feed water chemistry (oxygen dose in the figure) on plant corrosion loss rates. The technique has major advantages over conventional methods, giving sensitivity to submicron changes and enabling preventative measures to be rapidly assessed on line. This can give substantial savings in material, engineering costs and plant downtime. (d) Schematic diagram of the in situ TLA corrosion monitor probe and instrument.

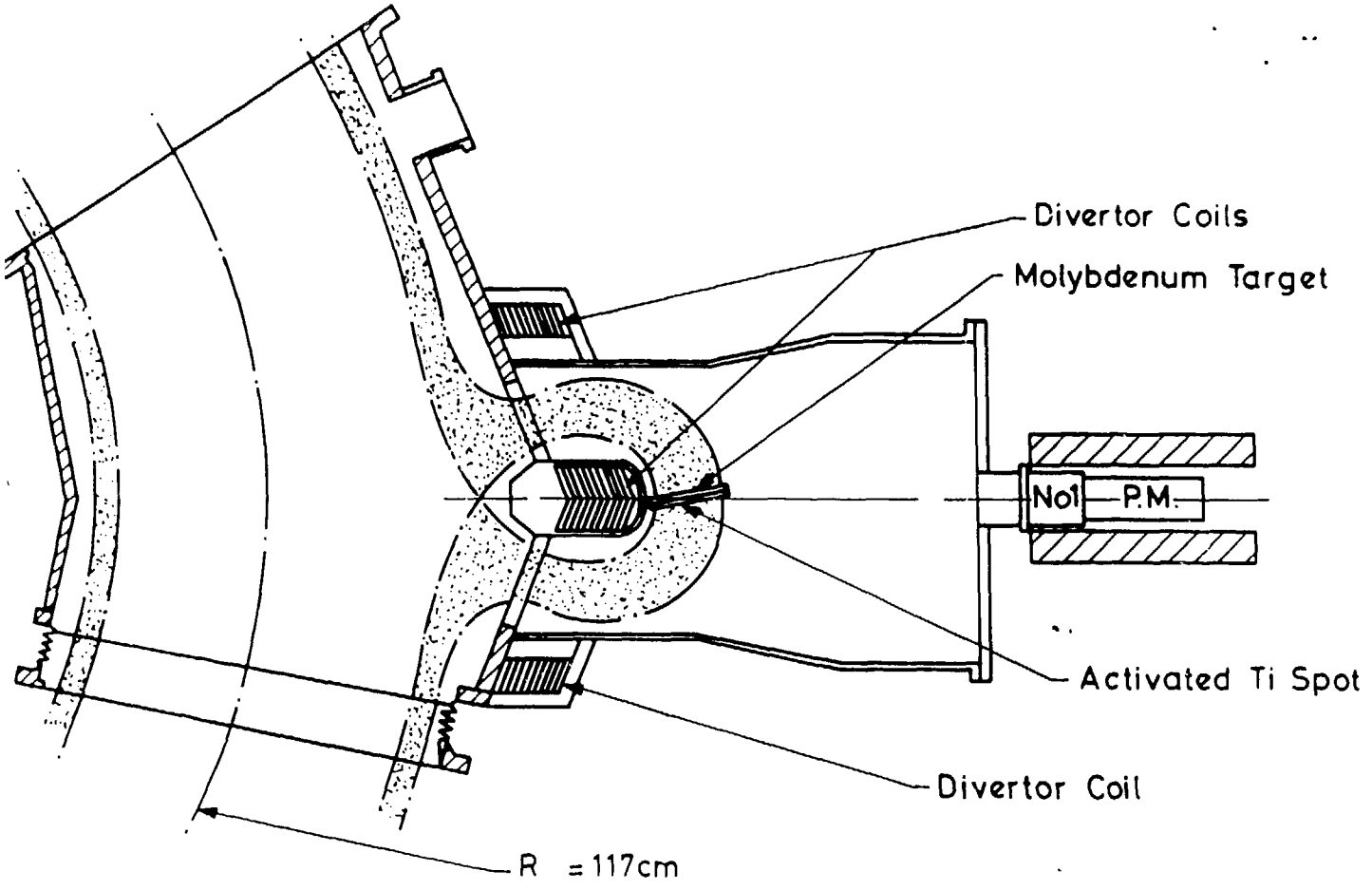


Fig. 2. Schematic diagram of the sector of the DITE torus containing the divertor channel, showing the activated target and the γ-ray counting system.

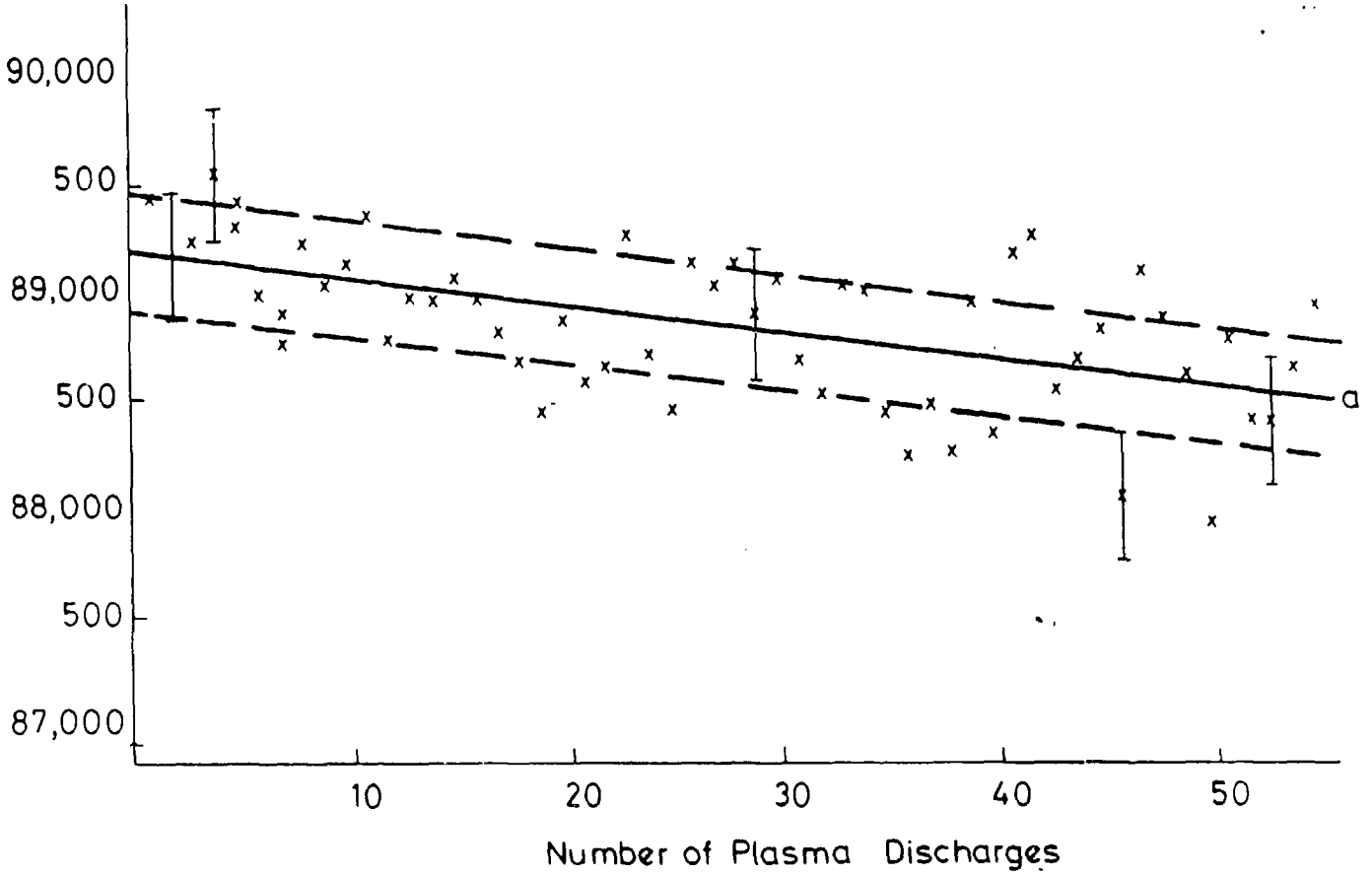


Fig. 3. Erosion rate of an activated specimen in DITE.

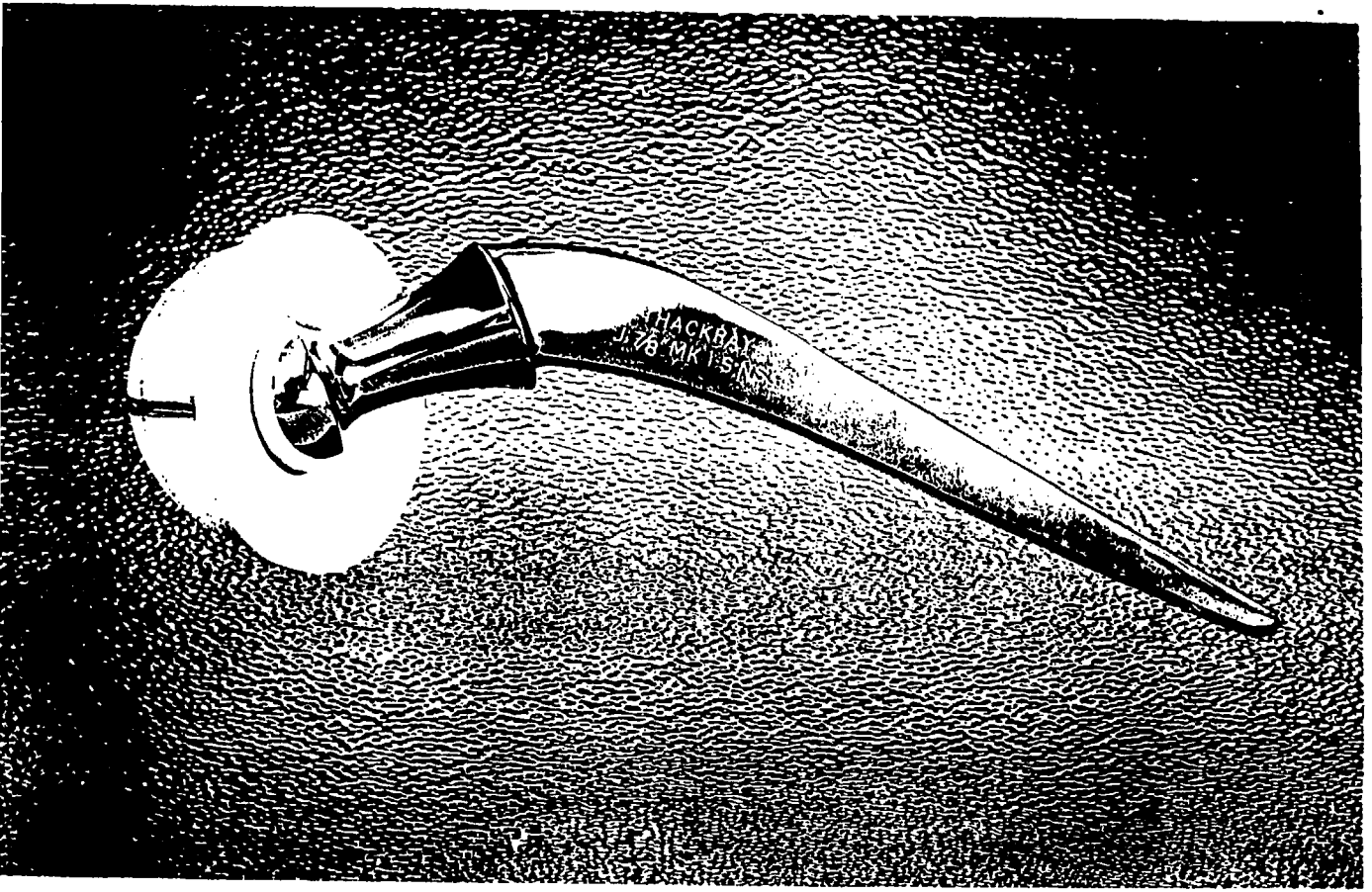


Fig. 4. A prosthetic hip joint with titanium femoral component and polyethylene acetabular cup.

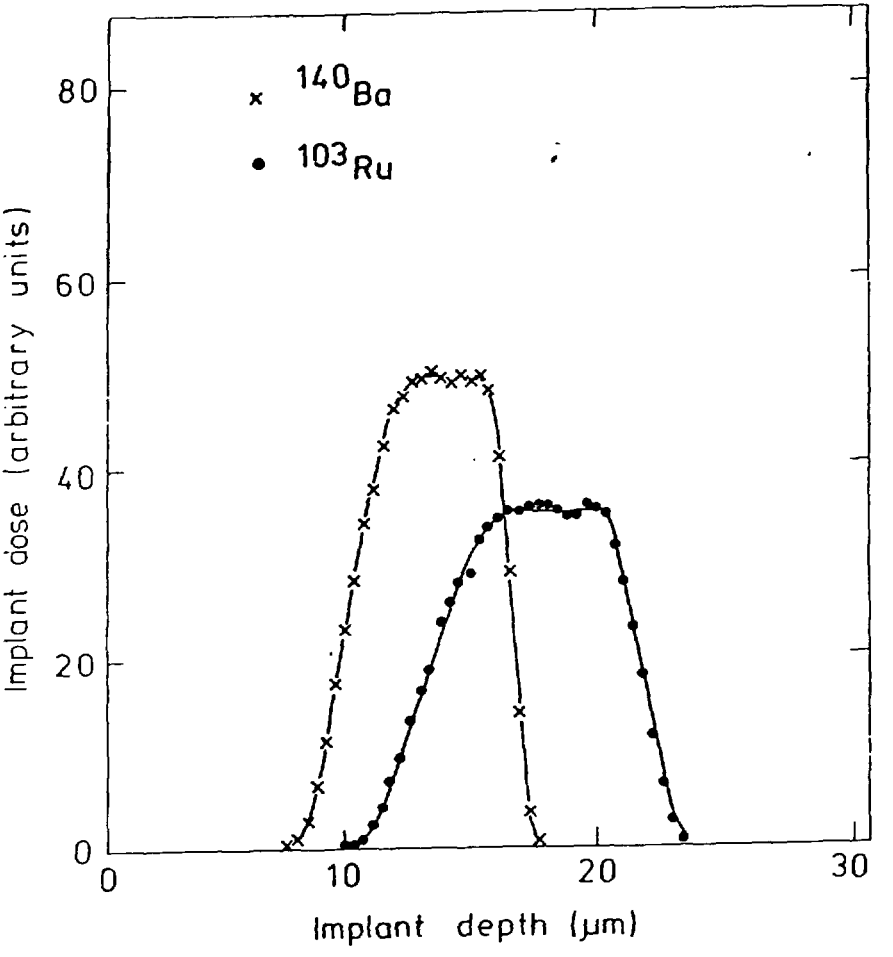


Fig. 6 Fission fragment implantation from a ^{252}Cf source

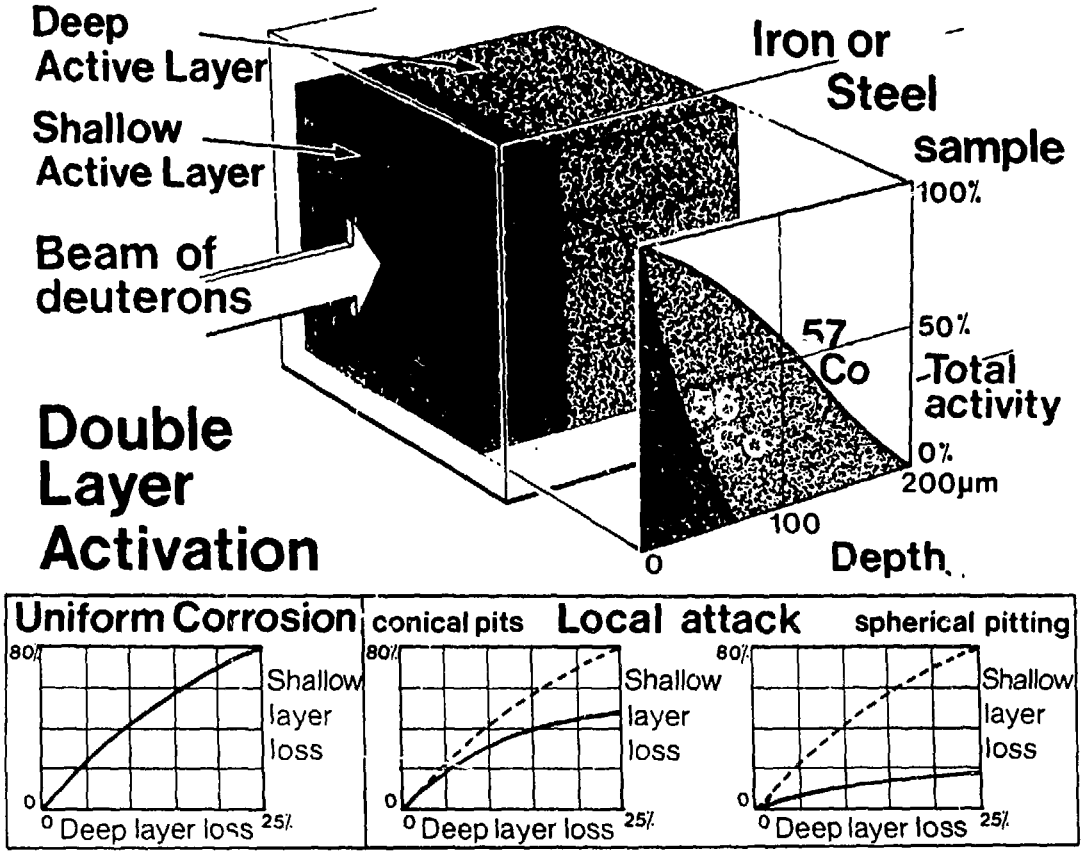


Fig. 6. Double layer activation for measurement of non-uniform or pitting corrosion.

COMMISSARIAT A L'ENERGIE ATOMIQUE

Office des Rayonnements Ionisants

Département des Applications et de la
Métrologie des Rayonnements Ionisants

Service d'Applications des Radioéléments

Rapport DTA/SAR/S/90-110/J118

Avril 90

THIN LAYER ACTIVATION WITH CHARGED PARTICLES

APPLICATIONS AND REMARKS

==========

Bernard JEANNEAU

(Commissariat à l'Energie Atomique)

THIN LAYER ACTIVATION WITH CHARGED PARTICLES

APPLICATIONS AND REMARKS

Bernard JEANNEAU

(Commissariat à l'Energie Atomique)

Agency's consultants' meeting 15-18 Mai 1990.

Real time non destructive control of wear and corrosion using thin layer activation techniques.

As improvements which occured in many fields such as metallurgy manufactoring of advanced materials, reliability of machine part subject to deteriorate agents, etc, control techniques try hard to obtain high quality results.

Among those improvement, one which allows to measure wear or corrosion of materials is Thin Layer Activation (T.L.A.) with charged particles.

THE METHOD T.L.A.

It consists in activating wholly or partly the component to be studied with charged particles and measuring the activity present in the wear fragments or remaining to the test specimen; a calibrati- permits to link the mass of eroded material to the measured activity.

This method offers the possibility to irradiate large size parts, in some case, to choice the produced radionuclide and with the control of activated surface and thickness, to reduce significantly the security aspects.

Since the activity is not proportionnel to the mass it is necessary to make a calibration, giving the distribution of activity versus the irradiated thickness, using piled thin foils of an element or material as similar as possible as the one tested, or making an abrasion.

MATERIALS

Most of metals and metallic alloys and some coating ceramics and a few plastics can be activated.

Thus the following materials have been studied and/or have been the object of industrials applications in France.

- carbon steel	active element	iron
- stainless steel	"	iron, chromium
- magnesium	"	magnesium
- zirconium, zircalloy	"	zirconium
- bronze, brass, copper	"	copper
- molybdenum	"	molybdenum
- precious metals	"	platinium, gold
		silver
- metallic coatings	"	titanium, vanadium
		chromium, tungsten
- beryllium, boron, carbon	"	beryllium, boron, carbon
- silicon	"	silicon
- ceramics	"	nickel yttrium
		chromium, scandium
		zirconium, calcium
		titanium, sodium
- composites	"	carbon
- platics	"	fluor, carbon
		aluminium

ELEMENT TARGETS AND UTILIZED REACTIONS

Element	Reaction	Threshold (MeV)	Radionuclide	Half-life
beryllium	p,p2n	22,9	$^{7}_{4}Be$	53,6j
boron	p, α	0	$^{7}_{4}Be$	53,6j
carbon	He_3,2α	7,1	$^{7}_{4}Be$	53,6j
fluor	p,pn	11,0	$^{18}_{9}F$	1,87h
magnesium	d, α .	0	$^{22}_{11}Na$	2,58a
aluminium	d, αp	5,8	$^{24}_{11}Na$	14,8h
calcium	p,n	0,5	$^{48}_{21}Sc$	44h
titanium	p,n	4,9	$^{48}_{23}V$	16j
vanadium	p,n	1,6	$^{51}_{24}Cr$	27,7j
chromium	p,n	5,6	$^{52}_{25}Mn$	5,7j
chromium	p,n	2,2	$^{54}_{25}Mn$	312j
manganèse	p,pn	10,4	$^{54}_{25}Mn$	312j

iron	p,n	5,44	$^{56}_{27}Co$	77,1j
iron	p,n	1,6	$^{57}_{27}Co$	270j
nickel	p,α	1,4	$^{55}_{27}Co$	18h
copper	p,n	2,2	$^{65}_{30}Zn$	245j
zinc	p,n	1,8	$^{67}_{31}Ga$	78h
yttrium	p,n	3,7	$^{89}_{40}Zn$	79h
zirconium	p,n	2,8	$^{92}_{41}Nb$	10,1j
molybdenium	p,n	3,8	$^{96}_{43}Tc$	4,3j
silver	p,pn	9,6	$^{106m}_{47}Ag$	8,3j
tin	p,n	3,5	$^{120}_{51}Sb$	5,8j
tin	p,n	2,4	$^{122}_{51}Sb$	2,8j
tin	p,n	1,4	$^{124}_{51}Sb$	60j
tungsten	p,n	4,6	$^{182}_{75}Re$	64h
tungsten	p,n	3,6	$^{184}_{75}Re$	50j
platinium	p,n	3,3	$^{194}_{79}Au$	39,5h
gold	d,p	1,2	$^{198}_{79}Au$	64,8h

MACHINES PRODUCING CHARGED PARTICLES BEAMS

There are different kind of accelerators.

Linear accelerator for light and heavy ions.
Cyclotron for light and heavy ions.
Synchotron for protons.

In France, there is few available accelerators permitting activations for industrial use. The cyclotron of Scientific Research National Center (CNRS) situated in Orléans La Source, only offers this possibility. The others are exclusively utilized in physics research or for medical radionuclides production.

CARACTERISTICS OF CNRS CYCLOTRON.

It is a isochronus cyclotron with variable energy with two beam track permitting irradiations with protons, deuterons, alphas and helium 3.

Charged particles	Energy (MeV)	Intensity (μA)
Protons	5 to 38	30 to 40 in the beginning of the range
Deuterons	5 to 25	100 at the top of the range
Helium 3	10 to 50	10 in the beginning of the range
Alpha	10 to 60	40 at the top of the range

LABORATORIES AND INDUSTRIES USING THIS TECHNIQUE

- Laboratories
  Generally, there are research laboratories working on materials. There are a few in France to have used nuclear method, more especially for coatings with Cr, Ti and for ceramics, like Technical Center of Mechanical Industries (CETIM-SENLIS) and Central Technical Center of Armament (ETCA-ARCUEIL).

- Industries
  Many industries have emploied this technique, armament, automobile, aeronautics, nuclear, petroleum, and space industries.

The most important users are Citroen, Peugeot, Renault and Armament establishments.

There is a light stagnation in automobile owed to the new definite direction, not relate to the facility of constitutive material of the motor but on energy economies (fuels and structure of vehicles).

Ceramics coatings remain perhabs the last materials being able to be studied in some definite configurations.

REALIZE STUDIES

The application of TLA has permitted test studies of various parts and products on in the running machines or test benches.

- Automobile piston, ring, jacket,
  inlets ports, valve, rocker arm, gearbox, brakes
  studies of sulphur influence in fuel, lubricants and theirs additives.
- Armament guns of middle and large caliper
  studies of influence of shape and projectile structure, powders (charge and composition).
- Marine Diesel motors
  Injector and valve seat
- Nuclear plant
  Wear of constitutive parts of machines used during the reprocessing of irradiated nuclear fuels.
  Corrosion of vapor generator in nuclear reactor.
- Space Gears of turbo-pump for space launcher.

All the countries using these technique worked nearly on the same studies, the weakness points of the different machines always being similar.

The improvement of performances, whatever in yield or reliability being got through adjustement of products; metallurgy of constituants and mechanical realization of machines being the obliged track for improvement during running conditions.

APPLICATION OF THE METHOD

Although being an efficient investigation mean, it is not possible to employ TLA in all cases. So utilization of activation necesserely requires an accelerator. Such machines are not frequent : (only one cyclotron for this kind of study) in France. This excludes routine studies on industrial sites, except if one has a local compact cyclotron at one disposal.
Conversely, TLA finds perfectly its place at the level of research department or for adjustment of new products. It permits to reduce experience time with its great sensibility and so, makes easier choice and/or directions to take for continuing researches.

An other point to be considered is profitability. One cannot forget that this method which is now perfectly adapted for some materials study can become a mean of wear and corrosion measurement adaptable for many industries which, until today, only use classical metrological means, whitout increasing notably the expenses inherent to this kind of measure.

There is a profitability calculation to be done, calculation based on the saving of time, the number of experiences being limited.

Three criterions must be takem in account :
1) sensibility
2) no dismantling of the studied parts
3) economy on the test duration.

In the majority of cases, the employement of this technique proved to be profitable.

We can take for example a study made by EDF (France Electricity Board) on wear corrosion in pumps and heat exchanger used in nuclear reactors. These parts are subject of wear, cavitation and corrosion. The loss of metal is about 200 μm per 30 years. With classical techniques, the duration of experiences is about 1,5 year to get significative results.

Now, using TLA, in laboratories with specially adapted machines one week is sufficient to get similar results.

The profitability of TLA is clearly demonstrated.

POSSIBLE DEVELOPMENTS OF THIS METHOD

They are linked to the disponibility of an accelerator and above all to the researchs which will expand in the future.

The development of new materials like high performance alloys and composites in marine, space will open new fields of applications.

If, in some cases, activation is already possible in others, in particular for plastics, there is still many points to study.

We can mention :
- reliability according to temperature during the activation
- lack of activable elements for low energies (studies of additional elements)
- too short-half lives of produced radionuclides to be used during a sufficient time and energy of emetted γ rays not always compatible with the needs of the experiment.

WHY TLA IS SOMETIMES DISDAINED

In our opinion, there are four reasons.
1) radioactivity
2) cost
3) established habits
4) accuracy needs.

1) Radioactivity

In France, as in others countries, people take fright where he heard the word "radioactivity". A certain number of Health and Safety Factories Comitties refuse the use of radioactivity in laboratories and industries generally, because bad information about the exact danger.

All the studies made out of a Nuclear Center need the obtention of an autorization of the Radionuclides Interministerial Commission (CIREA), autorization delivered after reading a technical safety file explaining the experience and safety means. This commission is independant so the dialogue is rather easy. Al last, a meeting with the concerned participants in the using laboratory or factory permit to bring the informations and to remove or reduce the hesitations.

2) Price

Although the profitability is demonstrated, the experience cost is not negligeable in comparison with technological research budget of a majority of industrial firms.

In general, for resolving their problem, they use all means, they have at their disposal in the firm itself before calling for extenal radioactive techniques.

So, the cost of beam accelerator hours, the amortization of detection apparatus, and the necessary manpower to realize the experience, do not permit to make a study for less than 50 000 FF, which is not negligeable for a little firm.

Some examples

- study of rocker arm on instrumented laboratory machine during one week : 65 000 FF.
- study of rehability of two ceramics during tests on trilological machine/two days : 50 000 FF.

Thus, only an imperative need, stopping the production will push the responsable to ask for this technique.

3) Established habits

Most manufacturers who need to study the evolution of certain parts during running test are equiped of conventional metrological means, like profilograph, tri-dimensional analysis and so an. They have acquired a valuable knowledge in these field.

For this reason, they have some hesitation to use an other technique, even if this can give them important advantages. It is out of their competence and they have to call on external teams. Over a certain number of years, they use theirs means which apparently are sufficient. So why to change ?

4) Accuracy needs

TLA give very accurate results in a thickness range situated down the micrometer. In some works, it becomes superfluous, micrometer being already, farther than their preoccupation. They do not find importance to pay for obtaining results they do not really need.

UTILIZATION OF THIS TECHNIQUE IN DEVELOPING COUNTRIES

Many criterions are necessary to establish efficiently wear measurement with TLA. Some of them are imperative, like the existence of specialists in nuclear measurements and of course access to an accelerator; but it also needs an industrial structure to apply these techniques.

In the case where a country get this conditions the field of applications can be large.

A few countries could be in a position of using this kind of measurement such as for instance : Brasil, China, Indonesia, Singapore.

ACTIVITIES OF AIEA

After a choice between countries having nuclear, financial and industrial means permitting to validly use the method, the Agency has many possibilities to develop it :

- publication and diffusion of scientfic reports such as a guide book on TLA
- reception of trainees in member country laboratory using this technique
- meeting with experts and manufacturers
- dispatching of expert to advise and/or form a research team.

REFERENCES

EDF

Direction des Etudes et Recherches
Epure N° 17 January 1988

CEA

- Use of Nuclear Techniques for wear measuring
Report ORIS/SAR/S/85-120/October 1987 **B. JEANNEAU**

- Wear measurement of engine parts with nuclear techniques
Presented to Automobile Ingeneers Society
Report ORIS/SAR/S/86-20 April 1986 **B. JEANNEAU**

- Use of thin layer activation techniques to assess mechanical parts wear.
A survey of industrial experience in France
Presented to the 7th conference of Applications of Accelerators in research and industry
North Texas State University
DENTON Texas USA November 1982 **B. JEANNEAU**

- Use of Nuclear techniques for wear measurement presented to 28th journey of special steel
LIEGE Belgique Mai 1989. **B. JEANNEAU**

THIN LAYER ACTIVATION TECHNIQUE APPLICATIONS IN THE USSR

I.O. Konstantinov, A.I. Leonov

Institute of Physics and Power Engineering
Obninsk, USSR

The thin layer activation technique (TLA) is one of the advanced and radiologically safe method of measurement of material loss due to wear or corrosion. Since 1964 TLA, is being used in the USSR [1]. Improvements of the method were accompanied by extending the types of investigated objects, such as combustion engines, mashine-tools, gears, cutting tools, bearing and pumps. Then, the method was extended on measurements of material loss due to corrosion [2,3], irregular wear and pitting [4].

The main advantages of the TLA technique are based on a small size of a radioisotope label. Because of the high specific activity of radioisotopes in label the high sensitivity of material loss measurements can be achieved when gamma-radiation of the label is detected and the total activity of radioisotopes in label is smaller than 10 μCi. According to USSR radiation safety standards, handling with these objects is allowed as with non-radioactive. Thus, the TLA technique allows to measure the material loss without stopping and dismantling of the machine.

Irradiation by accelerated charged particles enables to regulate the location, size and form of a radioactive label, as well as the number and depth profile of radioisotopes in the label. All these properties make the reasons of wide applications of the TLA technique in industry in different countries quite evident.

At present the traditional TLA technique applications are

sufficiently advanced. All essential stages of realization of this technique such as irradiatrion by charged particles, experimental determination of the radioisotope depth profile [5,6,7], calculation of the material loss and experimental errors [8,9], the multi-layer radioisotope labels production are described in details. The inital information enabling to to find out the type and energy of accelerated particles, irradiation time, minimum and maximum values of wear to be measured in different materials, is radioisotopes yield in charged particles nuclear reactions [10,11]. Accumulation and the following publications of experimental data on the radioisotopes yield in nuclear reactions with charged particles can support the development of the TLA technique in different countries and can be a subject of international co-operation.

A great number of applications of this technique in the USSR is carried out on cyclotron U-150 in the Institute of Physics and Power Engineering in Obninsk [12]. This cyclotron accelerates protons up to the fixed energy of 7.0, 11.4 and 22.8 Mev, deuterons- up to 22.8 Mev, helium-3 ions-up to 31.2 Mev and α-particles -up to 28.0 and 45.6 Mev. A number of devices to irradiate the samples of materials and machine parts were constructed. Thus the value of wear and corrosion loss can be measured from 0.03 μm to 1000 μm with the error approximetely 10-20% [13,14,15]. The main TLA technique applications can be conventionally divided into three fields: (first) material loss measurements in order to compare the influence of different construction materials, engine oils and fuels, working conditions and another factors on the rate of material loss; (second) real-time material loss measurements in unique objects; (third) material loss measurements to graduate another methods, for example the methods which are based on acoustic vibration measurements.

Some examples of TLA technique applications are described in the following text.

More often the TLA technique is used to measure the wear of different combustion engine parts [16,17,18]. In one case it was necessary to measure the wear rate of a piston ring under

different working conditions of the engine [16]. In order to achieve this goal the chromium-plated piston ring surface was bombarded by 28 Mev energy α-particles at 30 angle of incidence of the beam to the surface. To calculate the value of wear we measured intensity of 835 Kev γ-radiation of manganese-54, which was distributed in the 25μm-thick surface layer. Some results are shown in Fig.1. The error of wear measurements is approximatly 10%. This technique allowed us to decrease essentialy the measuring time. Later we produced two different radioactive labels in a piston ring. One of them is uniformly distributed over the friction surface, the second point label is introduced into unworn surface of the ring and serves to get an angular coordinate of the observed part of the ring surface. Measurements of the radiation intensity of both labels give us the values of wear for different parts of the friction surface without the engine being stopped.

Wear of different types of bearing also has been measured by the TLA technique. For example, wear of all parts of ball bearing was measured under different working conditions [19]. Balls were irradiated in a special device, which makes it possible to create uniform distribution of radioisotopes on the ball surface. The total friction surface of the inside ring of the bearing was irradiated under rotation of the ring. The external ring was irradiated only in one spot of the friction surface. Some results are showed in Fig.2.

Some recent applications were connected with material loss measurements of steam turbine vanes of Nuclear Power Plants due to erosion [20,21]. In this case in order to results of material loss measurements did't depend from the shape of surface damages, it was necessary to produce the label with uniform depth distribution of radioisotopes. To produce this label the samples of stainless steel were irradiated by protons six times in succession. The main radioisotope in the label was cobalt-56. In every case proton energy and irradiation time were different. As proton energies were chosen between 11.0 Mev and 22.5 Mev, all depth distributions of cobalt-56 have approached maximum at some distance from the sample surface. This fact allowed us to find

such values of proton energies and irradiation times, that the total distribution approached the uniform one. It is important, that the more is the number of different proton energies the closer is the total distribution to the uniform one. In our case, difference between maximum and minimum of specific activity of cobalt-56 in total distribution, measured by stack of foils technique approached 18% (Fig.3). Irradiated samples were soldered to turbine vanes and cobalt-56 gamma-radiation was measured on under different working conditions of the turbine. This tecnique allowed us, to carry on real-time control of errosion rate of turbine vanes.

Double-layer labels with cobalt-56 and cobalt-58 are used now to measure material loss and part of the damaged surface simultaneously [21,22]. For example, using the double-layer label to measure material loss due to pitting and wear of the cam-follower mechanism in a combustion engine allows us to control quality of lubricating oils [23].

It may be concluded, that the TLA technique has a great potential to real-time control of material loss due to wear or corrosion. International co-operation can support development of this technique applications.

REFERENCES

1. V.I. Postnikov. The new radioisotope real-time control tecnique of the wear of a machine parts. Izotopi v SSSR, 1966, N3, p.11-16.

2. I.O. Konstantinov, V.V. Maluchin, V.M. Brusnetsova, V.M. Novakovski, V.I. Sumets. The remote radioisotope control tecnique of the equipment corrosion under working conditions. Zashita metallov, 1977, v.8, N5, p.523-528.

3. I.O. Konstantinov. The remote radioisotope control technique of the corrosion of a chemical equipment. Express-Information N90-77. Ser Peredovoi opit v chimicheskoi promishlennosti. Izdanie НИИТЭХИМ, 1977.

4. I.O. Konstantinov, A.I. Leonov. The local surfase damages control by thin layer activation technique. Preprint IPPE (Institute Phisics and Power Engineering) -1811, 1986, g. Obninsk, SSSR.

5. I.O. Konstantinov, A.I. Leonov, V.N. Mironov. The graduation of the thin layer activation technique. Preprint IPPE-1383, 1982, g. Obninsk, SSSR.

6. I.O. Konstantinov, A.I. Leonov, V.N. Mironov. The thin layer activation technique applications. Isotopi v SSSR, 1983, N66, p.20-25.

7. I.O. Konstantinov, N.N. Krasnov. The error analisis of the machine parts wear measuring by thin layer activation technique. Izotopi v SSSR, 1969, N13, p.30-34.

8. A.I. Leonov, I.O. Konstantinov, M.Z. Tarasko. The detection limit and error parameters of the thin layer activation technique. Preprint IPPE-1405, 1984, g. Obninsk.

9. A.I. Leonov, I.O. Konstantinov, M.Z. Tarasko. The application of the detection limit and error of the thin layer activation technique. Preprint IPPE-1615, 1984, g. Obninsk.

10. I.O. Konstantinov, N.N. Krasnov. Determination of the wear of machine parts by charged particle surfase activation. Journal of Radional. chem. 1971, N8, p.357-371.

11. V.V. Maluchin, I.O. Konstantinov. Activation of

construction materials on cyclotron. Izotopi v SSSR, 1975, N44, p. 67-75.

12. N.N. Krasnov, P.P. Dmitriev, I.O.Konstantinov, et.al. The cyclotron of Institute Physics and Power Engineering use for radioisotopes production and others applications. Trudi Fiziko-Energeticheskogo Instituta. M. Atomizdat, 1974, p.399-413.

13. V.I.Postnikov. Investigation and machin wear control by thin layer activation technique. M. Atomizdat, 1973.

14. V.S. Arhipov, I.N.Garbar, I.O.Konstantinov, I.A. Pavlov. Thin layer activation technique application in industry. M. Atomizdat, 1975.

15. I.O.Konstantinov. Thin layer activation tevchnigue for wear and corrosion control. Izotopi v SSSR, 1988, N73, P.5-14.

16 I.O.Konstantinov, V.I. Miheev, A.A. Karpov, A.I.Leonov, N.A. Bayguzin. The wear rizistance investigation of combustion engine parts by thin layer activation tecnique. Izotopi v SSSR, 1983, N65, p.35-38.

17. V.I. Postnikov, L.K. Poliakovsky, K.D. Gurman. The investigation of combustion engine by radioactive tracer method under ship navigation condition. Izotopi v SSSR, 1968, N12, p.86-89.

18. D.G. Tochilnikov, N.A. Rossinsky. The investigation of diesel engine bearing wear by thin layer activation technique. Izotopi v SSSR, 1977, N50, p.10-14.

19. N.T. Minchenia, Y.B. Skorinin, I.O.Konstantinov. Wear of ball bearing with obrasive in lubricating oil. Vestnik machinostroenia, 1977, N4, p.33-34.

20. I.O. Konstantinov, A.I. Leonov, M.D. Roshal, M.V. Yavelski. The radioisotope control of local surface domages. Atomnaia Energia, 1987, v.63, N1, p.11-14.

21. M.B. Yavelski, M.D. Roshal, M.B. Porshuev, I.O. Konstantinov, A.I. Leonov. The investigation of errosion damages by radioisotope technique. Teplotchnika, 1989, N4, p.61-62.

22. S.P. Avdeenko, Y.S. Zaslavski, I.O. Konstantinov, A.I. Leonov, V.A. Kuzmin. The radioisotope method of investigation of pitting resistance engine oiles. Trenie i iznos, 1989, v.10, N6, p.1006-1012.

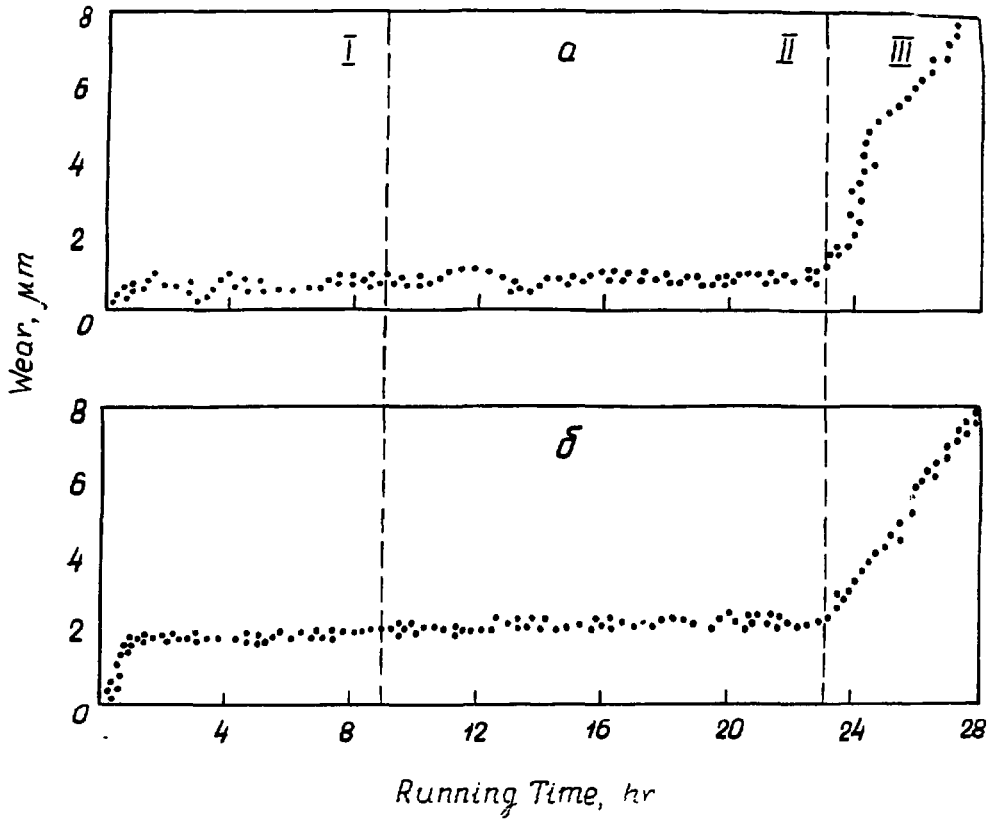


Fig. 1. Wear of the upper piston ring of KaMaz-740 engine under different working conditions. a- experimental piston ring, b-standard piston ring. I-beginning of the work, II- standard condition, III-abrasive wear.

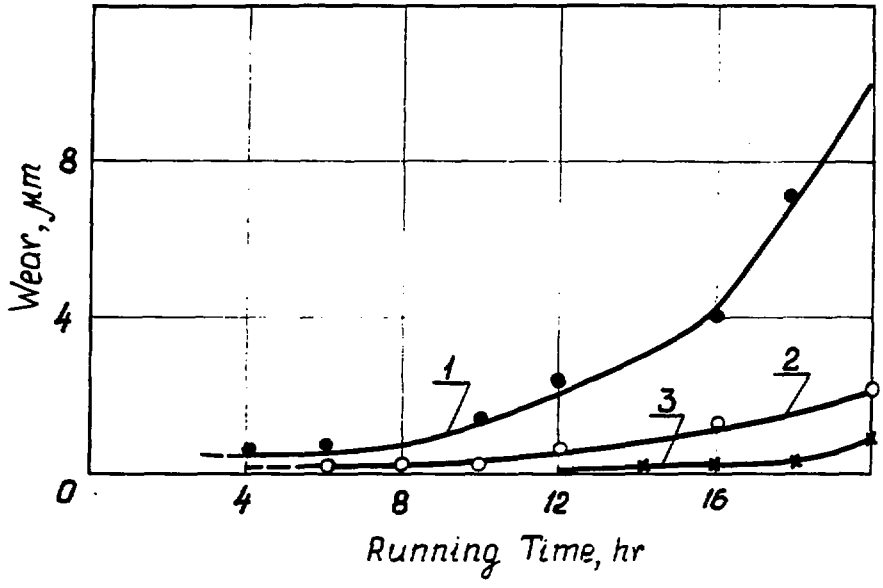


Fig. 2. Wear of the bearing parts.
1- ball, 2-external ring, 3-inner ring.

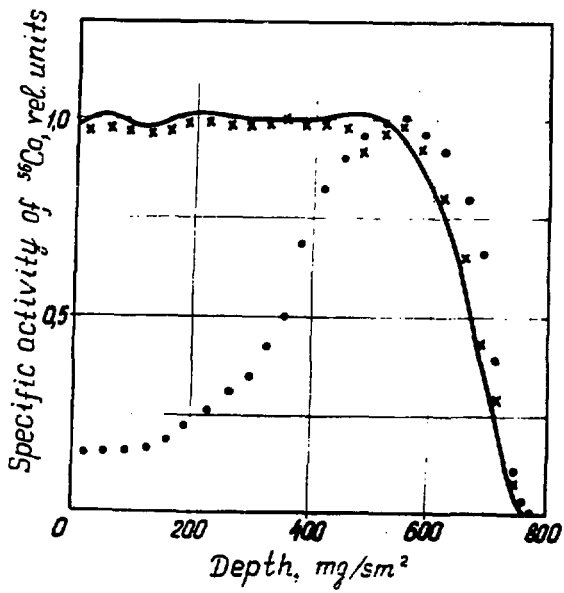


Fig.3. Distribution of cobalt-56 in stainless steel samples. •– distribution under 22.5 Mev protons, × – total distribution is measured by stack of foils technique, — calculated total distribution.

ACTIVATION TECHNIQUE FOR INDUSTRY AT THE DEBRECEN CYCLOTRON LABORATORY

(Status Report)

I. Mahunka and F. Ditrói

Institute of Nuclear Research of the Hung. Acad. of Sciences
H-4001 Debrecen, P.O.Box 51, Hungary

The cyclotrons, developed for the fundamental research in nuclear physics, have become a very useful and effective basic equipment of this field. After the development of the small compact isochronous cyclotron it has turned to be a basic equipment also in the applied research and practice. Nowadays the small cyclotrons are frequently used for industrial, agricultural and medical purposes.

At the establishment of the Cyclotron Laboratory in Debrecen it has been decided to use it both for fundamental and applied research. The cyclotron of the laboratory is a Soviet made MGC-20 isochronous mashine [1] produced by the NIIEFA (Leningrad), which can accelerate light ions up to 20 MeV for protons. The structure of the laboratory is shown on Fig.1. In accordance with the multipurpose use of the laboratory, it consist of 3 parts:

- Shielded area for the cyclotron and the beam lines.
- Radiochemical Laboratory.
- Medical Section.

In the shielded area there are 10 beam lines, 6 for the fundamental research in nuclear and atomic physics, and 4 for applications [2, 3]. Those for applications are specially equipped for isotope production; for production of fast neutrons; for the nuclear analytical measurements and for the Thin Layer Activation (TLA). Nuclear methods can be effectively used on these beam lines in different fields of the practice.

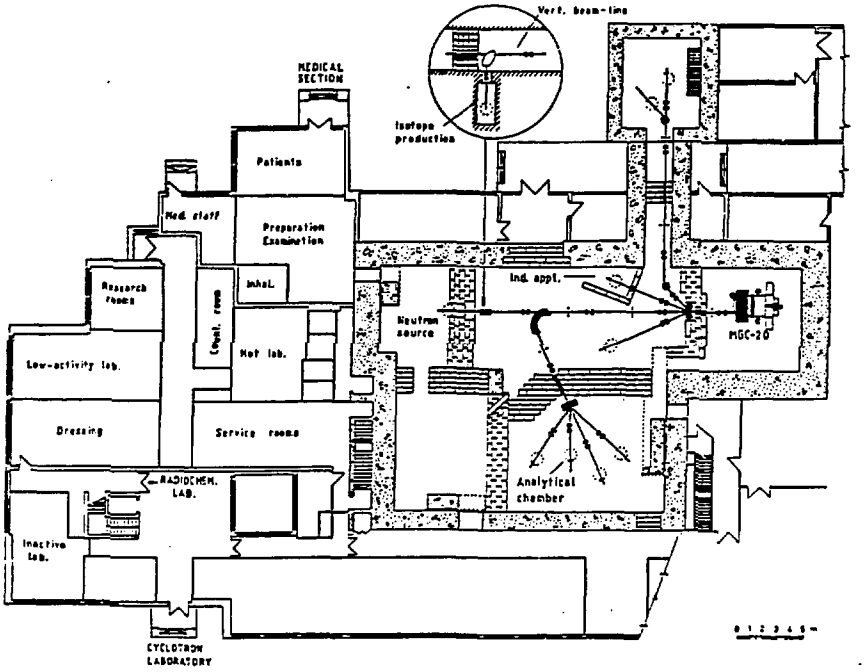


Fig. 1. Layout of the Cyclotron Laboratory

The demand for the application of nuclear technique in the industrial research and development is continuously growing. The activation technique is one of the most frequently used methods in the fields of materials science and in the high technology industry. Using this technique analytical information can be gained, or on the basis of TLA, the mechanical wear, corrosion and erosion can be measured or monitored also even at "in-line" arrangement. The charged particle beams or the secondary fast neutron sources of the cyclotron can be used for the irradiations.

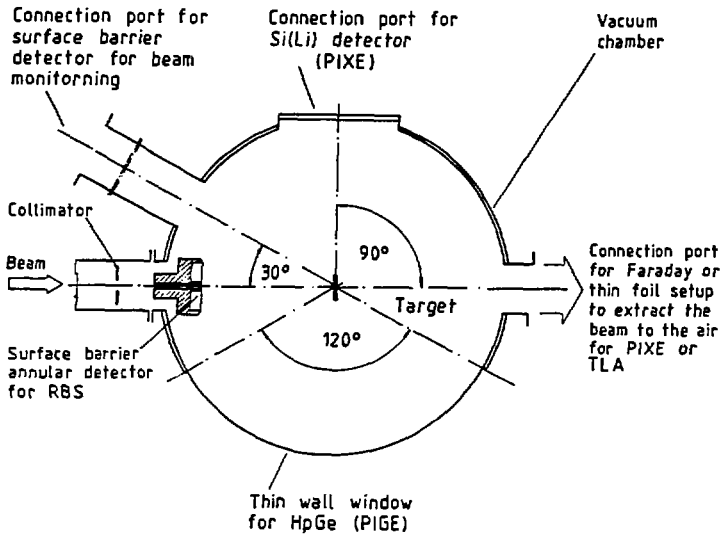


Fig. 2. Scheme of the analytical chamber

For the activation technique based on the charged particle beams of our cyclotron a complex analytical chamber has been developed (Fig.2).
With this chamber it is possible to use the prompt (PIXE, PIGE, NRA) and delayed (CPAA) analytical methods and to perform irradiations for the wear measurements in the vacuum chamber or outside.

The analytical chamber itself has a separate vacuum system and a remote controlled sample changer. There are different detector ports on the chamber wall. The X-ray (Si(Li)) or gamma (HpGe) detector port is mounted at a direction of 90° and can be replaced by a viewing window. The gamma detector (HpGe or Ge(Li)) can be aligned to directions between 60° forward and 60° backward and it can detect the gamma-rays through a thin metal window. A charged particle

detector port at 60° backward direction can be used as a beam monitor, too, and an annular particle detector can also be mounted. For beam current measurements in the case of thin samples a shielded Faraday cup can be replaced by a beam extractor unit, so we can have an external beam for PIXE or TLA through a thin metal or plastic (Kapton) foil for irradiations in the atmosphere. The chamber can be separated from the accelerator vacuum and filled up with any kind of gas even at over-pressure, to carry out measurements in different gas atmospheres.

For sample preparation and handling a small laboratory has been established [4] and equiped with vacuum evaporator, metal microscope, size measuring equipment, polishing machine, lead shielded box for the activated samples, etc. There are also two gamma-spectrometers with shielded HpGe detectors.

The nuclear analytical methods and the instrumentation of the laboratory give possibilities for investigation of the trace elements in high purity materials. Topics have been investigated from the point of view of industrial interest are the following:

- Investigation of oxigen and other trace elements in high purity Al materials [5, 6].
- Microelemental composition of motor oil after different duration of use [7].
- Trace elements in glass samples [8].
- Investigation of bulk oxigen concentracion of high purity gallium samples [9].

The Thin Layer Activation (TLA) method is that part of the nuclear activation technique which is especially used for the investigation of different type of wear. The principle of the method is the doping of thin surface layers with trace quantities of radioisotopes. These radioisotopes can be produced in the sample itself, or can be implanted with known distribution. By measuring the change of the activity at the sample or at some filter the loss from the surface and

thus the measure of the wear can be determined.

When using TLA method it is important to choose the radioisotopes proper to a given task, taking into consideration our possibilities and demands. To this aim the elements,which can be activated by small cyclotrons for wear measurements are compiled and shown in Table 1. Setting up this compilation "selection rules" have been introduced on the parameters:

1. Target elements
2. Nuclear reactions
3. Nuclear data of the produced isotopes,

as follows:

1. The stabil isotopes of an element are only included if their isotopic abundance (I) is higher then 10%.

2. Reactions are tabulated only fore light bombarding particles (p, d, ^{3}He, α). With the same particle there is included not more than two reactions. In the outgoing channel can be only maximum two nucleons or clusters because of the energy limits of the small cyclotrons.

3. The half-life should be longer than 1 day and the energy of the gamma radiation higher than 100 keV because of detection problems. For the identification there are tabulated only the two most intensive gamma lines. The noble gas products are not included because of the high mobility of them.

On the basis of the tabulated data it can be concluded that the use of the TLA method is economic and very effective on a wide range of elements and their composition serving as the basic material of the high technology industry.

In our institute we have a project for the TLA measurement in cooperation with the Institute for Engine Development. In the frame of this cooperation a set of

experiments on steel-based materials has been carried out. The samples were irradiated with different particles and energies. The measured and calculated activity-depth functions have been compared to build up the proper calibration curves [10].

The other project under development in our institute by using TLA method is the wear measurement of cutting edges of turning tools made from boronnitrid (BN) and industrial diamond (ID). At this investigations we have a plan for the "in-line" measurements. The cutting edges are activated in the case of BN via the $^{10}B(p,\alpha)^{7}Be$ and in the case of ID via the $^{12}C(^{3}He,2\alpha)^{7}Be$ reactions. The iron components of the cutting edges in both cases give possibility for the activation via the $^{56}Fe(p,n)^{56}Co$ reaction too.

Table 1.

Elements can be activated by a small cyclotron for wear measurement. (I>10%, $T_{\frac{1}{2}}$>1 d, E_g>100 keV)

Element			Reaction		Produced isotopes [11]		
S	A	I[%]	Type	Q[MeV]	S	$T_{\frac{1}{2}}$	E_g[keV]
Li	7	92.5	p,n	+	^{7}Be	53.3 d	477.6
Be	9	100.	^{3}He,αn	+	^{7}Be	53.3 d	477.6
B	10	19.8	p,α	+	^{7}Be	53.3 d	477.6
	11	80.2	p,αn	-10.3	^{7}Be	53.3 d	477.6
C	12	98.9	^{3}He,2α	-5.7	^{7}Be	53.3 d	477.6
N	14	99.6	p,2α	-10.5	^{7}Be	53.3 d	477.6
F	19	100.	α,n	-1.9	^{22}Na	2.6 y	1274.5
Na	23	100.	p,np	-12.4	^{22}Na	2.6 y	1274.5
Mg	26	11.	p,n	-4.8	^{26}Al	7.10^{5} y	1808.7
	25	10.	p,α	-3.1	^{22}Na	2.6 y	1274.5
	24	79.	d,α	+	^{22}Na	2.6 y	1274.5
Al	27	100.	p,np	-13.1	^{26}Al	7.10^{5} y	1808.7
Si	28	92.2	d,α	+	^{26}Al	7.10^{5} y	1808.7
Sc	45	100.	p,pn	-11.3	^{44m}Sc	2.4 d	271.2
	45	100.	d,p	+	^{46}Sc	83.8 d	889.3,1120.5
Ti	48	73.8	p,n	-4.8	^{48}V	16.0 d	983.5,1312.
	48	73.8	α,n	-2.7	^{51}Cr	27.7 d	320.1
V	51	99.8	p,n	-1.5	^{51}Cr	27.7 d	320.1
	51	99.8	^{3}He,2n	-2.7	^{52}Mn	5.6 d	935.5,1434.1
	51	99.8	α,n	-2.3	^{54}Mn	312.2 d	834.8
Cr	52	83.8	p,n	-5.5	^{52}Mn	5.6 d	935.5,1434.1
Mn	55	100.	p,pn	-10.2	^{54}Mn	312.2 d	834.8
	55	100.	^{3}He,n	+	^{57}Co	271.8 d	122.1,136.5
	55	100.	^{3}He,2n	-2.9	^{56}Co	77.7 d	846.8,1238.3
	55	100.	α,n	-3.5	^{58}Co	70.9 d	810.8
Fe	56	91.7	p,n	-5.4	^{56}Co	77.7 d	846.8,1238.3
	56	91.7	d,n	+	^{57}Co	271.8 d	122.1,136.5
	56	91.7	^{3}He,2n	-5.7	^{57}Ni	1.5 d	127.3,1377.6

Element			Reaction		Produced isotopes [11]		
S	A	I[%]	Type	Q[MeV]	S	$T_{\frac{1}{2}}$	E_g[keV]
Co	59	100.	p,np	-10.5	^{58}Co	70.9 d	810.8
	59	100.	^{3}He,2p		^{60}Co	5.3 y	1173.2,1332.5
Ni	58	68.3	p,pn	-12.2	^{57}Ni	1.5 d	127.3,1377.6
Cu	65	30.8	p,n	-2.1	^{65}Zn	244.1 d	1115.5
	65	30.8	^{3}He,n	+	^{67}Ga	3.3 d	184.6,300.2
	65	30.8	α,2n	-14.1	^{67}Ga	3.3 d	184.6,300.2
Zn	68	18.8	p,2n	-12.	^{67}Ga	3.3 d	184.6,300.2
	64	48.6	d,p	+	^{65}Zn	244.1 d	1115.5
	66	27.9	α,n	-7.4	^{69}Ge	1.6 d	574.1,1106.8
Ga	69	60.1	p,n	-3.	^{69}Ge	1.6 d	574.1,1106.8
	69	60.1	^{3}He,n	+	^{71}As	2.7 d	175.,1095.6
	71	39.9	^{3}He,2n	-3.1	^{72}As	1.1 d	834.
	69	60.1	α,2n	-15.1	^{71}As	2.7 d	175.,1095.6
	71	39.9	α,n	-4.9	^{74}As	17.8 d	595.9,634.8
Ge	72	27.4	p,2n	-13.5	^{71}As	2.7 d	175.,1095.6
	74	36.5	p,n	-3.3	^{74}As	17.8 d	595.9,634.8
	74	36.5	^{3}He,2n	-2.5	^{75}Se	119.8 d	136.,265.
	72	27.4	α,n	-6.1	^{75}Se	119.8 d	136.,265.
As	75	100.	p,n	-1.6	^{75}Se	119.8 d	136.,265.
	75	100.	^{3}He,n	+	^{77}Br	2.4 d	239.,298.
	75	100.	α,2n	-13.5	^{77}Br	2.4 d	239.,298.
Br	81	49.3	d,p	+	^{82}Br	1.5 d	554.,776.
	81	49.3	^{3}He,n	+	^{83}Rb	86.2 d	520.,529.7
	81	49.3	α,n	-3.9	^{84}Rb	32.9 d	881.7
Rb	85	72.2	p,n	-1.8	^{85}Sr	64.8 d	514.
	85	72.2	p,pn	-10.5	^{84}Rb	32.9 d	881.7
	85	27.8	^{3}He,n	+	^{87}Y	3.3 d	484.9
	87	27.8	^{3}He,2n	-1.5	^{88}Y	106.6 d	898.,1836.
	85	72.2	α,n	-3.8	^{88}Y	106.6 d	898.,1836.
Sr	88	82.6	p,n	-4.4	^{88}Y	106.6 d	898.,1836.
	88	82.6	p,2n	-13.8	^{87}Y	3.3 d	484.9
	88	82.6	^{3}He,2n	-4.3	^{89}Zr	3.3 d	909.2
Y	89	100.	p,n	-3.6	^{89}Zr	3.3 d	909.2
	89	100.	p,2n	-12.9	^{88}Zr	83.4 d	392.9
	89	100.	^{3}He,n	+	^{91m}Nb	62.0 d	1205.
	89	100.	α,n	-6.9	^{92m}Nb	10.2 d	934.5

Element			Reaction		Produced isotopes [11]		
S	A	I[%]	Type	Q[MeV]	S	$T_{\frac{1}{2}}$	E_g[keV]
Zr	91	11.2	p,n	-2.	^{91m}Nb	62.0 d	1205.
	92	17.1	p,n	-2.8	^{92m}Nb	10.2 d	934.5
	94	17.4	d,p	+	^{95}Zr	64.0 d	724.,756.7
Nb	93	100.	p,pn	-8.8	^{92m}Nb	10.2 d	934.5
	93	100.	^{3}He,n	+	^{95m}Tc	61.0 d	204.,582.1
	93	100.	α,n	-7.	^{96}Tc	4.3 d	778.2,813.
Mo	95	15.9	p,n	-2.5	^{95m}Tc	61.0 d	204.,582.1
	96	16.7	p,n	-3.7	^{96}Tc	4.3 d	778.2,813.
	95	15.9	^{3}He,n	+	^{97}Ru	2.9 d	215.2,324.4
Ru	102	31.6	p,n	-3.1	^{102}Rh	2.9 y	475.1,631.3
					^{102m}Rh	207.0 d	475.1
	104	18.7	p,pn	-8.9	^{103}Ru	39.3 d	497.
	104	18.7	d,n	+	^{105}Rh	1.5 d	319.
Rh	103	100.	p,pn	-9.3	^{102}Rh	2.9 y	475.1,631.3
					^{102m}Rh	207.0 d	475.1
	103	100.	^{3}He,n	+	^{105}Ag	41.3 d	280.5,344.5
	103	100.	α,n	-6.7	^{106m}Ag	8.5 d	451.,1045.9
Pd	105	22.3	p,n	-2.1	^{105}Ag	41.3 d	280.5,344.5
	108	26.5	p,n	-2.7	^{108m}Ag	127.0 y	433.9,614.3
	110	11.7	d,n	+	^{111}Ag	7.5 d	342.1
Ag	107	51.8	p,pn	-9.5	^{106m}Ag	8.4 d	451.,1045.9
	109	48.2	p,pn	-9.2	^{108m}Ag	127.0 y	433.9,614.3
	109	48.2	d,p	+	^{110m}Ag	249.8 d	657.8,884.7
	109	48.2	^{3}He,n	+	^{111}In	2.8 d	171.3,245.4
Cd	111	12.8	p,n	-1.6	^{111}In	2.8 d	171.3,245.4
	114	28.7	p,n	-2.2	^{114m}In	49.5 d	190.2,558.4
	111	12.8	^{3}He,n	+	^{113}Sn	115.1 d	391.7
	110	12.5	α,n	-7.7	^{113}Sn	115.1 d	391.7
In	115	95.7	p,pn	-9.	^{114m}In	49.5 d	190.2,558.4
Sn	120	32.6	p,n	-3.5	^{120m}Sb	5.8 d	1023.1,1171.4
	118	24.2	α,n	-8.2	^{121}Te	16.8 d	573.1
					^{121m}Te	154.0 d	212.2,1102.1

Element			Reaction		Produced isotopes [11]		
S	A	I[%]	Type	Q[MeV]	S	$T_{\frac{1}{2}}$	E_g[keV]
Sb	121	57.3	p,n	-1.3	^{121}Te	16.8 d	573.1
					^{121m}Te	154.0 d	212.2,1102.1
	121	57.3	p,pn	-9.2	^{120m}Sb	5.8 d	1023.1,1171.4
	121	57.3	α,n	-7.9	^{124}I	4.2 d	602.7,722.8
	123	42.7	α,n	-7.	^{126}I	13.0 d	388.6,666.4
Te	126	18.9	p,n	-2.9	^{126}I	13.0 d	388.6,666.4
	130	33.9	d,n	+	^{131}I	8.0 d	364.4
	130	33.9	α,n	-5.3	^{133m}Xe	2.2 d	233.2
I	127	100.	p,n	-1.4	^{127}Xe	36.4 d	172.1,202.8
	127	100.	^{3}He,n	+	^{129}Cs	1.3 d	371.9,411.4
	127	100.	α,2n	-7.8	^{129}Cs	1.3 d	371.9,411.4
Cs	133	100.	p,n	-1.3	^{133}Ba	10.5 y	302.8,355.9
					^{133m}Ba	1.6 d	276.
	133	100.	d,p	+	^{134}Cs	2.1 y	604.7,795.8
	133	100.	p,np	-9.	^{132}Cs	6.5 d	667.7
Ba	138	71.7	α,n	-6.1	^{141}Ce	32.5 d	145.4
La	139	99.9	p,n	-1.1	^{139}Ce	137.5 d	165.8
	139	99.9	^{3}He,p	+	^{141}Ce	32.5 d	145.4
Ce	140	88.5	d,p	+	^{141}Ce	32.4 d	145.5
	142	11.1	d,p	+	^{143}Ce	1.4 d	293.3,664.6
Pr	141	100.	^{3}He,n	+	^{143}Pm	265.0 d	742.
	141	100.	α,n	-10.3	^{144}Pm	363.0 d	618.,696.5
Nd	143	12.2	p,n	-1.9	^{143}Pm	265.0 d	742.
	144	23.8	p,n	-3.2	^{144}Pm	363.0 d	618.,696.5
	146	17.2	d,p	+	^{147}Nd	11.0 d	319.4,531.
Sm	152	26.7	p,n	-2.7	^{152}Eu	13.3 y	121.8,344.3
	154	22.7	p,n	-1.5	^{154}Eu	8.8 y	123.1,1274.5
	152	26.7	d,p	+	^{153}Sm	2.0 d	103.2
	147	15.0	^{3}He,n	-3.5	^{149}Gd	9.3 d	149.8,298.6
Eu	153	52.1	p,n	-1.0	^{153}Gd	241.6 d	103.2
	151	47.9	p,pn	-8.0	^{150m}Eu	36.0 y	334.,439.4
	153	52.1	d,p	+	^{154}Eu	8.8 y	123.1,1274.5
	151	47.9	^{3}He,n	-0.4	^{153}Tb	2.3 d	170.5,212.
	153	52.1	^{3}He,n	-0.1	^{155}Tb	5.3 d	105.3,180.
	153	52.1	α,n	-8.1	^{156}Tb	5.3 d	199.2,534.3

Element			Reaction		Produced isotopes [11]		
S	A	I[%]	Type	Q[MeV]	S	$T_{\frac{1}{2}}$	E_g[keV]
Gd	156	20.5	p,n	-2.4	^{156}Tb	5.4 d	199.2,534.3
	160	21.9	p,n	-0.9	^{160}Tb	72.3 d	298.6,879.4
	157	15.7	α,p	-7.9	^{160}Tb	72.3 d	298.6,879.4
Tb	159	100.	d,p	+	^{160}Tb	72.3 d	298.6,879.4
Ho	165	100.	^{3}He,n	-1.2	^{167}Tm	9.2 d	207.8
	165	100.	α,n	-9.2	^{168}Tm	93.1 d	198.2,816.
Er	167	22.9	p,n	-1.5	^{167}Tm	9.2 d	207.8
	168	26.8	p,n	-2.5	^{168}Tm	93.1 d	198.2,816.
	167	22.9	^{3}He,n	+	^{169}Yb	32.0 d	177.2,198.
Tm	169	100.	p,n	-1.7	^{169}Yb	32.0 d	177.2,198.
	169	100.	^{3}He,n	+	^{171}Lu	8.2 d	667.4,739.8
	169	100.	α,n	-10.9	^{172}Lu	6.7 d	900.7,1093.6
Yb	172	21.9	p,n	-4.	^{172}Lu	6.7 d	900.7,739.8
	173	16.1	p,n	-1.5	^{173}Lu	1.4 y	52.4,272.
	176	12.7	d,n	+	^{177}Lu	6.7 d	208.4
					^{177m}Lu	160.9 d	208.4,228.4
	173	16.1	^{3}He,n	+	^{175}Hf	70.0 d	343.4,432.7
	172	21.9	α,n	-10.3	^{175}Hf	70.0 d	343.4,432.7
Lu	175	97.4	p,n	-1.4	^{175}Hf	70.0 d	54.1,343.4
Hf	180	35.1	d,p	+	^{181}Hf	42.4 d	133.,482.
Ta	181	100.	d,p	+	^{182}Ta	115.0 d	1121.3,1221.4
	181	100.	^{3}He,n	+	^{183}Re	70.0 d	162.3
	181	100.	^{3}He,2n	-4.3	^{182m}Re	2.7 d	229.3
	181	100.	α,n	-11.2	^{184}Re	38.0 d	792.1,903.3
					^{184m}Re	165.0 d	104.7,252.9
W	184	30.7	p,n	-3.6	^{184}Re	38.0 d	792.1,903.3
					^{184m}Re	165.0 d	104.7,252.9
	186	28.6	p,n	-1.4	^{186}Re	3.8 d	137.1
	183	14.3	^{3}He,n	+	^{185}Os	93.6 d	646.1
	182	26.3	α,n	-11.1	^{185}Os	93.6 d	646.1

Element			Reaction		Produced isotopes [11]		
S	A	I[%]	Type	Q[MeV]	S	$T_{\frac{1}{2}}$	E_g[keV]
Re	185	37.4	p,n	-1.8	^{185}Os	93.6 d	646.1
	185	37.4	p,pn	-9.	^{184}Re	38.0 d	729.1,903.3
					^{184m}Re	165.0 d	104.7,252.8
	187	62.6	α,n	-2.1	^{190}Ir	11.8 d	186.7,605.2
Os	190	26.4	p,n	-2.9	^{190}Ir	11.8 d	186.7,605.2
	192	41.	p,n	-1.8	^{192}Ir	74.0 d	316.5,468.1
	190	26.4	d,p	+	^{191}Os	15.4 d	129.4
	190	26.4	^{3}He,p	+	^{192}Ir	74.0 d	316.5,468.1
	190	26.4	^{3}He,2n	-4.2	^{191}Pt	2.9 d	409.4,538.9
	189	16.1	α,2n	-17.	^{191}Pt	2.9 d	409.4,538.9
Ir	191	37.3	p,n	-1.8	^{191}Pt	2.9 d	409.4,538.9
	193	62.7	p,pn	-7.8	^{192}Ir	74.0 d	316.5,468.1
	193	62.7	^{3}He,2n	-3.5	^{194}Au	1.7 d	293.6,328.5
	193	62.7	α,n	-9.	^{196}Au	6.2 d	333.,355.6
Pt	194	32.9	p,n	-3.3	^{194}Au	1.7 d	293.6,328.5
	196	25.3	p,n	-2.3	^{196}Au	6.2 d	333.,355.6
	194	32.9	^{3}He,2n	-5.8	^{195m}Hg	1.7 d	261.8
Au	197	100.	p,pn	-8.1	^{196}Au	6.2 d	333.,355.6
	197	100.	d,p	-2.2	^{198m}Au	2.3 d	180.3,214.9
	197	100.	α,n	-9.8	^{200}Tl	1.1 d	368.,1205.7
Hg	200	23.1	p,n	-3.2	^{200}Tl	1.1 d	368.,1205.7
	202	29.8	p,n	-2.	^{202}Tl	12.2 d	439.6
	202	29.8	d,p	-2.2	^{203}Hg	46.6 d	279.2
	201	13.2	^{3}He,n	+	^{203}Pb	2.2 d	279.2,401,3
	200	23.1	α,n	-10.4	^{203}Pb	2.2 d	279.2,401.3
Tl	203	29.5	p,n	-1.8	^{203}Pb	2.2 d	279.2,401.3
	203	29.5	p,pn	-7.7	^{202}Tl	12.2 d	439.5
	203	29.5	^{3}He,n	+	^{205}Bi	15.3 d	703.5,1764.3
	205	70.5	^{3}He,n	+	^{207}Bi	32.2 y	569.1,1063.1
	203	29.5	α,n	-11.3	^{206}Bi	6.2 d	803.1,881.0
	203	29.5	α,2n	-18.4	^{205}Bi	15.3 d	703.5,1764.3
Pb	206	24.1	p,n	-4.4	^{206}Bi	6.2 d	803.1,881.0
	206	24.1	p,2n	-11.6	^{205}Bi	15.3 d	703.6,1764.3

References

1. Kormány Z., Valek A., ATOMKI közl., 26(1984)171.
2. L. Andó, F. Ditrói, A. Fenyvesi, I. Mahunka, T. Molnár, F. Szelecsényi, S. Takács, F. Tárkányi, ATOMKI Ann. Rep. 1986 p.45.
3. F. Szelecsényi, F. Tárkányi, ATOMKI Ann. Rep. 1988 p.116.
4. I. Mahunka, I. Dombi, S. Takács, F. Ditrói, IAEA 1989 INDC(Hun)-027/G p.21.
5. S. Takács, F. Ditrói, I. Mahunka, NIM B10/11(1985)1051.
6. S. Takács, F. Ditrói, I. Mahunka, NIM B43(1989)90.
7. F. Ditrói, I. Mahunka, S. Takács, S. Seif El-Nasr, J. Radioanal. Nucl. Chem. 130(1988)263.
8. F. Ditrói, S. Takács, I. Mahunka, Z. Gémesi, to be published in NIM B
9. I. Mahunka, F. Ditrói, S. Takács, ATOMKI Ann. Rep. 1989 p.60.
10. S. Takács, F. Ditrói, I. Mahunka, IAEA 1989 INDC(Hun)--027/G p.18.
11. E. Browne, R.B. Firestone, Table of Radioactive Isotopes, (Ed. V.S. Shirley) J. Wiley and Sons, 1986.

Radionuclide Technique in Mechanical Engineering in Germany

P. Fehsenfeld, A. Kleinrahm, H. Schweickert
Kernforschungszentrum Karlsruhe GmbH
Institut für Kernphysik III/Zyklotron
D-7500 Karlsruhe, Postfach 3640, Federal Republic of Germany

ABSTRACT

A subject of increasing application of cyclotron machines is the "Radionuclide Technique in Mechanical Engineering" (RTM), a measuring system that enables wear and corrosion diagnostics of components of operating machines, apparatus or processing plants. The three components of the RTM-system, the thin layer-activation at the cyclotron, the measuring methods and the measuring instruments for application in industry, have been developed systematically at KfK over more than 15 years and are being used increasingly by industry in Germany, Japan and the United States.

The present development of RTM to modern problems in engineering and material research as well as the successful application in new industrial areas will be reported.

1. INTRODUCTION

The working principle of RTM may be illustrated by the example of a combustion engine, very schematically delineated in Fig. 1 by the piston ring, the cylinder wall, the cooling water jacket and the housing wall. Subject to wear measurement is the cylinder wall, which has been labelled in its critical zone around the upper dead point of the piston ring by thin layer activation at a cyclotron. The thickness of the radioactive surface layer is adjustable to within 20 micrometer and around 0.2 mm according to the expected wear measurement depth.

The characteristic gamma radiation emitted from the labelled zone of the component penetrates the cyclinder wall, water jacket and housing wall without major attenuation and is recorded by a radiation measuring equipment (detector) appropriately located outside the machine, as indicated in Fig. 1 (upper part). The lower part of the figure shows a simplified calibration curve of the measured radiation intensity (or total activity) versus depth in the material. Thus the wear of the component can be observed easily and exactly via the variation of the activity caused by loss of material.

The measured radiation values are converted into wear values by a computer, integrated in the measurement equipment and displayed in a comprehensible and informative manner. With these introductory explanations of the function principle, it is evident that RTM is not only "thin-layer activation" but represents a technical system consisting of the three components

- Measuring Methods
- Measuring Instruments
- Thin Layer Activation Technique (TLA)

which are interrelated to each other.

Basic know-how and data as well as technical equipment to each of the three components of RTM have been developed continuously at KfK over the recent years to reliable applications in industry, engineering research and development.

2. THE COMPONENTS OF RTM

2.1 Measurement Methods

There are basically two methods which are applied in registering wear of an irradiated part, the measurement either of the activity removed from it (henceforth called the concentration measurement method (CMM)) or of the residual activity (the thin layer difference method or direct measurement method (DMM)). The first method is shown schematically in Fig. 2. The oil that lubricates the part or parts under study (tooth wheel and wheel bearing in Fig. 2) is pumped in a closed circuit and passes by a gamma ray detector in a flow chamber, which measures the activity of the wear particles suspended in the lubricant. Since the wear particles can be assumed to be distributed homogeneously and a constant fraction of the oil surrounds the detector the countrate is proportional to the total wear after the start of the experiment. The second method has already been mentioned in the introduction and is illustrated by Fig. 3. The activity of the irradiated part inside the machine is measured by a gamma ray detector close to the machine. In both types of measurements one has to make sure, of course, that the wear particles are removed from near the part under investigation. In some cases, such as wear of railway wheels, the direct measurement method is the only one which can be applied because the wear particles are inevitably dispersed.

The wear resolution capacity of both measurement methods is in the region of nanometers or nanograms at measuring times of some minutes and activity levels of the labelling around 0.1 millicurie (= 4 MBq). Both measurement methods have been developed by KfK to high performance and used in industry for more than ten years. The concentration measurement method is patented by KfK.

2.2 Measuring Instruments

The activity is measured almost exclusively by Sodium-Iodide-Detectors (NaI(Tl)). Germanium detectors offer a much better gamma energy resolution for wear studies with different radionuclides but they suffer from the sensitivity to shock and vibrations and the need of cooling by liquid nitrogen, often not available in industry.

So the instrument consists of conventional radiation measurement technique with a special fastpulse electronic fulfilling the following requirements:

- reliable counting of statistical pulse rates up to 300 kHz

- automatical dead-time correction
- temperature-compensated spectrum stabilizer
- on-line display of the wear propagation
- reliable operation under industrial environmental conditions

The measuring systems developed at KfK are manufactured and marketed by two different firms in licence of KfK.

2.3 Thin-Layer Activation

2.3.1 Basic physical considerations

The physical background of thin layer activation process is well known and will be described briefly by the example illustrated in Fig. 4. When fast charged particles from an accelerator enter a solid they are slowed down in a weildefined way. The particles usually employed in this type of study, mostly protons, deuterons and ^4He at energies between 6 and 100 MeV, come to rest at depths of the order of a millimeter below the surface. In the upper part of Fig. 4 the decreasing energy of protons over the travelling distance in iron, zero energy at the range of 1.35 mm is shown. Some of the protons interact with the ^{56}Fe-nuclides of the iron material resulting in the production of the radioactive nuclides ^{56}Co, via the $^{56}Fe(p,n)^{56}Co$ reaction. These radioactive nuclides represent the labelling which is used in the wear studies. The cross section for the production of ^{56}Co in iron material by proton changes drastically with the energy of the particles, resulting in the marked variation of the induced activity with depth. This is illustrated in the lower part of Fig. 4. The hatched area of the activity distribution indicates the depth range of approximately constant activity concentration. By choosing the suitable energy of the incident protons (in Fig. 4): E_p = 14 MeV - a layer of homogeneous activity concentration at the surface can be achieved. The quality of this procedure is demonstrated by
Fig. 5 showing the measured total activity (A) of ^{56}Co versus depth
(S, micrometer) in a steel (ST 37) sample activated by 14 MeV protons.

Within a depth range of 200 micrometer at the surface the correlation between measured activity and material loss is strictly linear.

The thickness of the homogeneous activity layer can be varied by different technical means in the range between 20 micrometer and 1 millimeter just

according to the requirements of the wear measuring problems. The chemical composition of the material to be activated is determined by engineering design considerations in virtually all cases. The physicist therefore has to choose the kind of particle and energy best suited for the material under study. This may be a complicated task because usually several different radionuclides with differing depth distributions are produced in the material. These make decay corrections complicated even in simple measurements, and frequently it is necessary to determine the depth distribution by experiment. This can be done by irradiating a small pin made of the same material, grinding off the surface step by step and measuring the residual activity each time.

In many cases it is possible to produce different radionuclides (even in the same material) by choosing the energy and the bombarding particle appropriately. This allows a simultaneous measurement of wear on different parts of the machine if the characteristic γ-radiations of the radionuclides can be separated.

The irradiation parameters and technique have been developed at KfK for thin layer activation of all industrial iron and steel grades, low-alloy steels up to high-alloy steels, non-ferrous metals and their alloys of Aluminium, Cobalt, Chromium, Copper, Molybdenum, Nickel, Lead, Tin, Vanadium, Tungsten, Zinc, sintered and hard metals and ceramic materials. Only the plastics and elastomers cannot be activated because of the modification of their mechanical properties when irradiated with charged particles.

The development work in thin layer activation has always been accompanied by investigation of damage in activated materials. The radiation dose of charged particles applied for thin layer activation is in the case of metals usually by a factor of 10^{-3} to 10^{-4} less than the critical dose at which radiation damage may occur and in the case of ceramics sometimes only 10^{-1} of the critical dose. Hence routine tests for radiation damage in ceramics have been introduced.

2.3.2 The irradiation of machine parts

Thin layer activation of a larger machine part may be demonstrated by the irradiation of a cyclinder block of a combustion engine illustrated schematically in Fig. 6. The beam from the cyclotron, 3 to 5 mm of diameter, leaves the evacuated beam tube through a thin metal window and hits the cylinder bore of the engine block adjusted at a distance of 150 mm in front of the tube head. The engine block rotates precisely around the axis of the bore. The incident ion beam produces a regular, annular label in the Top Dead Center (TDC) of the piston ring.

The precise labelling enables the directed wear measurements under real operation conditions. Very fast and reliable optimization to long lived components of the system piston ring-cylinder wall is possible. Fig. 7 shows the rotating engine block in front of the beam line of KfK Cyclotron. In the head of the beam line various equipment for controlling beam position and intensity (left part of Fig. 7) is integrated. The irradiation facility at Karlsruhe Cyclotron for thin layer actication of machine parts and various examples of irradiation are described in [1].

3. RECENT DEVELOPMENTS

3.1 New Areas of Industrial Applications

Textile and chemical industries are using advanced techniques. On the interest of these branches the activation technique and the measuring methods have been adapted to their special requirements. An example for application of these developments is demonstrated in Fig. 8 showing the setup for the wear measurement of a needle guidance system of a high speed knitting machine at the Institut für Textil Technik, Denkendorf. Needle guidances of different materials have been investigated. The result of the measurement, illustrated in Fig. 9, was an improvement of the machine service life by a factor of seven.

RTM enables a wear rate resolution down to few nanometer per hour.

3.2 Thin Layer Activation Technique for New Materials

Ceramics, cermets and hardcoatings are increasingly in use for the construction of modern engines, machines and apparatus. The enormous wear resistance of these new materials requires a sensitivity of the wear measurements - inevitable for development work - that can be achieved only by RTM.

Adequate irradiation procedures for thinlayer activation of the essential materials Al_2O_3, SiC, Si_3N_4, ZrO_2, TiC, TiN, cermets and a various types of coatings have been developed in cooperation with several industrial companies (Daimler-Benz AG, Detroit Diesel Corp., Feldmühle-Plochingen, Krupp-Essen) and material research institutes (IMF-KfK/Karlsruhe, MPA-University-Stuttgart). The developed activation technique has been successfully applied in wear measurements of these modern materials in industry and research laboratories.

A typical example for thin-layer activation of ceramics is illustrated in Fig. 10 by the activity-depth profile of ^{22}Na in Al_2O_3. The region of strict homogeneously

distributed activity over $S_M = 45$ µm near the surface, well suited for precise wear measurements, is demonstrating the high quality of activation technique.

There are still two problems remaining to be ' 'ved in further development work:

a) The minimum thickness of radioactive layer in some ceramics is limited to about 40 microns. Preferably a layer of 10 microns to 20 microns should be achieved because of the gain in sensitivity of wear measurement.

b) The yield for the production of suitable radioactivity in Al_2O_3, SiC, Si_3N_4 is as low as 3 % to 5 % of the yield of ^{56}Co in iron. The results are long irradiation times at the cyclotron and therefore high costs for the activation of these materials.

The most efficient technique for the achievement of the desired extreme thin layer activation of ceramics may become the ^{7}Be- and ^{22}Na-Ion-Implantation, which is under investigation at Michigan State University [2] as well as at KfK-Research Center. This activation method may also be suitable for the radioactive labelling of plastic materials, that could not be activated up to now because of its high sensitivity to radiation damage.

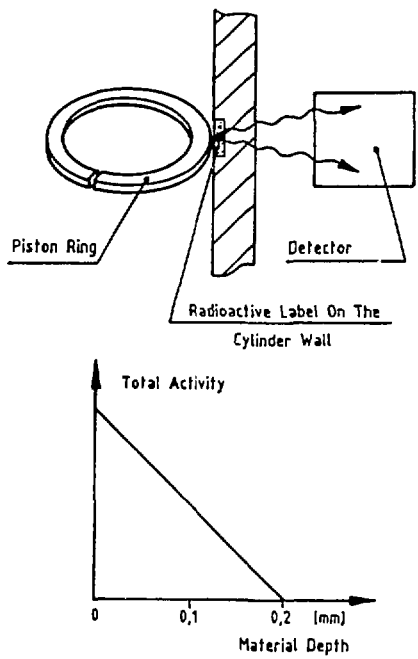
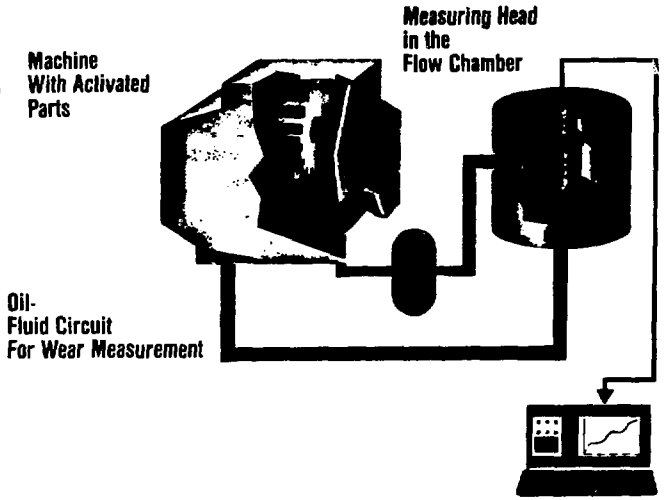


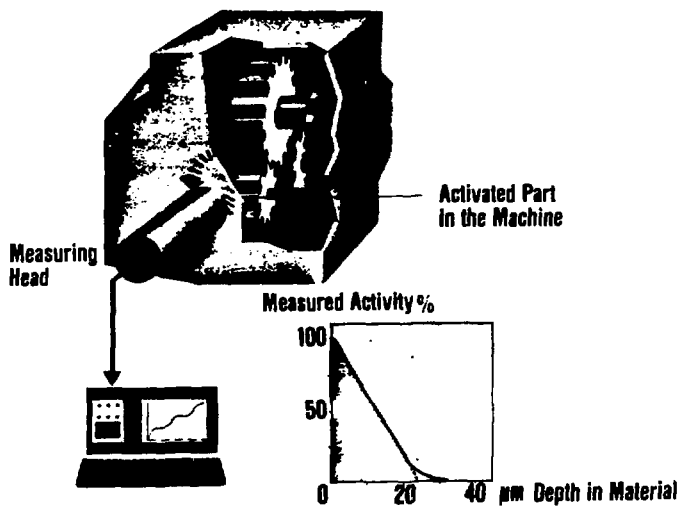
Fig. 1: Working principle of RTM:
The activity of the cylinder wall is monitored by a detector outside the engine. The lower part shows a simplified calibration curve of total activity versus material depth.



KfK

The Concentration Method (Flow Through Method)

Fig. 2



The Thin Layer Difference Method

Fig. 3

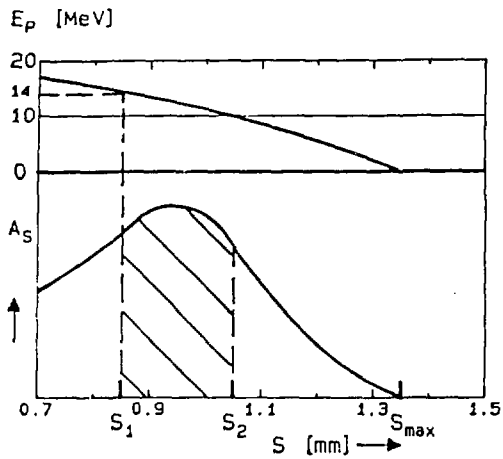


Fig. 4: Dependence of proton energy (upper part) and activity concentration (lower part) on depth for an irradiation of iron by 30 MeV protons. Only the last part of the range is shown. The hatched area indicates the depth range of approximately constant activity concentration.

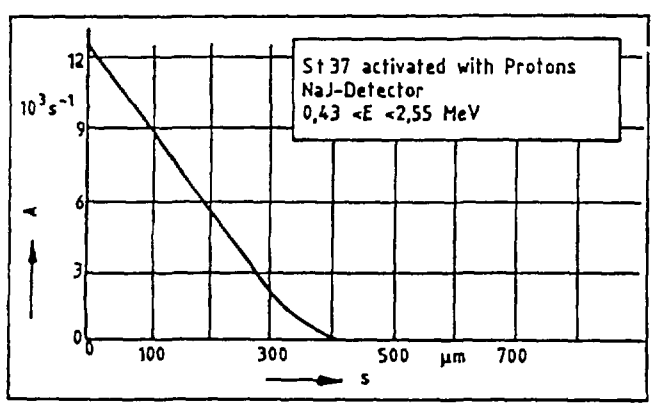
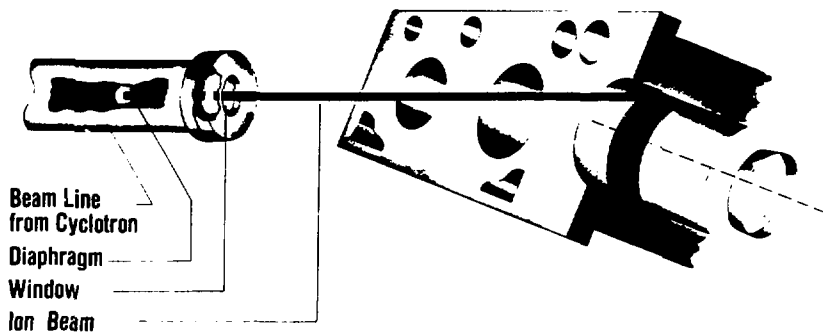


Fig. 5: Total activity versus penetration depth for 14 MeV protons in steel (ST 37).



Irradiation of an engine block

Fig. 6: Irradiation of an engine block: precise and uniform labelling on the cylinder bore for wear measurement in the T.D.C. of the first piston ring ("gusset wear").

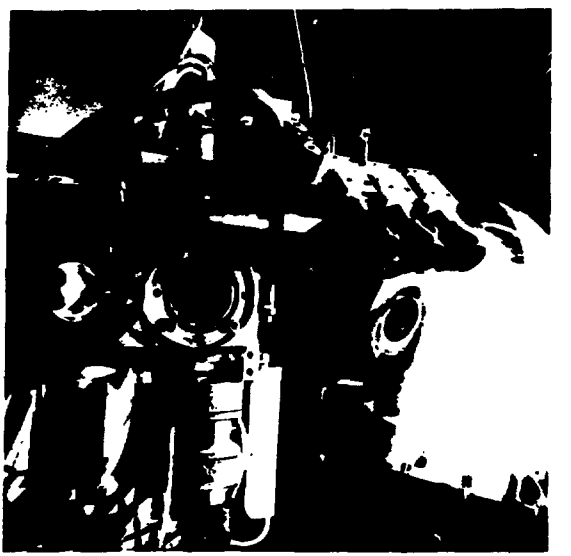


Fig. 7: Irradiation of an engine block at the cyclotron:

The engine block rotates around the axis of the bore. The incident ion beam produces a regular annular label in the T.D.C. of the piston ring. The precise labelling enables the directed wear measurements under real operation conditions and with that the very fast and reliable optimization to long-lived components of the system piston ring-cylinder wall.

Fig. 8: Wear measurement at a knitting machine.

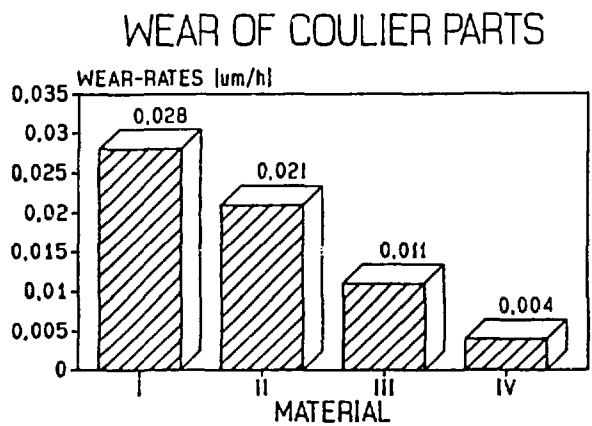


Fig. 9: Wear rates for different materials of the needle guidances in a knitting machine.

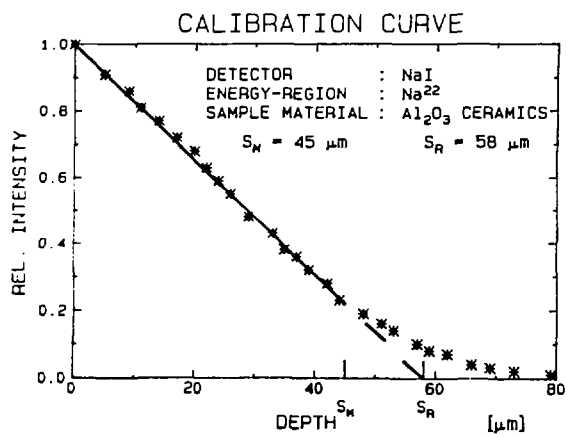


Fig. 10: Activity-depth profile of ^{22}Na in Al_2O_3.

Conclusions and Recommendations

Thin layer activation technique is one of the most effective methods of corrosion and wear monitoring which permits the measurement of wear and corrosion of critical parts in a machine or a processing plant under real operating conditions. This method is mainly being developed in France, Federal Republic of Germany, United Kingdom and USSR, and used in different branches of industry.

The methods of machine part and sample activation using accelerators are sufficiently developed and permit to measure the rate of wear and corrosion over the range (0,0001/1) mm per year. The latest achievements in this field permit to monitor the pitting corrosion, erosion and other complex processes of surface destruction.

The benefits from TLA application in industry exceed significantly the expenditure for irradiation of machine parts at accelerators and for purchasing of adequate equipment.

TLA as a method itself has some scientific intrinsic problems. For instance, the possible influence of high-density charged particle beam on the physical and chemical properties of the irradiated area of sample is of great importance, especially in the case of non-metallic samples (ceramics, superconductors, composite materials, etc.). Another problem is the lack of recommended nuclear data such as thick target yields, depth distribution of radionuclides, calibration curves for materials with complex chemical composition. It should be pointed out that above problems have much in common with other accelerator-based methods such as charged particle activation analysis, production of radionuclides, generation of neutrons, etc.

.../

Thin Layer Activation Technique in particular and Accelerator-Based Methods in general encompass a valuable set of techniques for the nondestructive evaluation of materials in their operating environments. These methods are extensively exploited in the developed countries and could be readily deployed in the developing countries given the appropriate infrastructure.

The Consultants consider that international co-operation in the above-mentioned problem areas is strongly needed.

The International Atomic Energy Agency can play a central promotional role in establishing a format for the international co-operation in this field and for transfer of technology. One of the posssibilities for such co-operation would be the strengthening of mutual exchanges of experience and information, i.e., in the form of co-ordinated research programmes, workshops and training courses.

The Consultants recommended for the establishment of a new Co-ordinated Research Programme on "Accelerator-Based Methods in Material Evaluation".

Research and development are required on the following topics:

1. Thin layer activation technique;

2. Nuclear analytical techniques based on accelerator technology;

3. Accelerators in neutron and proton radiography;

4. Influence of charged particle irradiation on physical and chemical properties of targets.

INTERNATIONAL ATOMIC ENERGY AGENCY

Consultants' Meeting
on
"Real-time Nondestructive Control of Wear and Corrosion Using Thin Layer Activation Technique"

IAEA Headquarters, Vienna
15 - 18 May 1990

LIST OF PARTICIPANTS

1. **Dr. B. Jeanneau**
C.E.A. Isotopes Applications Service
CEN-Saclay, DAMRI/SAR
BP 6 91192 Gif Sur Yvette Cedex
FRANCE
Telephone No. 33 (1) 69-08-25-51
Telex No. ENERGX 60461 F MRI
Fax NO. 33 (1) 69-08-60-30

2. **Dr. H. Schweickert**
Kernforschungszentrum Karlsruhe GmbH
IK III/Zyklotron
P.O. Box 3640
D-7500, Karlsruhe 1
FEDERAL REPUBLIC OF GERMANY
Telephone No. (07247) 82 2433
Telefax No. (07247) 82 3156

3. **Dr. I. Mahunka**
Institute of Nuclear Research, H-4001
P.O. Box 51
Debrecen
HUNGARY
Telephone No. (52) 17-266
Telex No. 72-210 ATO
Short Code HHINR

4. **Dr. T.W. Conlon**
Accelerators Branch
Nuclear Physics & Instrumentation Division
B8, Harwell Laboratory
United Kingdom Atomic Energy Authority
Oxfordshire OX11 ORA
UNITED KINGDOM
Telephone No. (0235) 433322 or 821111
Telex No. 83135
Fax No. (0235) 432424

5. **Dr. A.I. Leonov**
Department of Cyclotron Isotopes
Institute of Physics and Power Engineering
Bondarenko Square, 4
Obninsk
USSR

.../2

6. **Dr. J. Debrun**
CNRS - Cyclotron/CERI
3A Rue de la Ferolerie, F-45071
Orleans-Cedex 2
FRANCE

7. **Prof. F.V. Frazzoli - Observer**
Universita Degli Studi
Di Roma "La Sapienza"
Via A. Scarpa, 14-16
00161 Roma
ITALY
Fax No. 06/4270183

8. **B. Zatolokin - Scientific Secretary**
International Atomic Energy Agency
P.O. Box 100
A-1400 Vienna
AUSTRIA
Telephone No. 43 1 2360 1745
Telex No. 1-12645
Fax No. 43 1 234564

1206