ATOMINSTITUT
DER ÖSTERREICHISCHEN UNIVERSITÄTEN

APPLICATION OF RADIONUCLIDES IN NUCLEAR TECHNOLOGY*

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AIAU 83301

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AUSTRIA

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CONTENTS

Abstract:

Four main applications of radionuclides in nuclear technology are presented which are level-, density- and thickness gauging and moisture determination. Each method is surveyed for its general principle, various designs, accuracy, errors and practical designs.

INIS-Subject Category D22

INIS-Keywords. Radiometric gages (M)
densimeters
level indicators
moisture gages
thickness gages

USES

LIQUID LEVEL GAUGING BY RADIONUCLIDES

General remarks:

Level gauging without contact between the sensor and the medium becomes increasingly important in various industries. Here radioactive sources play an important role, because of many advantages such as reliability, contact free instruments, applicability especially for aggressive, corrosive, ultra-pure liquids, suspensions, slurries or fine grain solid materials such as powders, grains, dust etc. Therefore this method is widely used in chemical-, ore-, coal and oil industry. A level gauging unit consists of a radioactive gamma-source, usually ^{60}Co or ^{137}Cs and a detector located diametrally in respect of a container or a vessel. As long as the level in the container is below the connection line of source and detector, the gamma radiation is not attenuated except by air. If the level increases above that line, the gamma radiation is attenuated depending on the density of the material and the radiation intensity at the sensor is considerably smaller.

If I_o is the intensity of the source at an empty container and I is the intensity when matter is located between source and detector, then $I = I_o.e^{-\mu d\rho}$ with ρ the density in /$g.cm^{-3}$/, d the distance in /cm/ and μ the mass attenuation coefficient in /$cm^2.g^{-1}$/. For ^{60}Co μ = o,o5 $cm^2.g^{-1}$, for ^{137}Cs μ = o,o77 $cm^2.g^{-1}$. With a given distance d and for a given material with specified μ and ρ the optimal source activity A can be calculated according to

$$A = \frac{D.d^2.S}{k}$$

d - distance /m/

S - attenuation factor for the empty container $S=\exp(\mu.\rho.d)$

k - dose constant / $R.h^{-1}/mCi.m^{-2}$/ ^{60}Co k=1,35, ^{137}Cs k= o,355

D - dose rate at the sensor for the empty container / $mR.h^{-1}$/

The attenuation factor is shown in fig.1 as a function of the mass per unit area for the three most important radiation sources.

As an example the source strength shall be calculated for a container consisting of a 1o mm Fe wall and a 5o mm inner coating with a density similar to concrete for a ^{6o}Co source. Figs. 2 & 3 show the attenuation coefficients for the materials lead, iron and water.

Container wall 2 x 2o mm Fe : $S_{fe} = 1,45$
Coating 2 x 5o mm Concrete (= 2 x 17 mm Fe): $S_c = 1,8$

$S_t = 2,6$

If the detector should record an intensity of o,5 mR/h at a distance of 3 m, the activity is calculated according to

$$A = \frac{D.d^2.S}{k} = \frac{o,5\ mR/h.\ 9\ m^2.2,6}{1,32\ mR/h} \cdot \frac{mCi}{m^2} = 8,9\ mCi$$

The intensity decreases due to a material between source and detector and can be easily estimated from fig.2 & 3 for water and concrete .

Some technical examples:

The most simple construction using one source and one detector is shown in fig.4,5. Using one source and two detectors (fig.6,7) three signals can be obtained which are level high, normal or low. In this case the source has to be mounted in the same level than the upper detector, for the source strength calculations the distance of the source to the lower detector has to be used. If however the distance between the two sensors becomes greater than the vessel diameter, two sources with two detectors have to be used (fig.8). Another construction type uses a rod-type

radiation source and one sensor, a method which allows a continuous level control (fig.9). If the container diameter is very large and demands a high source strength, another solution shown in fig. 1o can be applied. Here the source is located in a tube extending into the container volume. The detector is located outside along the vessel. This construction allows a low source strength even at large vessels, because the tube containing the source can be installed close to the container surface.

For some special cases and small containers also ß-radiation is applied using either ^{9o}Sr or ^{85}Kr sources with 1 to 1o mCi source strength. Some examples are the control of level of liquid gas as in cigarette lighters or the liquid in vials in the pharmaceutical industry. The precision level is $\pm$ o,1 mm typically and a control speed of 2 containers per second can be achieved. As detector a G-M end window counter is used.

Some technical examples for the application of radionuclides in areas of high vibration, high temperature or in conveyor band control are shown in figs. 11 a-d.

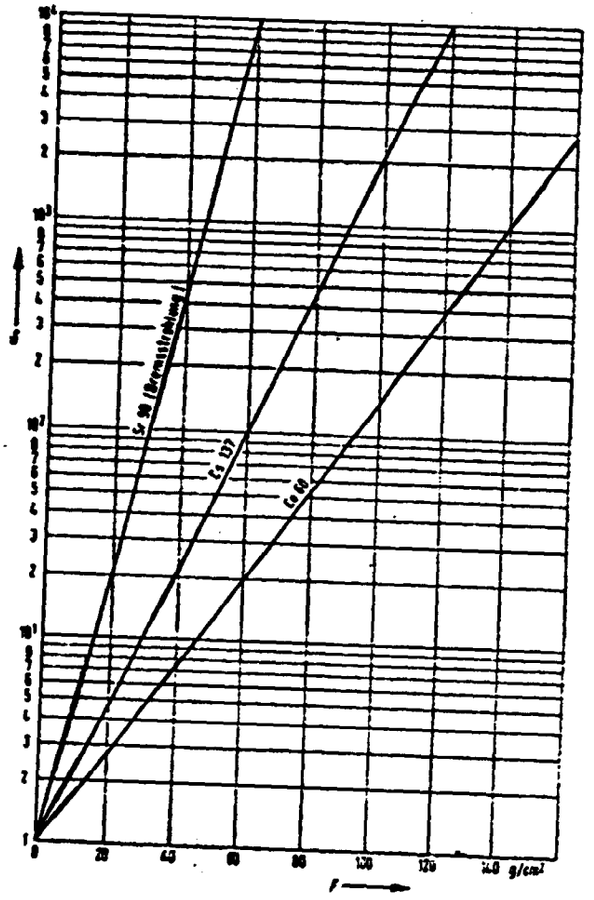
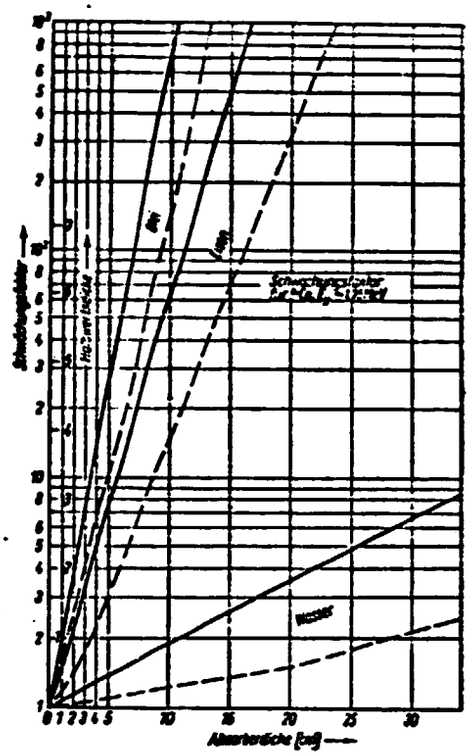


Fig.1: S = exp(μ .F) as a function of F (= mass per unit area = ρ.d)
Abb.1: S als Funktion der Flächenmasse



Strahlungsschwächung durch Blei, Eisen und Wasser für Gammastrahlung des ^{60}Co.

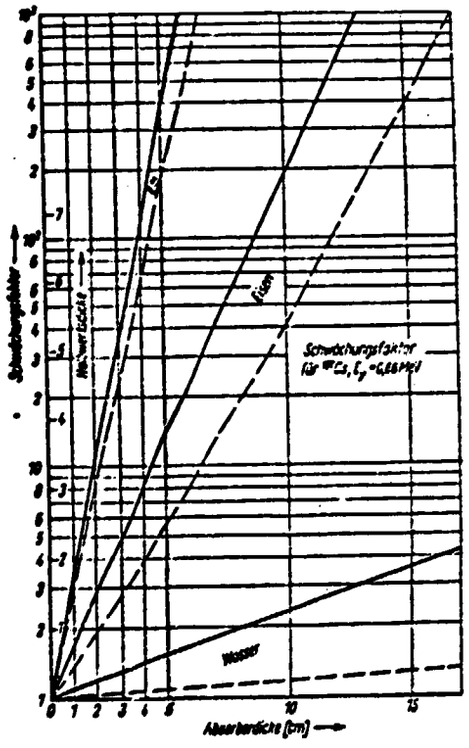
Vollinie: schmales Strahlenbündel mit linearem Schwächungskoeffizienten:

Blei $\mu = 0{,}63\ cm^{-1}$,
Eisen $\mu = 0{,}42\ cm^{-1}$,
Wasser $\mu = 0{,}063\ cm^{-1}$;

Strichlinie: breites Strahlenbündel nach Gusew und Kowalew

Fig.2: Radiation attenuation for lead, iron and water for Co-6o.Full lines are valid for for well collimated beams, broken lines are valid for broad beams

Fig.3: Radiation attenuation for lead iron and water for Cs-137.Full lines are valid for well collimated beams, broken lones are valid for broad beams.



Strahlungsschwächung durch Blei, Eisen und Wasser für Gammastrahlung des ^{137}Cs.

Vollinie: schmales Strahlenbündel mit linearem Schwächungskoeffizienten:

Blei $\mu = 1{,}2\ cm^{-1}$,
Eisen $\mu = 0{,}57\ cm^{-1}$,
Wasser $\mu = 0{,}087\ cm^{-1}$;

Strichlinie: breites Strahlenbündel nach Gusew und Kowalew

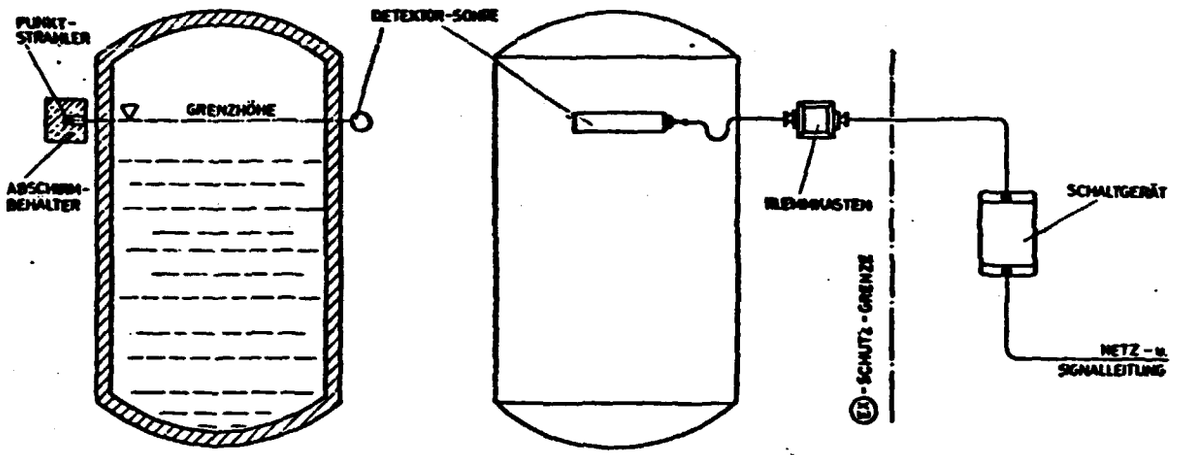


Fig.4: Principal arrangement for maximum level surveillance

Abb.4: Prinzipieller Aufbau für Maximum-Füllstandsüberwachung

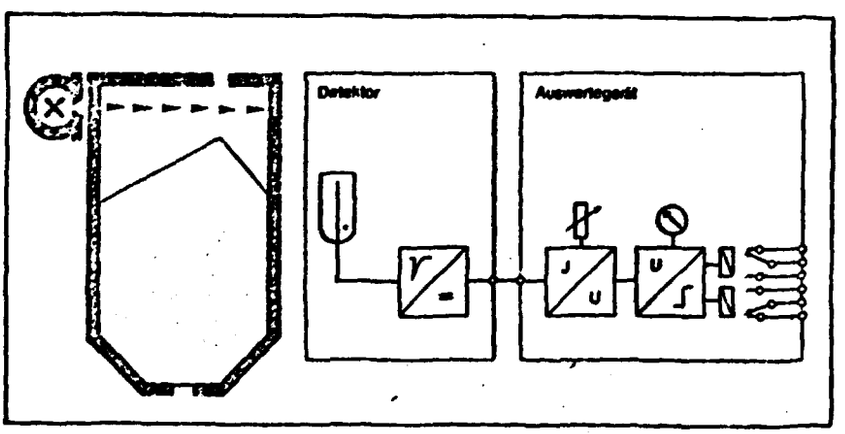


Fig.5: See fig.4

Abb.5: Siehe Abb.4

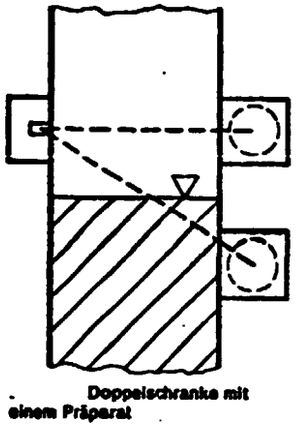


Fig.6: Arrangement for maximum-minimum surveillance using one source

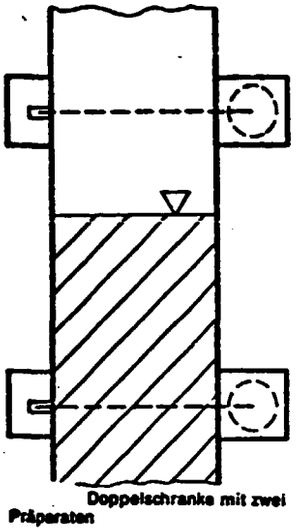


Fig.8: Arrangement for maximum-minimum surveillance using two sources and two detectors

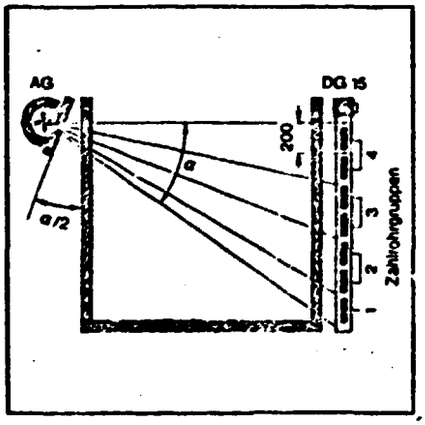
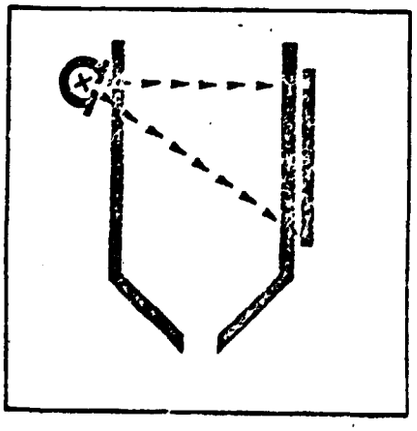
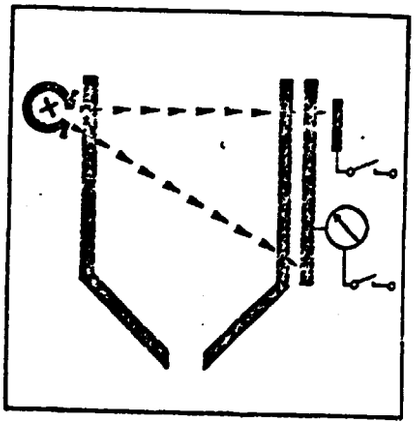


Fig.: 7,a,b,c:Various designs for level control with one source and one or more detectors





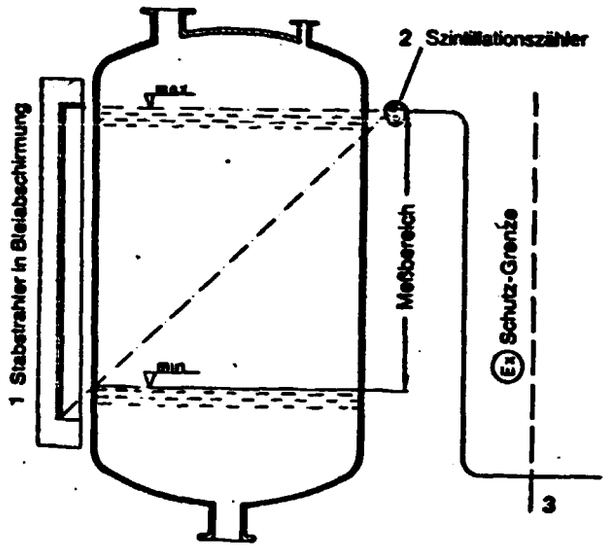


Fig.9: Level control with a rod type source and one detector
Abb.9: Füllstandskontrolle mit einer stabförmigen Quelle und einem Detektor

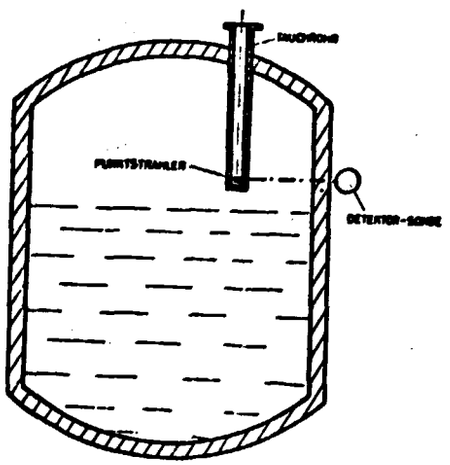
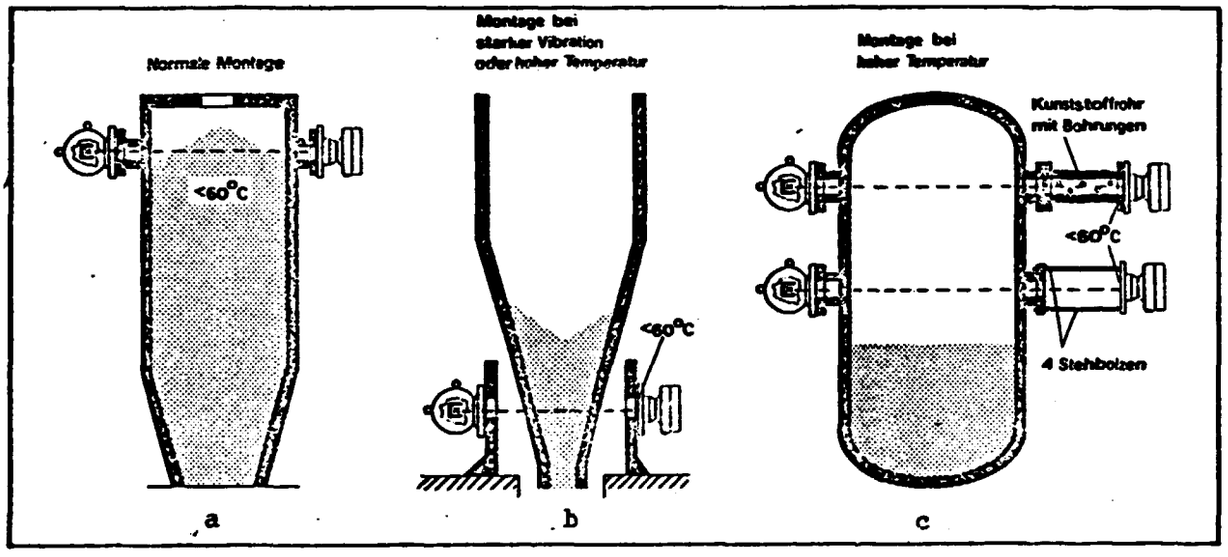
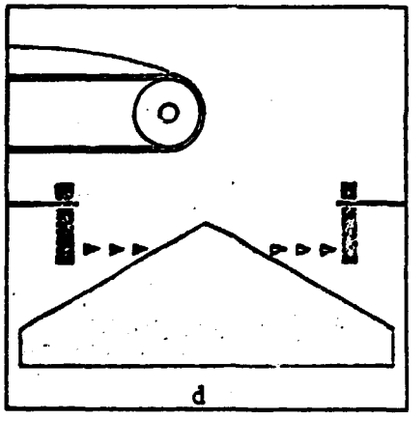


Fig.1o: Level control with a radiation source located inside the vessel
Abb.1o: Füllstandskontrolle mit einer im Behälter befindlichen Strahlenquelle



Figs. 11 a,b,c,d: Various designs for level control with radionuclides in case of high vibration,high temperature or for conveyor band control.
Abb.11 a,b,c,d: Verschiedene Ausführungsarten für Füllstandskontrolle mittels Radionukliden bei Anwendung im Bereich starker Vibrationen, hoher Temepratur oder bei Förderbändern.



DENSITY MEASUREMENT BY RADIONUCLIDES

General survey:

Compared with conventional methods of density determination the radiometric methods have very important advantages which are

- no direct contact with the media
- on-line determination possible
- no or easy to compensate dependance of temperature, pressure, viscosity of the media
- simple installation
- high efficiency and accuracy
- long-term stability
- especially suited for liquids or liquids with solid particles such as slurries, mixtures or solutions.

Due to this advantage the radiometric methods are widely applied in chemical industry where corrosive, chemical aggressive, inflammable or ultr-pure liquids have to be monitored. Other application fields are food- and drink industry, pulp- and paper industry, oil industry, coal-, sand- and silt industry.

The density determination is based on the fact that the mass $F = \rho . d$ of some material acts as an absorber for a given radiation intensity I according to

$$I = I_o . e^{-m.d.\rho}$$

where I (I_o) is the intensity without (with) absorber, d is the thickness, ρ the density and m the attenuation coefficient

of the unknown material. If d remains constant like in pipelines, ρ can be determined.

A density gauge consists basically of a radiation source and a detector. The material to be measured has to have a constant thickness. In case of gases, liquids or suspensions for which most density gauges are designed, the material passes the gauge through a tube in which case the inner tube diameter determines the thickness of the material. The tube walls have no influence on the measurment as long as they remain constant. The calibration of the gauge has to be made by a substance with known density, accuracies of o,1 % are possible.

If one combines a density measurement with the measurement of the flow speed, the product of both quantities gives the mass flow in the system. Massflow meters are very often used for liquids or two-phase systems of liquids plus some solid material i.e. mineral slurries in ore processing plants.

In figs. 1,2,3 some basic designs of density gauges are displayed.

Density gauges use ß- or γ-emitters, either in the transmission- or in the back-scattering mode. The radiation source has to be selected according to the given industrial problem in view of its radiation type, source strength, decay energy and half-life

Density determination by the gamma transmission method

This is the most widely used method especially for liquids in containers or pipes, because it can be applied from outside without interfering with the liquid or the container construction. The most important radiation sources due to their decay energy and half-life are ^{60}Co and ^{137}Cs with activities

between 1o to 1ooo mCi. Attention has to be paid that the liquid does not contain any gas bubbles, that the flow rate is not too low in order to avoid deposition of crud and that the temperature is kept constant. In case that temperature ccnstance cannot be assured, a temperature compensation has to be provided. Usually if the pipe diameter is not too small (∿ 1oo mm), the radiation penetrates the liquid perpendicular to the flow direction. In certain cases where the radiation should transverse a longer path inside the medium the pipe form has to be changed to a S-bend form (fig.4), where a path length up to 1ooo mm can be achieved. Increasing the path also effects the mean error $\Delta\rho$ in the density determination. For one given installation the influence can be seen from fig.5. The collimation of the beam must be good enough not to interact with the pipe walls to reduce scattering effects. Another possibility to measure the density of liquids in larger containers is to position the radiation source inside the container and the detector outside (fig.6).

From the wide range of applications three types are most important which are

- density measurement of slurries with a high percentage of solid material (fig.7)
- density in oil industry to discriminate between oil products of different density (fig.8)
- density measurement of concrete in prefabricated appartement construction (fig.9)

Besides there are a wide range of typical applications, some of these are listed below:

Acids (numerous and various including nitric, sulphuric, hydrochloric, phosphoric and boric), alcohol and water, asbestos rock, bauxite, cement, clay, coal, coal tar, corn syrup, drilling mud, fly ash, fuels, gypsum, lime mud, magnesium compounds, phenol, salt, sand, sewage, sludge, sodium compounds, sugar syrup.

Density determination by the beta-transmission method:

The attenuation of ß-radiation by matter is several orders of magnitude stronger than for gamma-radiation. Therefore is the application of ß-transmission for density measurement limited to very few specific problems. Due to the short range in matter the radiation source has to be implemented directly into the medium which has sevral important disadvantages (fig.1o). One example where the ß-method is applied is the control of sedimentation in suspensions. Some other advantages are in the application in liquid/gaseous mixtures i.e. moisture content of steam, because the ß-range is higher in gaseous media.

The most important industrial application is the control of the density of tobacco during the manufacturing process of cigarettes which is performed by ^{90}Sr radiation. An accuracy of o,3% can be obtained when controlling the filling density of tobacco which may help to save considerable tobacco costs. By feedback of the density data the amount of tobacco is regulated (fig.11). The production speed can be as high as 2 m/s.

Density measurement by gamma-backscattering:

The scattered radiation of gamma rays is composed of Compton-scattered photons, Bremsstrahlung and electrons. For this method the most important parts origin from Compton-scattering which is proportional to $\frac{Z}{A} \cdot \rho$. With optimized geometry the intensity of the scattered radiation is nearly linear with density (fig. 12) Using the backscattering method two effects superpose: The penetrating radiation produces more Compton electrons with increasing Z, but the scattered radiation is attenuated with increasing density before reaching the detector. Therefore the intensity of less collimated beams show a non-linear dependence of ρ, depending on the type of radiation source.(fig.13). With increasing density and decreasing gamma energy the volume seen by the radiation is reduced.

The gamma-backscattering method can take advantage of two density dependent effects:

1. The increase of scattered radiation with density
2. The increase of attenuation of the scattered radiation by density.

If the measurement is based on the first effect, the sensitivity depends very much on the wall thickness of the container where the material is stored. This poses many problems, therefore the industrial application is mostly based on the second effect, where the impact angle and the distance of the source and the medium has to be optimized.

The main technical application of this method is borehole logging to obtain information of the density profile of the soil. Such a device is shown in fig.14 or 15. Usually ^{137}Cs sources are applied with a source strength in the mCi range combined with a scintillation crystal. In optimal cases the accuracy is about 2%.

Other types of gamma backscattering units are shown in fig.16 & 17, using ^{137}CS or ^{60}Co with an activity of a few mCi. The layer thickness which is penetrated by the radiation is about 100 to 150 mm. Density variation of 0,03 $g.cm^{-3}$ have been reported to be detected with an accuracy of about $\pm$ 2%. Problems can arise with good contact of the surface backscattering unit and with inhomogeneous layers.

Density measurement by beta-backscattering:

The scattering cross section of beta radiation is directly dependent on the atomic number Z according to $I \sim Z^k$ $(0,5 \leq k \leq 1)$. The backscattering coefficient i.e. the fraction of backscattered radiation in relation to the primary radiation varies according to Z^2/A.

As the density of the elements is not steadily increasing with Z, the ß-backscattering cannot be used for a true density measurement, but using calibration standards, a density determination can be performed.

Two typical detector designs are shown in figs. 18 & 19, using ^{90}Sr with an activity ranging from 50 Ci to 100 mCi. The method can be used for the determination of coating thickness of thin layers (Ni,Cr on SST, Au on Cu, or printed circuit boards, paints on steel) or for the sedimentation speed in liquids.

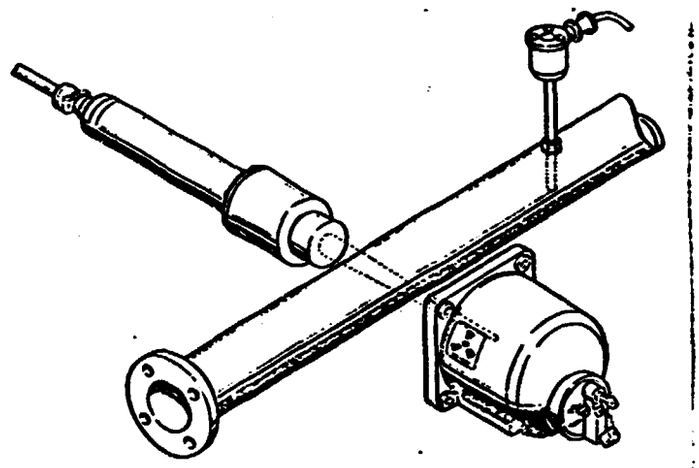


Abb. 1
*Prinzipielle Anordnung für die Dichtemessung bei **Querdurchstrahlung** einer Produktleitung (mit zusätzlichem Fühler für Temperaturkompensation).*

Fig.1: Density measurement with transversal beam penetration of a pipe including temperature compensation

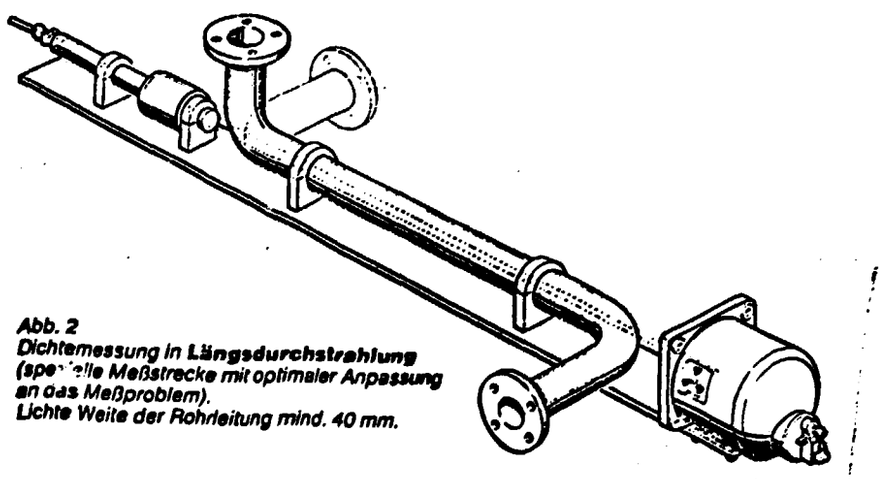


Abb. 2
*Dichtemessung in **Längsdurchstrahlung** (spezielle Meßstrecke mit optimaler Anpassung an das Meßproblem).*
Lichte Weite der Rohrleitung mind. 40 mm.

Fig.2: Density measurement with longitudinal beam penetration of a pipe, minimum diameter 40 mm.

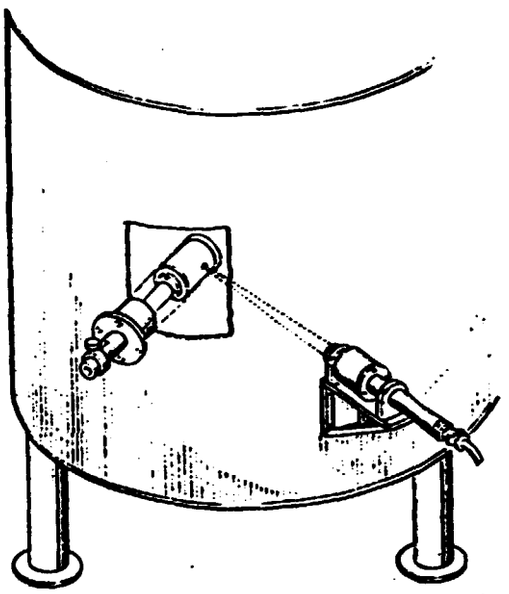


Abb. 3
Einbau des Strahlers in einer verschließbaren Abschirmung in ein Tauchrohr zur Dichtemessung an großen Behältern oder bei großen Rohrdurchmessern.

Fig.3. Density measurement of liquids in large containers with the radiation source inside the container and the detector located outside on the container wall.

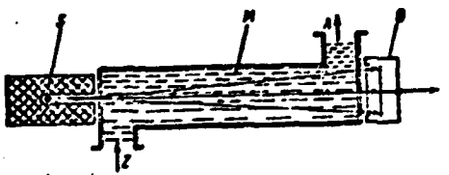


Bild 4 Meßstreckenanordnung in Rohrlängsrichtung.
A Abfluß; *D* Detektor; *M* Meßgut; *S* Strahler; *Z* Zufluß

Fig.4: Density measurement in axial direction. S-source, D-Detector, Z-liquid in, A-liquid out, M-medium

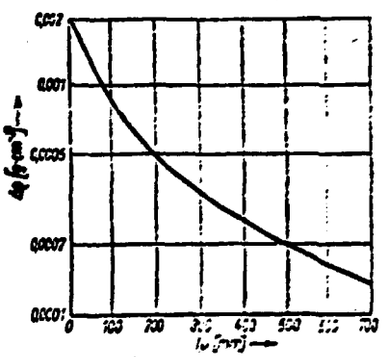


Bild 5. Mittlerer Fehler $\Delta\varrho$ (in g·cm^{-3}) beim Dichtemeßgerät „Quaeleon 5060" als Funktion der Meßweglänge l_M

Fig.5: Mean error as a function of the measurement length l_M

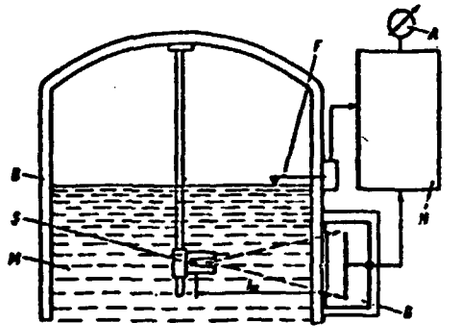


Bild 6 Anordnung der Meßstrecke in einem Behälter *B*, dessen Durchmesser größer als die Meßstreckenlänge l_M ist.
A Anzeige; *D* Detektor; *F* Füllstandskontrolle; *H* Hauptgerät; *M* Meßgut; *S* Strahler

Fig.6: Source - Detetctor arrangement in a large container
S-source, D-detector, M-medium, F-level control,
A-display, H-electronics, B-container

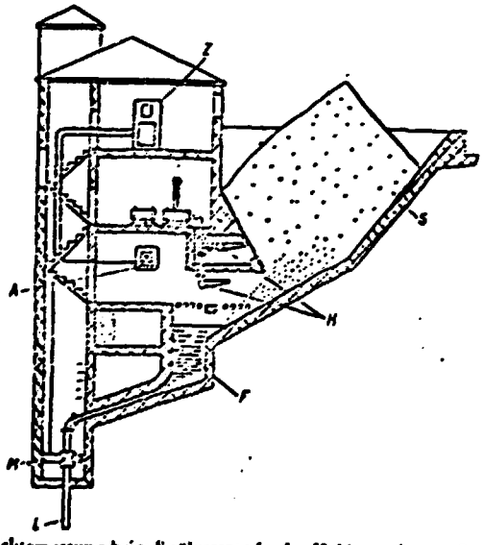


Bild 7 Dichtemessung beim Spülversatz in der Kohlengrube von Sosnowice
A Großsichtanzeige; *F* Spülversatzflüssigkeit; *H* Hydromonitore; *S* Sandvorrat; *Z* Zentralgerät

Fig.7: Density control of coal slurry, A-display, F-transport
liquid,

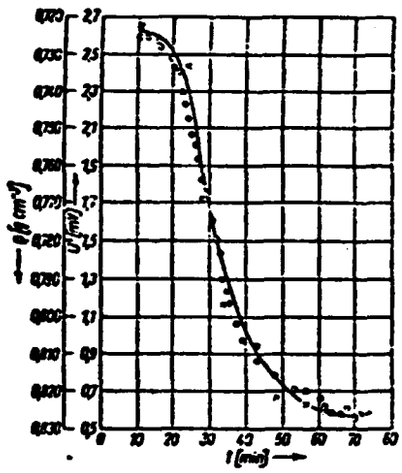


Bild 8 .. Durchgang einer Benzin/Petroleum-Grenzschicht in einer Ölleitung
Dichte ϱ bzw. Ausgangsspannung U des Dichtemeßgerätes als Funktion der Zeit t.
O mit dem Kernstrahlungs-Dichtemeßgerät GP-1 aufgenommen,
× aräometrisch ermittelt (Probenentnahme)

Fig.8: Passage of two petrol charges with different densities in a pipe line.
o measured by radiation, x measured by other methods

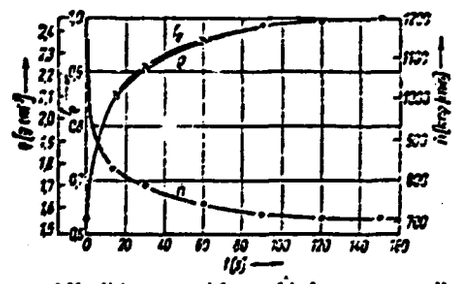


Bild 9 Dichte ϱ und Verdichtungsgrad f_ϱ von frisch vergossenem Beton sowie Impulsdichte h einer geschwächten Gammastrahlung als Funktion der Vibrationszeit t

Fig.9: Density and compaction of fresh concrete and gamma count-rate as a function of time

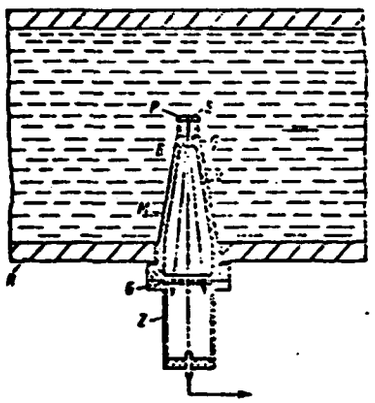


Bild 10 Meßkopf für Dichtemessungen mit Hilfe der Betastrahlungsschwächung [80].
B Blende; *G* Glimmerfenster; *M* Meßkopfgehäuse; *P* Präparathalter; *R* Bohrleitung mit Meßgut; *S* Strahler; *V* evakuierter Raum; *Z* Zählrohr

Fig.1o: Density determination by ß-attenuation in liquids. S-source, Z-counter, G-end window, M-medium, B-collimator V-evacuated space.

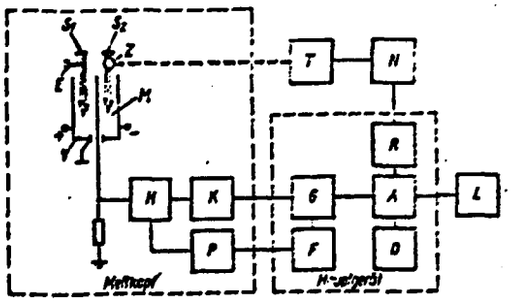


Bild 11. Blockschaltbild des Strangdichtemeß- und -regelgerätes VA-T-73
A Ausgangsstufe; *D* Abweichungsanzeige; *E* Einstellung des Sollwertes; *F* Vergleichssignal; *G* phasenempfindl. Gleichrichter; *H* Modulator; *K* Verstärker; *L* Linienschreiber; *M* Meßkammer; *N* Motor der Tabakzuführung; *P* Phasenschieber; *R* Regelungseinrichtung; $S_{1,2}$ Strahler; *T* Tabakzuführung; *V* Vergleichskammer; *Z* Zigarettenstrang

Fig.11: Blockdiagram of tobacco density control unit. Z-cigarette string, S_1, S_2-sources, M-detector, E-reference unit, T-tobacco supply, electronics

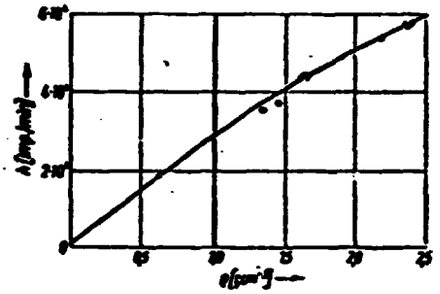


Bild 12. Streustrahlungsintensität I_S (ausgedrückt durch die Impulsdichte $\dot{n}$) als Funktion der Dichte ϱ einer Streusubstanz bei schräger Einstrahlung eines engen Bündels

Fig.12: Intensity of scattered radiation I_s as a function of the density of the scattering medium

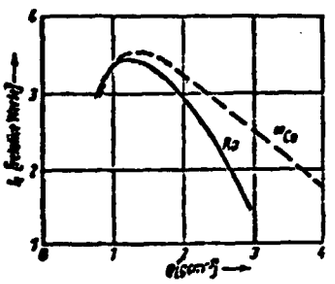


Bild 13 Streustrahlungsintensität I_1 in Abhängigkeit von der Dichte ϱ der Streusubstanz bei wenig gebündelter Strahlung

Fig.13: Intensity of scattered radiation I_1 as a function of the density of the medium for non-collimated radiation.

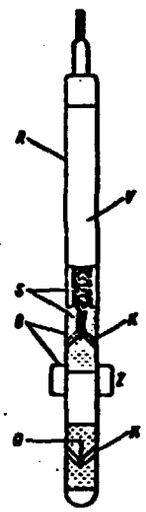


Bild 14 Gamma-Gamma-Sonde für Bohrlochuntersuchungen (Tiefensonde) mit Kollimierungskanälen *K* vor der Strahlenquelle *Q* und dem Szintillationszähler *S*.
B Bleiabschirmungen, *R* Sondenrohr, *V* Vorverstärker, *Z* Zentrierung

Fig.14: Gamma probe for borehole logging. Q-source, K-collimators B-lead shield, R-tube, Z-alignment

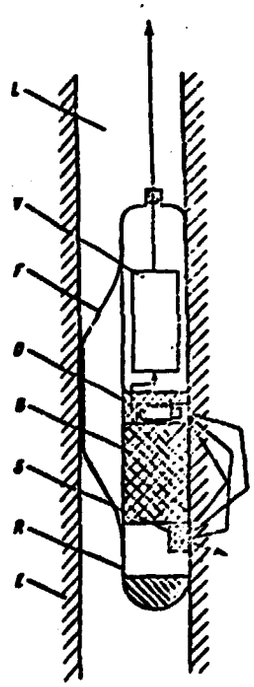


Bild 15. Bohrlochsonde für variable Bohrlochdurchmesser
B Bleiabschirmung, *D* Detektor, *E* Eintritt, *F* Feder, *L* Bohrloch, *R* Sondenrohr, *S* Strahler, *V* Vorverstärker

Fig.15: Gamma probe for borehole logging with variable diameter. S-source, D-detector, B-lead shield, F-spring

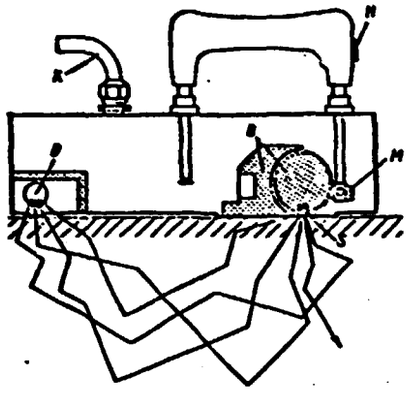


Bild 16 Oberflächensonde (Typ P 22) der Nuclear-Chicago
B Bleiabschirmungen; *D* Detektor; *H* Handknopf; *M* Mechanismus zur Bewegung der Strahlenquelle für Transport bzw. Betrieb; *K* Kabel; *S* Strahlenquelle

Fig.16: Surface probe for density determination by scattered radiation. S-source, D-detector, B-lead shield,

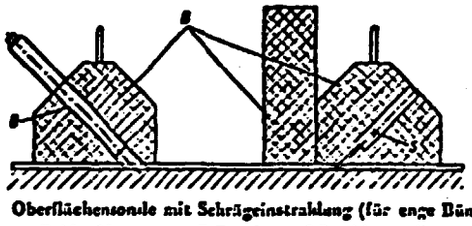


Bild 17 Oberflächensonde mit Schrägeinstrahlung (für enge Bündel)
B Abschirmungen; *D* Detektor; *S* Strahlenquelle

Fig.17: Surface probe for inclined penetration. D-detector, S-source, B-lead shield

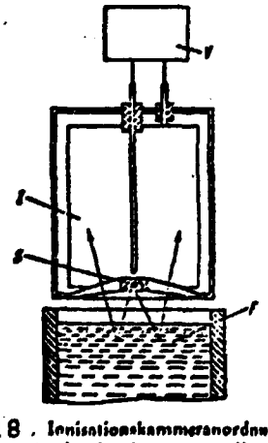


Bild 18. Ionisationskammeranordnung für die Konzentrationsbestimmung an offenen Flüssigkeitsoberflächen mit Hilfe der Betarückstreuung.
F Flüssigkeit; *I* Ionisationskammer; *S* Strahler; *V* Verstärker

Fig.18: Density determination of liquids by beta-reflection F-liquid, S-source, I-ionization chamber

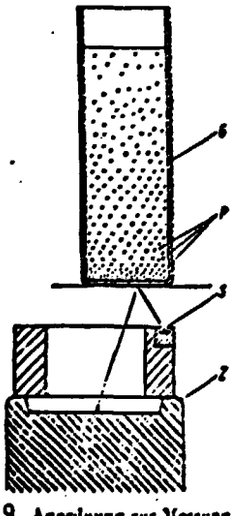


Bild 19 Anordnung zur Messung der Dichteraufnahme am Boden eines Sedimentationsgefäßes
G Sedimentationsgefäß; *P* suspendierte Partikel; *S* Strahler; *Z* Szintillationszähler

Fig.19: Density determination of sediments by beta-reflection G-sediment container, S-source Z-detector, P-sediment

THICKNESS GAUGING WITH RADIONUCLIDES

General survey:

The contact free method of thickness gauging with radioisotopes is applied in many industries which produce an endless flat product such as the paper-, rubber-, foil industry, but also in the production process of metal foils and stripes. Its main advantage is the absence of any contact between the material and the detector and it is unimportant whether the material is an electric conductor or not, if it has magnetic properties or not. According to the position of the source and the detector the backscattering method and the transmission method have to be distinguished.

Backscattering method:

If the material is only accessible from one side or if a thin layer has to be measured on another material this method is applied. In this case the radiation source can be situated either in the detector center (fig.1) or it can surround the detector as a ring (fig.2) For backscattering only ß-sources are used, which interact with the material. The following empirical relation between the parameters exist:

I_s - detector current
I_∞ - saturation current
μ_r - backscattering coefficient /$m^2.g^{-1}$/
s - area weight /$g.m^{-2}$/

$$I_s = I_\infty \quad (1 - e^{-\mu_r \cdot s})$$

With increasing area weight of the reflector the detector current increases until the saturation area weight s_∞ is reached (fig. 3). Fig.4 shows the saturation current as a function of the atomic number Z which can be empirically related by $I = B.Z^n$ (B- geometry factor, $n \sim 2/3$).

The value of the backscattering coefficient μ_r is mainly determined by the maximum ß-energy: $\mu_r\ [m^2.g^{-1}] = 0{,}004\ E_{max}\ [MeV]$. It is very important that the supporting layer Z_m and the surface layer Z_s have different atomic numbers. One of the two conditions must be fulfilled:

$$1{,}2 \leq \frac{Z_m}{Z_s} \leq 0{,}8 \qquad |Z_m - Z_s| > 3$$

The detector current for a two layer system can be determined as follows:

$I_s = I_{s\infty} + (I_{m\infty} - I_{s\infty}).e^{-\mu_r s}$ under the conditions that the supporting layer has its saturation area weight $S_{m\infty}$

I_s - current for area weight s of the surface layer
$I_{s\infty}$ - current for saturation area weight s_∞ of surface layer
$I_{m\infty}$ - current for saturation area weight of support layer

Depending now whether $I_{s\infty} \lesseqgtr I_{m\infty}$ or whether $Z_m > Z_s$, $Z_m < Z_s$, the detector current I_s will increase or decrease with increasing s If s changes the detector signal will change according to

$$\Delta I_s' = (I_{s\infty} - I_{m\infty}).e^{-\mu_r . s}\ \mu_r . \Delta s$$

A constant distance between material and detector is very important. In addition for each problem an optimal distance can be determined where the detector current reaches a maximum. In general this is around 25 mm.

The backscattering method is most widely used in the plastic- and rubber industry but also in the galvanizing industry for protective coating of metals. It can also be used for wall-thickness measurements of tubes and metal plates which are only accessible from one side.

Transmission method:

When applying this method the material is located between the source and the detector. In fact this method is more widely used in industry than the backscattering method especially because it has a higher sensitivity than the backscattering method. The attenuation of the radiation depends mainly on the product of density times thickness (which is also called mass per unit area = $g.cm^{-2}$), on the atomic number Z and on the type and energy of the radiation. Therefore this method gives only direct results of the thickness if the density is constant. Problems may arise when measuring alloys.

Radiation sources:

To select the optimal radiation source several aspects have to be taken into consideration. The energy must be high enough that even in the thickest part of the material it is not absorbed completely. It should also show an obvious attenuation in the thinnest part of the material. In order to estimate the measuring limits the relative sensitivity S_r is important which can be derived from the intensity attenuation:

$$I = I_o . e^{-m.d.\rho} \quad \text{and by differentiation}$$
$$S_r = -m.d.\rho . e^{-m.d.\rho}$$

Fig. 5 shows the resolution of different radiation sources for various materials. S_r gives the relative change of the radiation intensity triggered by a change Δd in thickness at a given d.

The measuring range using the transmission method is from 1o to 1o ooo $g.m^{-2}$, for the backscattering method 5 to 3 ooo $g.m^{-2}$ with a typical source strength of 5 to 75 mCi. For thick materials ß-Bremsstrahlung is used with Kr- or Sr-sources from 5oo to 2ooo mCi, extending the range from 1ooo to 3oo ooo $g.m^{-2}$.

Besides ß-sources also gamma sources are used for thickness gauging. Due to the energy and half-life limit only a few nuclides are important which are listed below:

Nuclide	$T_{1/2}$	Type	Energy	Range /g.m^{-2}/	Max.Reso-lution	Al /mm/	Fe /mm/
Pm-147	2,6 a	ß	o,23 MeV	o,o5-2oo	o,o5	o-o,4	o-o,12
Kr-85	1o,6 a	ß	o,7 MeV	o,1-15oo	o,1	o-o,4	o-o12
Sr-9o	28 a	ß	2,27 MeV	o,5-1oooo	o,5	o-2	o-o,7
Am-241	458 a		o,o6 MeV	1-4oooo	1	2-5o	o-7
Cs-137	3o a		o,66 MeV	3o-5ooooo	3o		4-7o
Co-6o	5,3 a		1,17+				
			1,33 MeV	5o-8ooooo	5o		6-1oo

In addition secondary sources can be used which emit γ-radiation on a target which again emits monoenergetic photons. Using a target with Z ∿ 4o to 6o monoenergetic photons with energies of o,o15 and o,o4 MeV are obtained which can be used to penetrate 5 to 8 mm of Al.

Kr-85 and Sr-9o are mostly applied for thin foils, because a higher sensitivity is obtained. However the ß-electrons are also attenuated in air or in lubricant which may cover the foil and this may produce errors. In example a temperature change of the air influences the density of the air and the attenuation. A temperature change of 5°C with 6o mm of air produces an error of approximately o,5 µm with Al. An oil film of 1o µm produces an error of 3 µm with Al.

Gammradiation is less sensitive to such influences, because the scattering- and attenuation coefficients are smaller.

Radiation detectors:

To detect reflected or penetrating radiation basically all detectors can be used, but experience showed that the ionization chamber has many advantages. It is very reliable, simple and has an unlimited life-time. Its temperature coefficient is approximately 1 to 3 o/oo per 1o°C. The detected radiation pro-

duces an ionization current of approximately $1o^{-9}$ A. By various compensation methods it is possible to obtain a current which depends only on the thickness and type of material.

Time constant:

The accuracy and efficiency of a thickness control unit depends especially how fast the instruments react to a change in the input parameter Δd. In general it can be written by the following equation

$$S_d = d + \Delta d(1 - e^{-t/T})$$

S_d = signal, d - thickness before change of Δd
t - time, T - time constant 5o to 5oo ms

After 1 x T only 63% of Δd are indicated.

Thickness gauging with alloys:

The composition of the material influences the signal through the attenuation coefficient. A very important parameter is the atomic number Z. In example it is very difficult to determine Mg (Z=12) and Si (Z=14) in Al (Z=13), but small amounts of Cu(Z=29)or Zn (Z=3o) can easily be detected in pure Al.

It is important that these elements do not change strongly like Mn, Fe, Cu, Zn in Al , Mo,W in steel and Sn or Pb for other metals. In example if in a given Al, Zn, Mg alloy with 4,1% Zn this contents changes for $\pm$ o,5% an accuracy of $\pm$ 2% can be obtained with Am-241, if the 4,5% Mo content in a steel alloy changes for $\pm$ o,5% an accuracy of $\pm$ 1% is measurable.

Practical designs:

Areas of application are foil- and plate production industries and metall-, paper- and plastic coating industries. The thickness

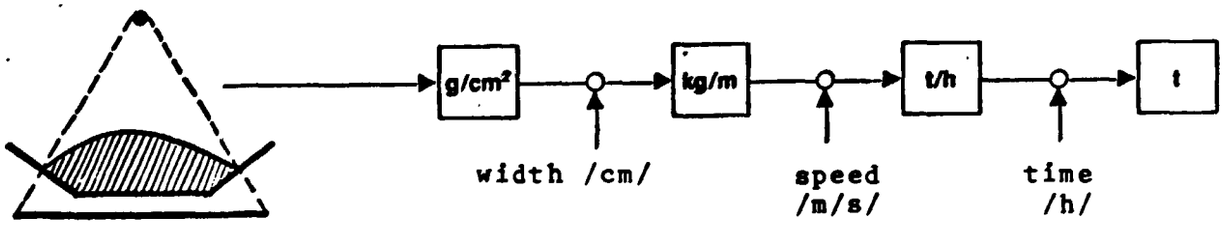
of coating layers is not only for economical reasons (as thin as possible) but also for industrial safety reasons (thick enough to protect the material throughout the life-time) important. In general the source and the detector are incorporated in a common C-shaped frame to assure a constant distance. The material passes in between the source and the detector at a given speed.

Various examples:

- to control foils and plates before further processing for their thickness
- to control the area weight of plastic foils over the whole width
- to regulate the amount of glue coated to paper
- to control the wall thickness of tubes, usually both walls are controlled together due to the production process
- thickness control of Al-plates
- thickness control of iron- and steel plates during the production process
-

Control of mass flow:

With some modification the total mass flow can be determined especially for corrosive, abrasive, hot or any other hard to handle material. (see fig. below)



Areas of application for thickness and mass per unit area (mpua) measurements:

Industry	Parameter	Material controlled
Pulp & Paper	mpua	Paper, paper board, coated paper, cellophane

Rubber & Plastic	thickness	plastic film and sheet, coated plastic film & sheet rubber strip & sheet
	mpua	tire fabrication (textile)
Wood produtcs	mpua	particle board, hard board chipboard
Textile products	mpua	double knit fabrics, carpets carpet backings, coated fabr
Electrical products	mpua	coated circuit board materia
	thickness	ceramic capacitor tape
Tobacco	mpua	cigarette paper

Areas of application for mass flow:

Fertilizers, ores, magnesium compounds, sodium compounds, grains wood (flakes,fibres,chips), rock (phospates,gypsum), clay,lime-stone, coal, coke, cement, tobacco, syntethic detergents, sand, sewage, vegetables, fruits etc.

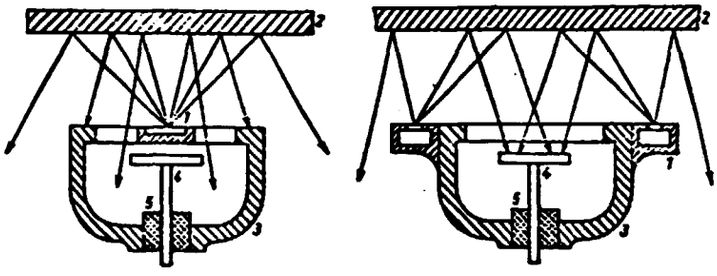


Fig.1 & Fig.2: Principal arrangement of radiation source and detector for the backscattering method
1-source, 2-material, 3-shielding, 4-detector
5-isolator

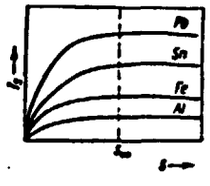


Fig.3: Detector current as a function thickness s for various materials

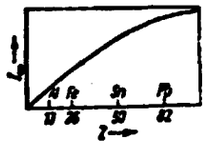


Fig.4: Detector current as a function of the atomic number Z

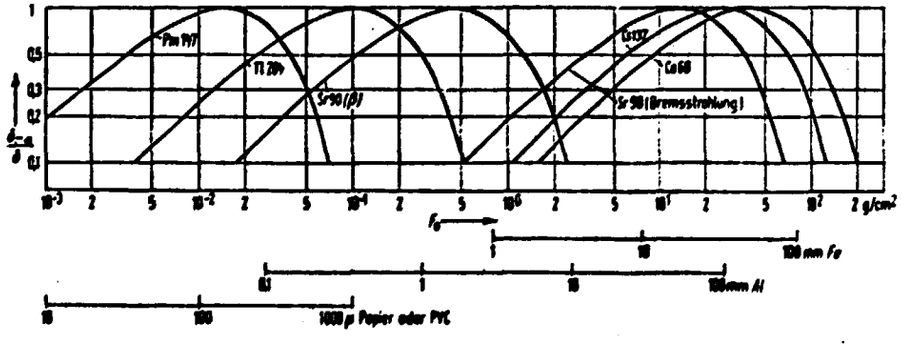


Fig. 5: Resolution of different radiation sources for various materials

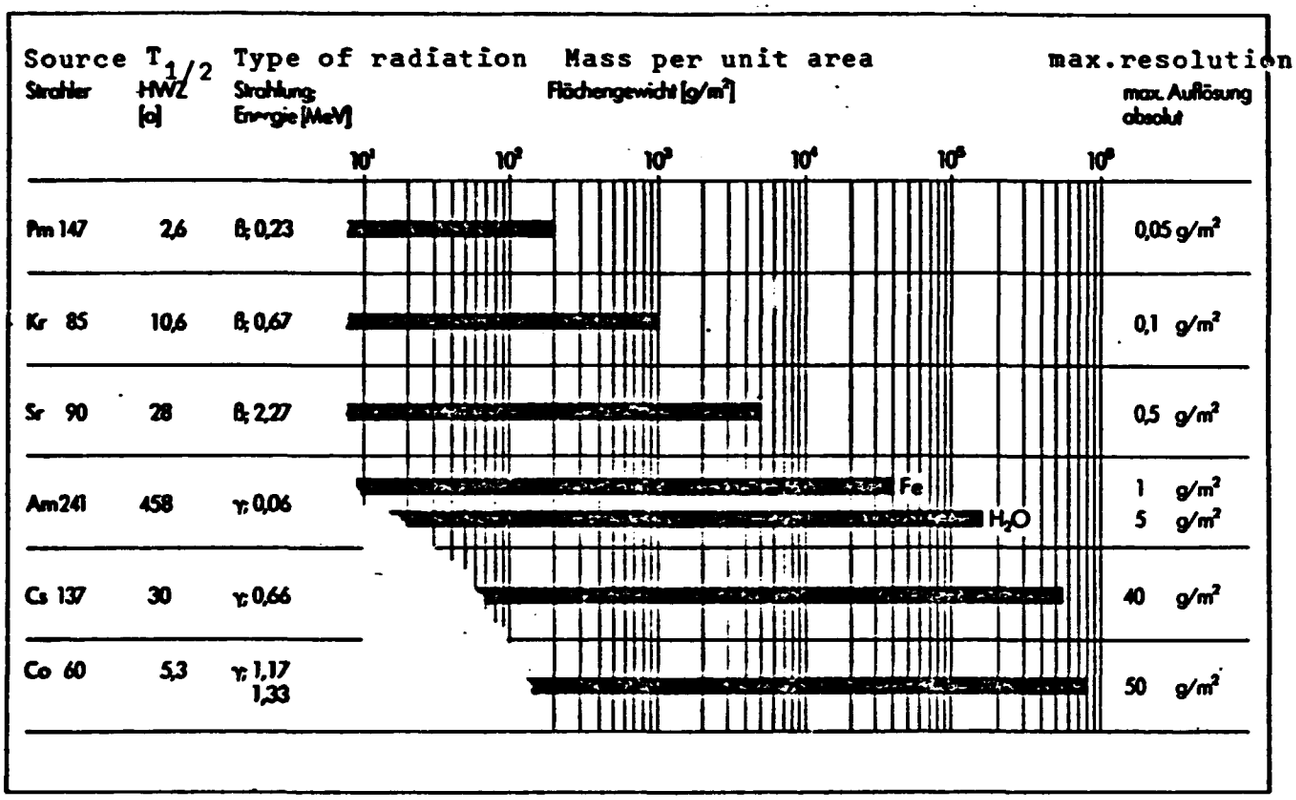


Fig. 6: Range of application of various radiation sources

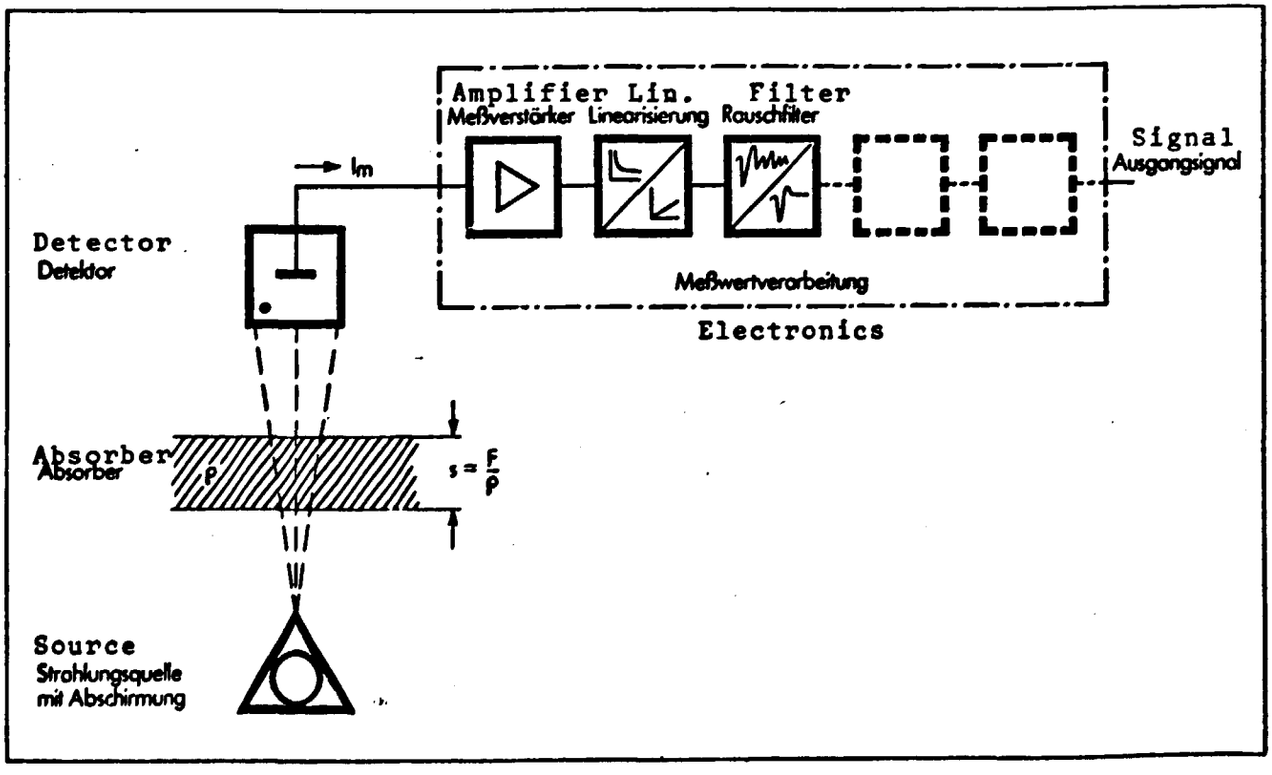
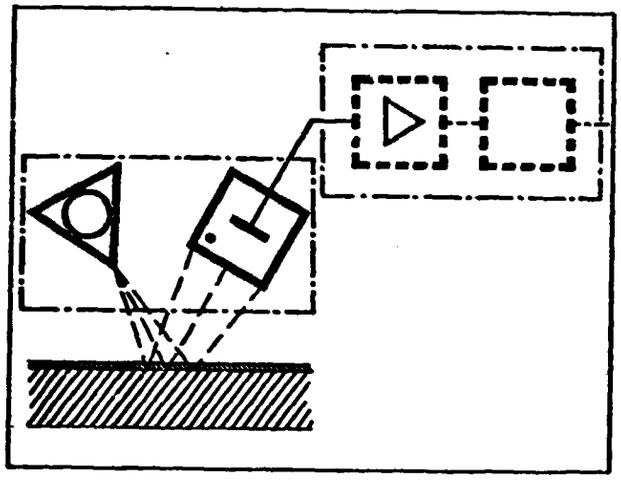


Fig. 7: Blockdiagram of the transmission method

Fig. 8: Blockdiagram of the backscattering method



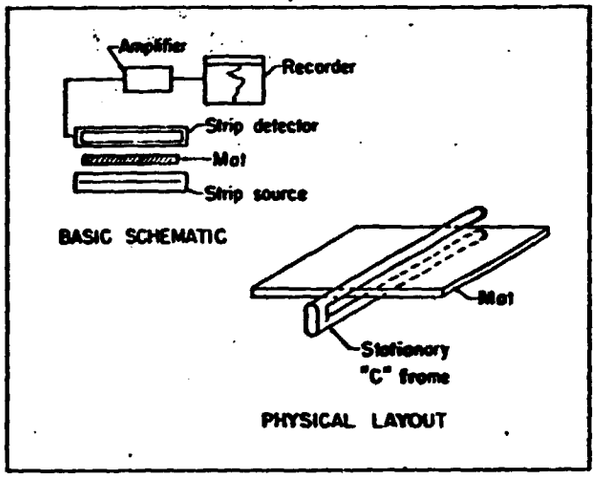
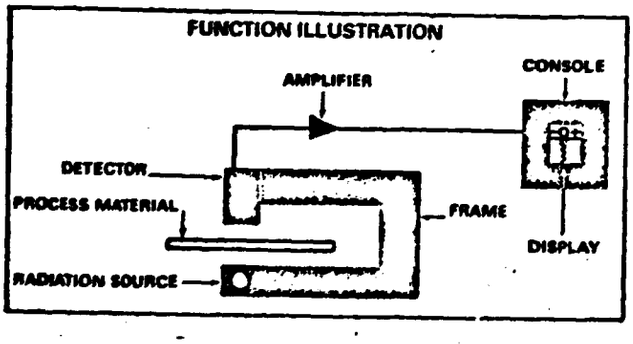


FIG. 9 — Strip Measurement Geometry

Fig. 1o: C-frame arrangement for thickness gauging



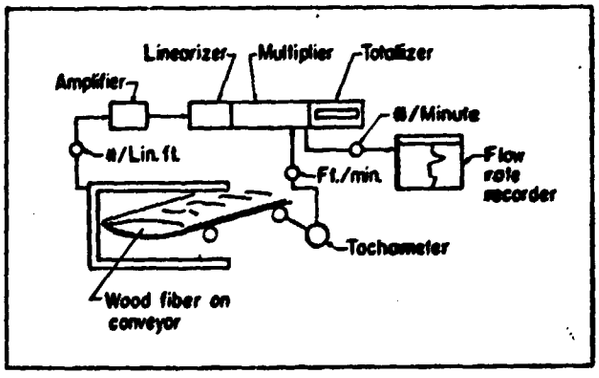


FIG. 11 — Mass Flow and Total Weight Schematic

DETERMINATION OF MOISTURE IN MATERIALS

Introduction:

Since 2o years the investigation of materials for their moisture content becomes increasingly important. At the beginning only off-line methods were used to determine moisture in soil, but now many industries make use of this method on-line for measuring moisture in mining industry, construction- or chemical industry.

The method is based on the interaction of neutrons with matter by elastic scattering and absorption. The strong dependence of the energy loss of neutrons on the atomic mass of the partner allows an investigation of the material composition. Neutrons are slowed down strongly when colliding with partners of equal atomic mass such as hydrogen. The following table shows the properties of various elements in respect of neutron scattering:

	H	He	C	O	Si	U
A	1	4	12	16	28	238
ν	18	43	114	15o	26o	2172

A- atomic mass, ν- number of interaction to slow down neutrons from 2 MeV to thermal energy.

It can be seen that hydrogen is most effective in slowing down neutrons, all other elements are negligible compared to H_2. Fig.1 shows the effect of a given layer of material (water, coal, sand) on the thermalization of neutrons. It is obvious that the result is a function of the total hydrogen content per unit volume. If chemically bounded hydrogen is present it has to be considered separately.

General requirements:

To determine the effect of neutron thermalization by interaction with hydrogen a source of fast neutrons and a detector for thermal neutrons has to be brought into a given geometric arrangement which depends on the special conditions of the problem. A detailed theoretical analysis of the problem may request a multi-group calculation which usually does not solve the problem exactly due to many uncertainties in the material composition and in geometric uncertainties. For some simple geometries i.e. a source of fast neutrons in the centre of a sphere the problem can be solved using Fermi's age theory. The Fermi age is proportional to the length when neutron reaches thermal energies. Another important parameter is the migratiom area $M^2 = L^2 + \tau$ which is proportional to the length from birth to absorption.

Therefore it is recommended to perform experiments and to calibrate the arrangement with standards.

Material	SiO_2	SiO_2+1o% H_2O	H_2O	Graphite	Paraffin
M in cm	5o	18	7,4	53	6,1

Due to the fact that the neutron flux density increases rapidly when approaching the neutron source it is evident that the neutron source and the detector should be as close as possible for high efficiency. Only in some special cases when the hydrogen content is very small a certain distance between source and detector can be of advantage. Using detectors with a certain gamma sensitivity it may be necessary to insert some gamma shielding material to reduce the gamma background.(Fig.2).

BF_3 counters and ^3He counters are practically unsensible to gamma radiation but their geometric length requires a certain distance between source and detector. GM counters with Cd converters are more sensitive to gamma radiation. Using in combination with a Po-Be source a 6 cm Pb shield is necessary.

Backscattering method:

In this case detector and source should be as close as possible. The method is based on the fact that the fast neutrons emitted from the source into the material are slowed down and some of the thermalized neutrons are measured by the detector. Two methods have to be distinguished which are

- the penetration method
- the surface method

Penetration method:

In this case the sensor is put right into the material to be investigated. Fig.3 shows the neutron flux density as a function of the hydrogen content with the volume $V(r_o)$ as parameter in semilogarithmic scale. It is obvious that at low H_2 concentrations the neutron flux density increases fast until reaching some saturation value especially for large measuring volumes. In the other direction the effect is limited by the background. Therefore in order to obtain a certain lower limit sensitivity the measuring volume has to be increased. In example with a small volume (1,8 dm^3) the lower limit is about 12o $mg.cm^{-3}$. The penetration method has also positive aspects for radiation protection, because the material acts as radiation shield and in typical constructions the source is directly drawn into the shielding container.(Fig.4)

Surface method:

In many cases it is not possible to penetrate the material with the source and the experiment has to be carried out from the surface. Due to diffusion losses the efficiency is much lower in this case than with the penetration method. However if possible some reflector material is applied on the opposite side of the material, usually an Fe plate with 25 mm thickness. Thus the reflector simulates an increase of the material volume.(Fig.5)

The effect of a reflector compared to non-reflected material is shown in fig.6. Further also the efficiency of the penetration method compared to the surface method is shown in fig.7. In general for the same efficiency the surface method needs 3-times the source strength than the penetration method.

ransmission method:

The backscattering method can be applied very well if the moisture is distributed in the material evenly.If the distribution is inhomogeneous the backscattering method gives a wrong information because it only sees the volume close to the detector.
Such samples should be investigated preferably with the transmission method, because it gives an average over the whole material. The signal first increases with the material thickness and then decreases after a maximum due to absorption and scattering processes. Therefore a constant thickness of the material is necessary. Fig.8 shows the results of the transmission method for a 16 cm layer with homogeneous and inhomogeneous moisture distribution, the difference is only 1,3%.

Scattering of slow neutrons:

These methods differ from the previous mentioned methods, because the source is in the center of a moderator (D_2O, Paraffin) which thermalizes the neutrons. These slow neutrons penetrate the unknown material and are measured in the detector (fig.9). The intensity loss in the sample for a collimated beam is

$$I = I_o \cdot \exp(-\Sigma_t \cdot h)$$

Σ_t - total cross section, h - sample thickness
This method gives good results at low water content and an accuracy of $\sim$ o,1 mass % H_2 is reported (Pu-Be, D_2O). The disadvantage is the high neutron source strength necessary for this method.

In order to increase the detector efficiency and to reduce the neutron loss the detector should be surrounded completely by the investigated volume. This is not possible when only the surface of the material is accessible. Some consideration must also be given to the structural material for the detector construction. Aluminium should be used instead of steel (Σ^{Al}_{tot} = o,15 cm^{-1}, Σ^{Fe}_{tot} = o,31 cm^{-1}).

Depending on the hydrogen content the investigated volume may vary between 1 dm^3 to 5oo dm^3, this results in a hydrogen concentration between 3 to 17o mg H_2/cm^3. The lower limit is due to the increase of noise which reduces or covers the net signal. In general the following parameters are important:

- high specific neutron source strength
- low gamma emission
- long half-life
- small geometric dimensions
- no decay in gaseous decay products
- mechnical resistance to damage

Therefore (α ,n) sources are most widely used

Source	$1o^5$ $n.s^{-1}.Ci^{-1}$	$T_{1/2}$	γ-dose rate mR in 1 m for $5.1o^5$ $n.s^{-1}$	Price	Remark
$^{21o}Po/Be$	2o	138 d	o,5	cheap	
$^{226}Ra/Be$	1oo	162o a	65	exp.	very small
$^{239}Pu/Be$	1o	243oo a	o,5	av.	
$^{241}Am/Be$	25	458 a	o,5	av.	long $T_{1/2}$
$^{227}Ac/Be$	15	22 a	4	exp.	

Main requirements for the neutron detectors are

- high sensitivity for thermal neutrons
- low sensitivity for fast neutrons and gammas
- strong detector signal

- low temperature sensitivity
- mechanical resistance
- long half life
- small dimensions

Besides activation foils which are exposed at given positions but give only discontinuous results the GM counter with Cd-shield is the most simple detector. In this case the capture gamma rays (n_{th}, γ) are detected. One disadvantage is the detector sensitivity to background gammas. Another detector type is the Boron scintillator ZnS(Ag)+B which needs a more expensive and complicated electronic.

A widely used detector in industrial application is the BF_3 counter with high neutron- and low gamma efficiency. In general BF_3 gas with a ^{10}B enrichment is used. Similar properties are shown by He^3 detectors having higher sensitivity and longer life-time than BF_3, but a lower signal output.

A presently widely used detector is the ionization chamber which shows excellent behavior even under most difficult conditions. It has hwoever to be redesigned for maximum neutron sensitivity which may be achieved either by Boron coating of the electrodes or BF_3 filling of the chamber.

Table 1: Intercomparison of various neutron detectors

	γ-sensitivity	n-sensitivity	life-time	electronics
GM+Cd	big	small	short	simple
Boron-sci.	average	big	long	expensive
BF_3 or ^3He	small	big	average	large amplification
n-sens. ioniz.ch.	average	average	long	medium

Accuracy and sensitivity:

The overall sensitivity indicates how strong a variation in the concentration is shown by the detector output It can be written as

$$W = \frac{\partial\phi/\phi}{\partial C/C} \qquad C = H_2 \text{ concentration}$$

Fig.1o shows typical results for the penetration method, while fig.11 shows results for the backscattering method.

Errors:

Besides the H_2-concentration some other parameters may have an influence on the thermal neutron flux density. An example is the material density ρ which is seen from fig.12 where the density of sand is shown as a function of its humidity. If the density of the material is always constant the instrument can be calibrated in vol% or mass% of the H_2 concentration. If the density varies, ρ has to be determined separatly i.e. be gamma transmission or other methods. Another important factor which may cause errors is the material composition or elements which influence the neutron scattering. The presence of light elements like Carbon may simulate higher H_2 concentrations, while elements with high absorption cross section like B, Li, Cl, Cd may reduce the signal. In example NaCl in SiO_2 may considerably influence the signal even if the moisture is constant (fig.13).

As long as the fraction of these elements remains constant the instrument can be calibrated. If these disturbing elements vary the effects become very complicated and the method may fail. Another factor influencing the results may be the structure of the material itself. It is obvious that layers close to the source and to the detector influence the total signal more than layers

further away. If a material with different grain sizes has to be measured like coal or sand the detector output may vary even if the water content remains constant. This problem can be reduced if a certain distance (some cm) between detector and the material is observed.

Errors may also be due to geometric reasons, as the distance between source and detector may change, the distance between detector and material may vary, or the size or the volume of the measured volume may change. The most important factor is the volume: The detector signal increases with the volume until a saturation value is obtained which depends on the hydrogen content (fig.14).

Summary of properties:

- no direct contact with the material is necessary, therefore no contamination will occur,
- due to the large neutron migration length a big volume may be controlled,
- the interaction neutron - material is short, therefore the necessary measuring time is also very short,
- a continuous control is possible,
- the total hydrogen content will be measured, therefore bounded H_2 in the material must be considered,
- the instruments can be easily calibrated in an environment with known hydrogen concentration .

Typical applications:

Humidity of grains, powders, coal, sand etc.: The sensor is located at the lower outlet of the material container and is installed in aprotection tube of steel. One mm of steel will reduce the signal for 5%. If the temperature exceeds 50°C additional cooling

will be necessary. Typical data are: 1oo mCi Am-241/Be = $2,5.1o^5$ s^{-1}, Detector:Scintillation counter doped with Li-6, sensitivity 1%vol moisture results in 25 pulses/s.

Surface detectors: They are used when the material flow may be disturbed by the dtetector. The sensitivity is 5 to 1o times smaller than with the penetration methód. Again 1 mm steel reduces the signal for 5%, therefore the wall thickness should be as small as possible. Source: 3oo to 1ooo mCi Am-241/Be,Li-6 scintillation counter, sensitivity about 15 pulses/s for 1 Vol% H_2

Conveyor belt detector: The material thickness should be smaller as the neutron penetration depth, but not too small to moderate most of the neutrons. Minimum material weigth is about 1,5 $g.cm^{-2}$ which equals 15 cm material thickness at 2 $g.cm^{-3}$ and 5% water content. To obtain this constant layer an equalizer has to smoothen the surface before the detector. To minimize lateral effects on the detector, the material should be 4oo mm large and covered by a 2o mm steel reflector. Also below the material some steel reflectors should be installed (figs.15,16).

<u>Sensitivities for special materials:</u>

- Sand to about - o,1% humidity (penetration method)
- Coal to about - o,5% humidity (")
- Ore to about - o,3% humidity (surface method)
- Concrete to - o,3% humidity (penetration)
- Ceramic materials to about - o,3% humidity (penetration,surface)
- Grounded wood to about - 1,5% humidity (penetration)

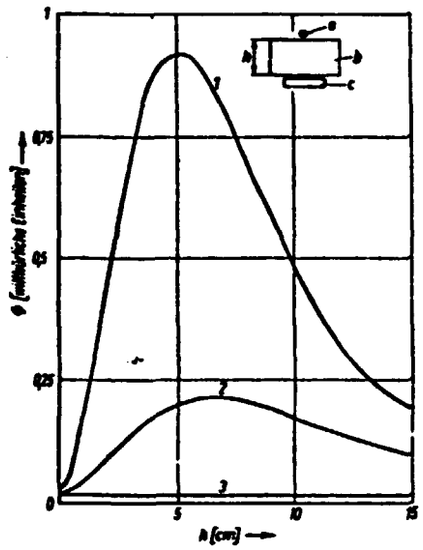


Fig. 1 Resultierender thermischer Neutronenfluß bei Durchstrahlung verschiedener Substanzen mit schnellen Neutronen in Abhängigkeit von der Schichtdicke
Meßanordnung: a Neutronenquelle; b Prüfsubstanz; c Detektor für thermische Neutronen.
Kurven: 1 Wasser; 2 Steinkohle; 3 Siliziumoxid

Fig.1.:Thermal neutron flux density after penetration through various materials as a function of the layer thickness. 1-water, 2-coal, 3-sand a-source, b-material, c-detector

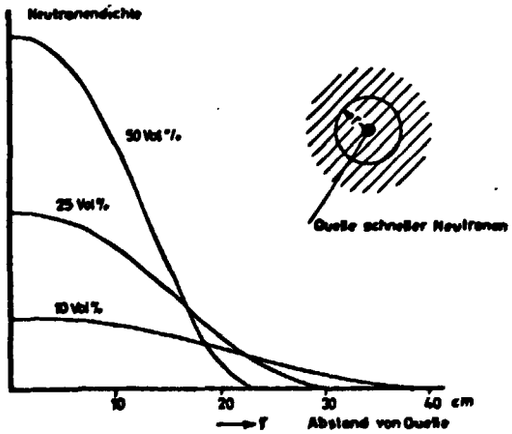


Fig.2. *Reichweite therm. Neutronen bei verschiedenen Volumenfeuchten (schematisch)*

Fig.2.: Range of thermal neutrons as a function of the moisture content.

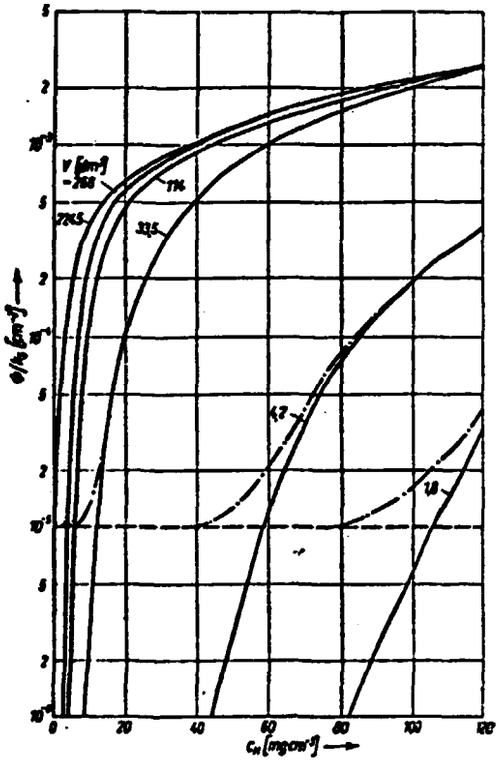
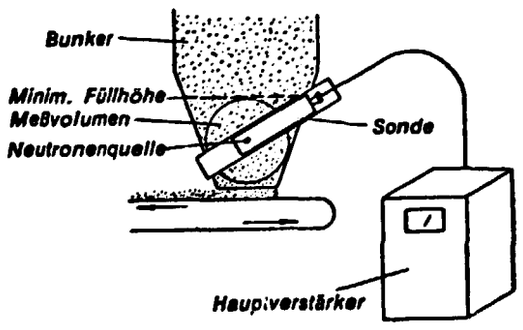


Fig. 3 „Normierter Neutronenfluß Φ^* in Abhängigkeit vom Wasserstoffgehalt
Parameter: Volumen (kugelförmig). Gestrichelte Linie: Untergrundstrahlung Φ_0^*; Punkt-Strich-Linie: vom Untergrund überlagerter Neutronenfluß

Fig.3.: Normalized neutron flux density as a function of the moisture content for a spherical volume.
----- background -.-.-. signal less background



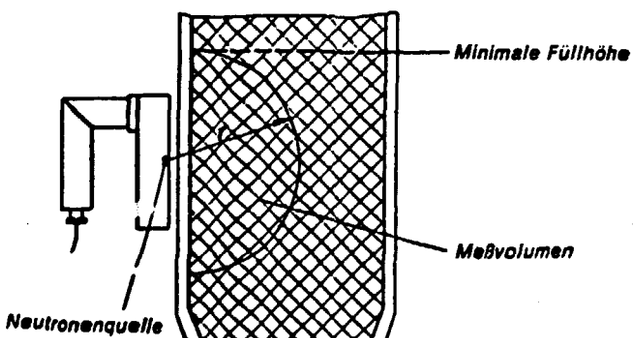


Fig.4.: Tiefensonde in Behälterauslaß
Fig.4.: Penetration method inside a container

Fig.5.: Oberflächensonde an Behälterwand.
Fig.5.: Surface method at the container wall

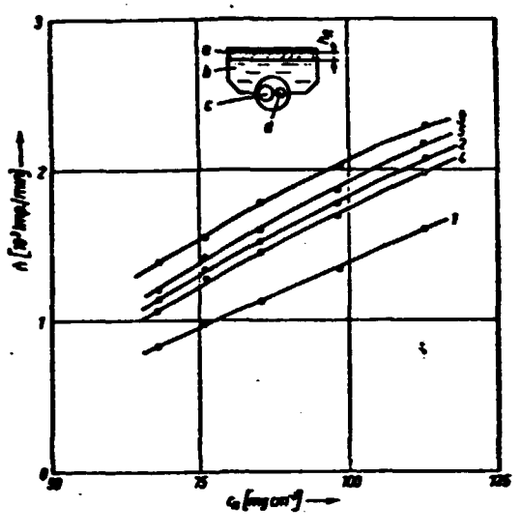


Fig. 6. Kennlinie für Oberflächensonde mit Volumen (entsprechend der Schichtdicke) und Reflektordicke als Parameter. Meßgut: flüssige Kohlenwasserstoffe.
Meßanordnung: a Reflektor, b Meßvolumen, c Detektor, d Quelle. Kurven: 1 $V = 2{,}3$ dm³, ohne Reflektor; 2 $V = 3{,}3$ dm³, ohne Reflektor; 3 $V = 4{,}3$ dm³, ohne Reflektor; 4 $V = 2{,}3$ dm³, $h_R = 20$ mm; 5 $V = 2{,}3$ dm³, $h_R = 45$ mm

Fig. 6.: Signal of a surface detector as a function of the reflector thickness

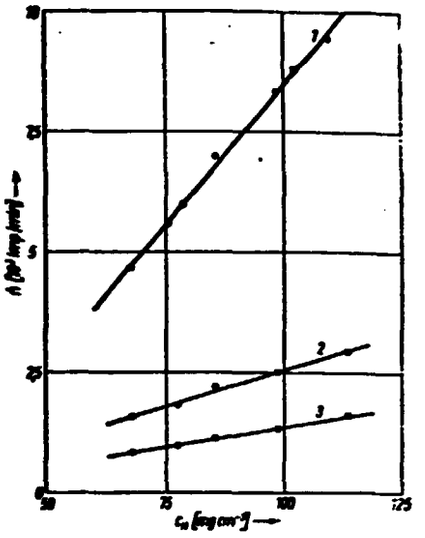


Fig. 7 Vergleich von Eintauch- und Oberflächenanordnung. Meßgut: flüssige Kohlenwasserstoffe.
Kurven: 1 Eintauchsonde; 2 Oberflächensonde mit Reflektor; 3 Oberflächensonde ohne Reflektor. Das Meßvolumen wurde so gewählt, daß sich eine annähernd konstante Meßempfindlichkeit ergab ($W \approx 1{,}4$)

Fig. 7.: Comparison of penetration- and surface method.
1-penetration detector
2-surface detector with reflector
3-surface detector without reflector

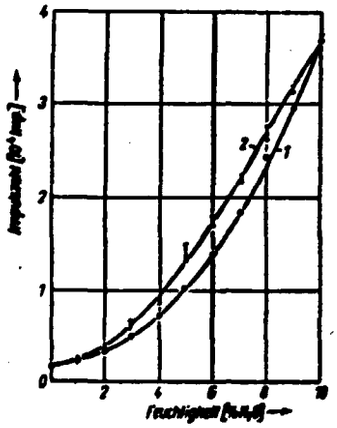


Fig. 8 Kennlinie für Durchstrahlungsanordnung bei homogener und inhomogener Feuchteverteilung. Schichtdicke: 10 cm;
1 homogene Verteilung; 2 inhomogene Verteilung

Fig. 8.: Signal of the transmission method with homogeneous and inhomogeneous moisture distribution.

Fig.9: Anordnung zur Bestimmung des H-Gehaltes nach dem Prinzip der Streuung langsamer Neutronen.
a Reflektor; b Quelle schneller Neutronen; c Kadmiumabdeckung; d Detektor für thermische Neutronen; e Meßgut; f Moderator

Fig.9.: Principal arrangement for the scattering method
a-reflector, b-neutron source, c-Cd-shield, d-detector
e-material, f-moderator

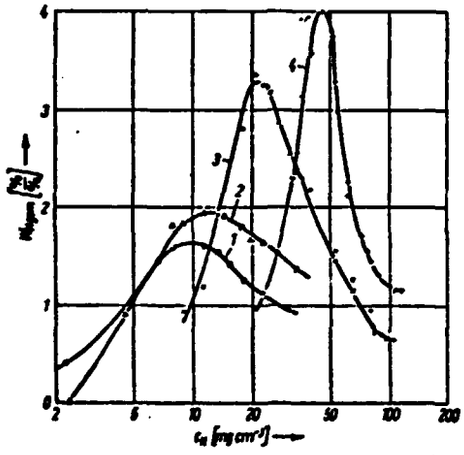


Fig. 10 Meßempfindlichkeit in Abhängigkeit vom Wasserstoffgehalt für Eintauchanordnung, nach experimentell aufgenommenen Kurven ermittelt
Parameter: Volumen 1 $V = 141$ dm³, 2 $V = 61$ dm³, 3 $V = 18$ dm³, 4 $V = 7{,}5$ dm³

Fig.10: Sensitivity as a function of the hydrogen contents for the penetration method

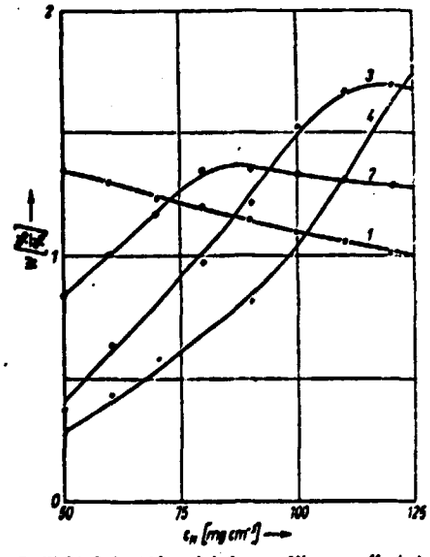


Fig. 11 Meßempfindlichkeit in Abhängigkeit vom Wasserstoffgehalt für Oberflächenanordnung, nach experimentell aufgenommenen Kurven ermittelt. Parameter: Volumen 1 $V = 3{,}3$ dm³, 2 $V = 2{,}3$ dm³, 3 $V = 1{,}5$ dm³, 4 $V = 1$ dm³

Fig.11.: Sensitivity as a function of the hydrogen content for the backscattering method

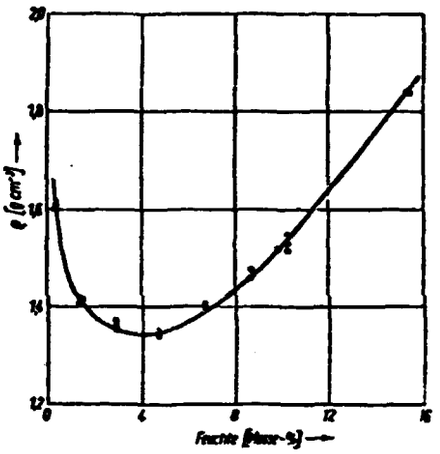


Fig. 12 Abhängigkeit der Materialdichte ϱ von der Feuchte für Sand bei lockerer Schüttung

Fig.12.: Density of sand as a function of the moisture contents

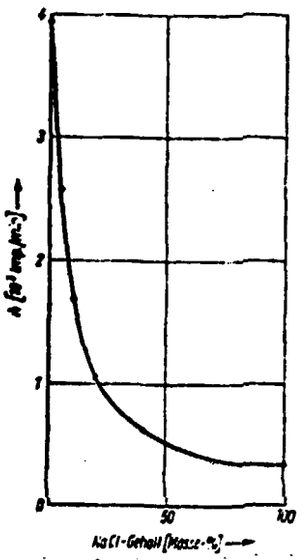


Fig. 13 Einfluß des Chlorgehaltes im Meßgut, Zählrate in Abhängigkeit von NaCl-Gehalt in SiO_2 bei konstanter Feuchtigkeit (7 Masse-%)

Fig.13.: Influence of NaCl on the detector signal for constant moisture

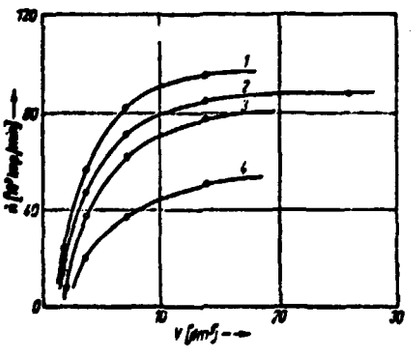


Fig. 14 Impulsdichte in Abhängigkeit vom Volumen (Schichtdicke). Parameter: Substanzen mit unterschiedlichem Wasserstoffgehalt. Kurven: 1 $C_{10}H_{18}$; 2 H_2O; 3 $C_{10}H_{22}$; 4 C_6H_6

Fig.14: Detector signal as a function of the volume

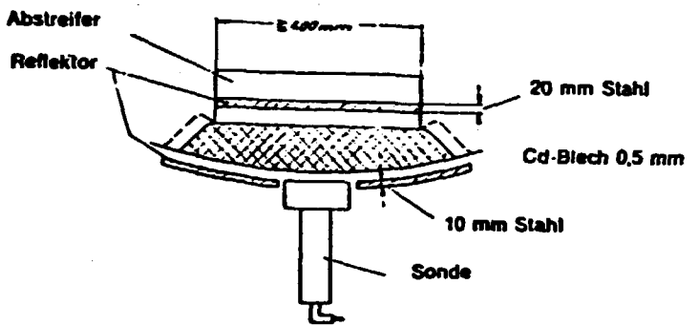


Fig.15: Anordnung einer Fließbandsonde
Fig.15: Arrangement for a conveyor belt detector

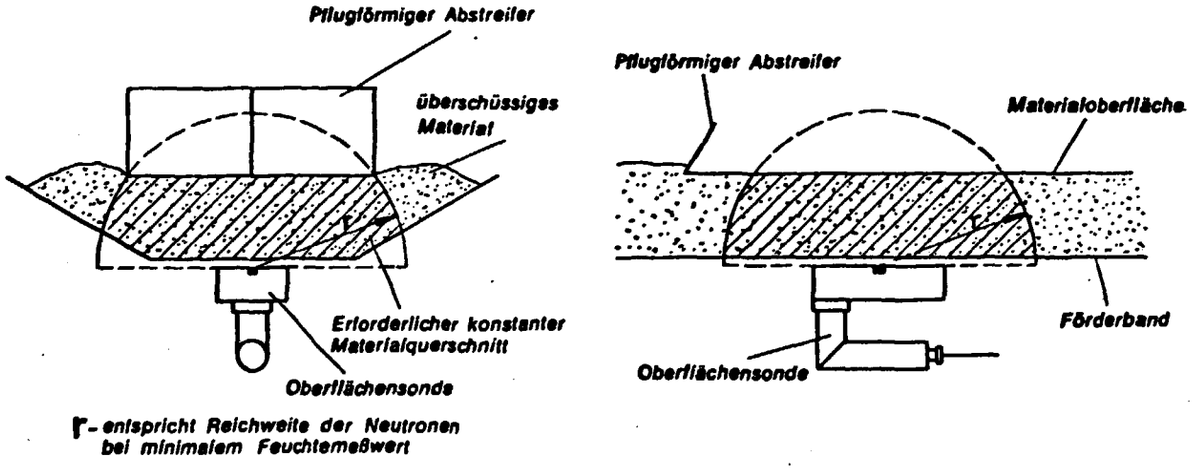


Fig.16: Längs- und Queransicht einer Fließbandsonde

Fig.16: Front- and lateral view of a conveyor belt system

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