Endress+Hauser

People for Process Automation

Radiometric Solutions

White Paper: Gamma density measurement & calibration

Endress+Hauser

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1 General information

1.1 Slurry density measurement

As mines are often located in areas with limited water resources, it is crucial to monitor the quality of the slurry with a density measurement to efficiently apply the available water in the production process.

The high solids content of the slurry makes it very abrasive and additionally the chemicals used to separate the ores also make the slurry very aggressive against the process equipment.

Radiometric measurement is applied when other technologies fail, for example when invasive measurement techniques may not be considered due to abrasive process media. So far other known technologies still do not work under these conditions, whereas the radiometric density measurement provides a reliable and stable density signal.

The measuring system consists of a source, a source container (shielding), a detector and a clamping device. The measuring instruments can be installed with the clamping device directly on the pipe; the density signal can be shown onsite with a separate display.

**Source inside
source container**

Detector
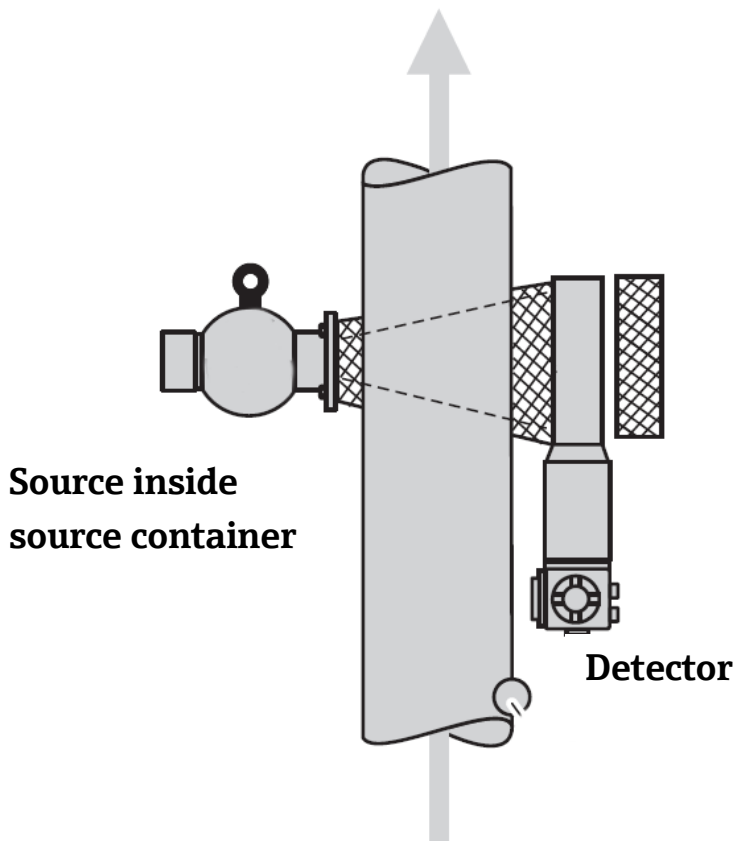
2 Basics on measuring system

2.1 Gamma radiation

As radio- and microwaves, light and X-rays, for our measuring purposes, Gamma radiation is emitted as an electromagnetic wave. Electromagnetic waves differ from one another only with regard to wavelength and frequency. Compared to other type of electromagnetically wave emission, Gamma radiation has a high-energy with a short wavelength and a high frequency. It is radiated from a radioactive isotope and the waves have high penetration energy. In radiometric measurement technology, the industrial isotopes cesium 137 and cobalt 60 are used.
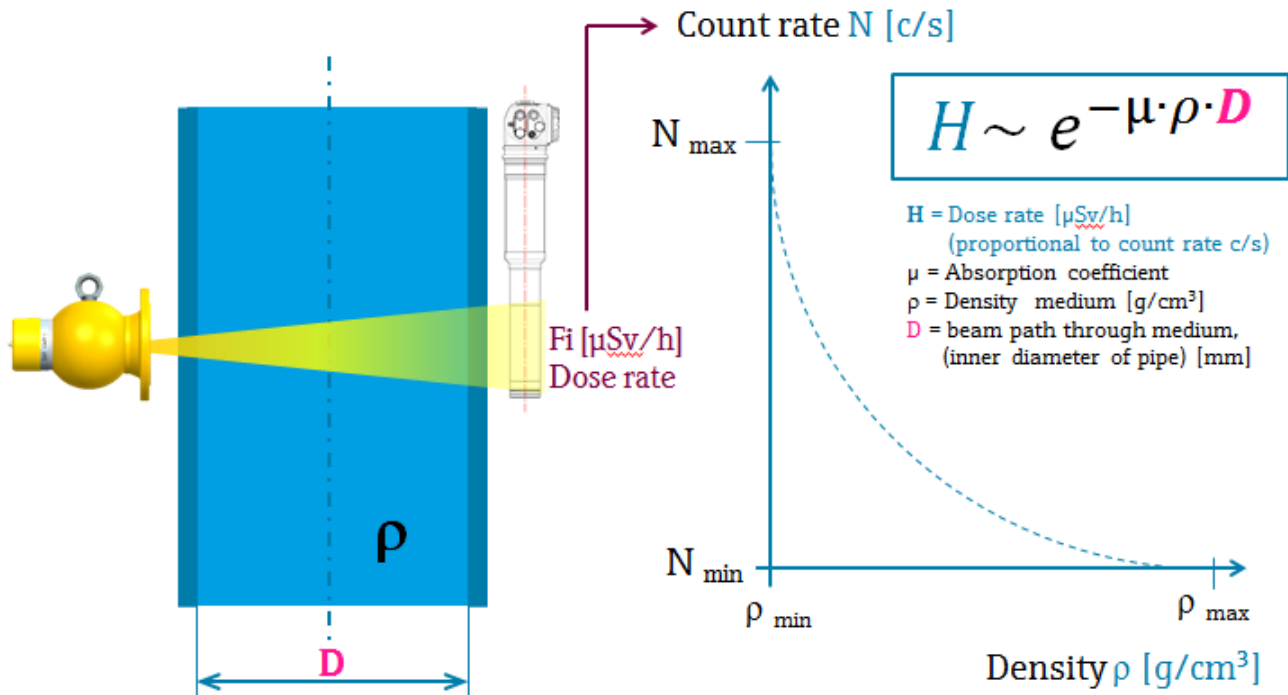
For the purpose of measuring the density inside a pipe, Gamma radiation is used to irradiate the pipes. Gamma radiation is radiated by the isotope (source) in the direction of the pipe. On the opposite side of the process equipment, a detector detects the non-absorbed rays and converts them into an electric signal. In process condition, the detector receives the maximum radiation, when the pipe is filled medium with the lower density (typically water or a comparable fluid). Radiation decreases as the density of the medium rises.

The sensing element of the detector is a scintillator, converting the radiation into flashes of light. These flashes reach the photomultiplier, where they are converted into electric pulses. The count rate (number of pulses per second; c/s or cps) is a unit for expressing the intensity of the radiation.
The count rate is converted by the evaluation electronics into the density signal.

2.2 Measuring principle

Depending on the diameter D and density ρ of the medium, the count rate (proportional to dose rate) decreases with a negative exponential-function. The absorption increases with a positive exponential-function.

Depending on the calibration method and the actual medium density to be measured the absorption factor µ is aligning the function for a decent measurement, which is calculated by the computing unit of the detector.

$$H \sim e^{-\mu \cdot \rho \cdot D}$$

H = Dose rate [µSv/h]
    (proportional to count rate c/s)
µ = Absorption coefficient
ρ = Density medium [g/cm³]
D = beam path through medium,
    (inner diameter of pipe) [mm]

3 Measuring system

Our product range for Gamma measurement covers the radiation source, source container and detectors, as well as accessories for evaluation and assembly.

Based on project specific requirement (process conditions and equipment) the required activity (strength) of the source is calculated for every measuring point and the required type of isotope (cesium 137 or cobalt 60) will be selected. According to the source activity the type of source container with a suitable shielding effect will be selected.

To measure density in a pipe, different detector length can be used depending on pipe diameter and expected accuracy.

3.1 Source (Radioactive Isotope)

The isotopes Ceasium 137 (Cs137) and Cobalt 60 (Co60) differ with regard to their half-life and penetration energy. With a half-life of 30 years, Ceasium 137 has an advantage over Cobalt 60 with only 5.3 years, whereas Cobalt 60 has the higher penetration energy. Cobalt 60 is only selected if the measurement cannot be achieved with Ceasium 137 due to large pipe diameters, large wall thicknesses or high density of the process media.

3.2 Detector

The detector Gammapilot M (FMG60) is available with a sodium iodide (NaI)-crystal scintillator or PVT plastic scintillator in various lengths. Both are suitable for density measurement.

A NaI-crystal scintillator is used for small pipe diameters (D<200mm/8") with the very high temperature stability (±0.1%). For larger pipe diameters (D>200mm/8") a well-priced solution with a PVT plastic scintillator can be considered. For even larger pipe diameters (D>400mm/16") a longer plastic scintillator is recommended, to reduce the necessary source activity. Double length of scintillator → source activity can be reduced to the half activity.

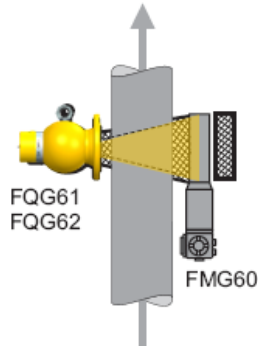| Scintillator type	Sensing element length	Sensitivity for Cs137 in c/s @ 1µSv/h	Sensitivity for Co60 in c/s @ 1µSv/h
NaI	50mm	1250 c/s	350 c/s
PVT	200mm	2000 c/s	1000 c/s
PVT	400mm	4000 c/s	2000 c/s
PVT	800mm	8000 c/s	4000 c/s
PVT	1200mm	12,000 c/s	6000 c/s

Table 3: Sensitivity and length of scintillator types
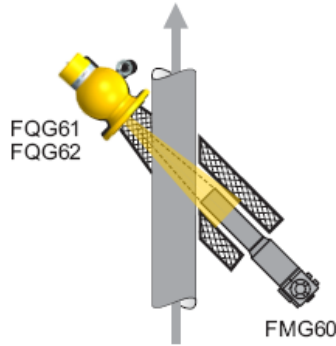
3.3 Configuration / Mechanical setup

The configuration of the source container and the detector depends on the pipe diameter (respectively the length of the irradiated measuring path) and the measuring range. These two parameters determine the measuring effect (relative change of the pulse rate). The measuring effect increases with the length of the radiation path through the medium. Therefore, a diagonal irradiation or the use of a measurement section is necessary for small pipe diameters.

- most constant conditions, if unit is mounted on a vertical pipe
- flow direction is from bottom to top
- If only horizontal pipes are accessible:
  horizontal beam path to reduce influence of air bubbles and build-up
- For a larger measuring effect → longer beam path (diagonal beam/measuring path)
- The required straight length (=distance from the density measurement to pipe bends) is
  ≥ 3 x pipe diameter and ≥ 10 x pipe diameter for pumps.

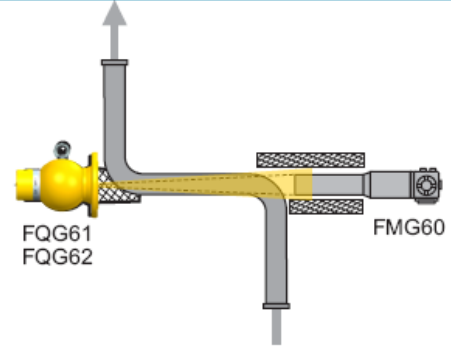## Vertical pipes (most constant conditions)

Vertical / straight beam

Diagonal beam
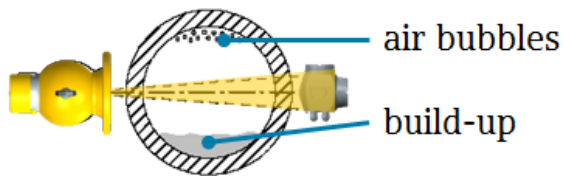
For **larger measuring effect** → longer beam path

Measuring path

FQG61 FQG62

FMG60

Horizontal pipe

air bubbles

build-up

If only horizontal pipes are accessible: horizontal beam path to reduce influence of air bubbles and build-up

3.4 Clamping device with source container FQG61/62

Additional the clamping device FHG61 is needed to clamp the source container FQG61/62 together with the detector FMG60 direct on the pipe.
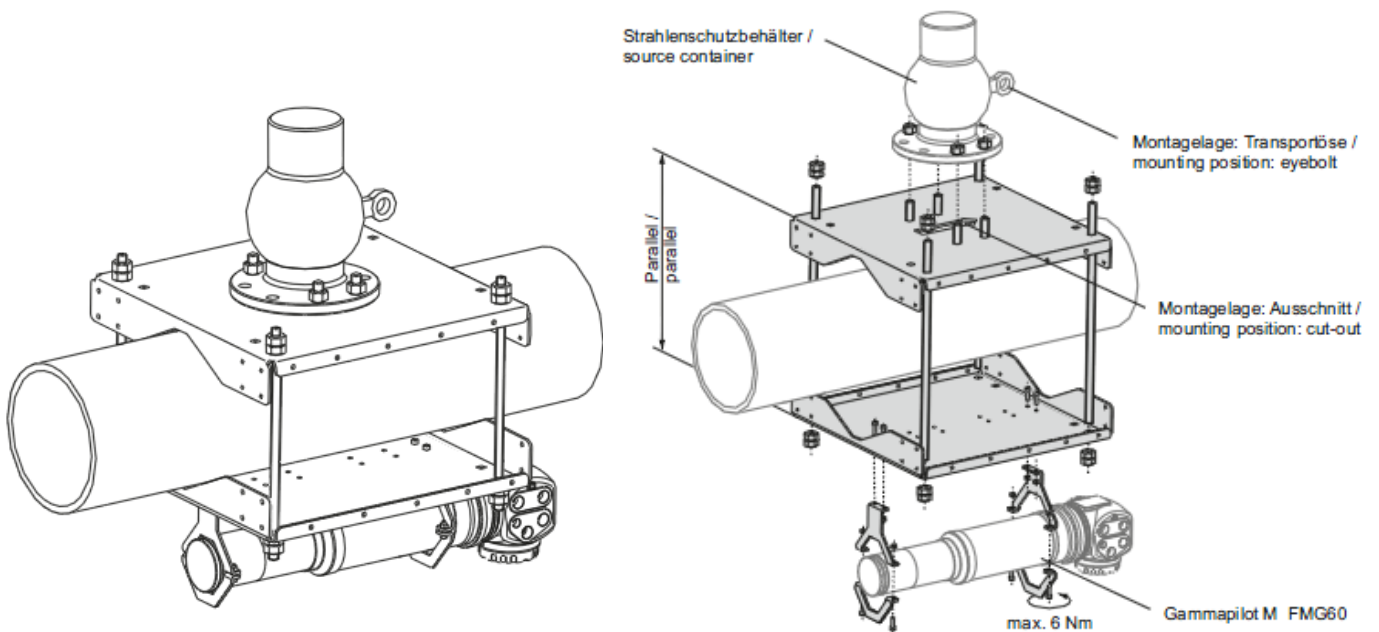
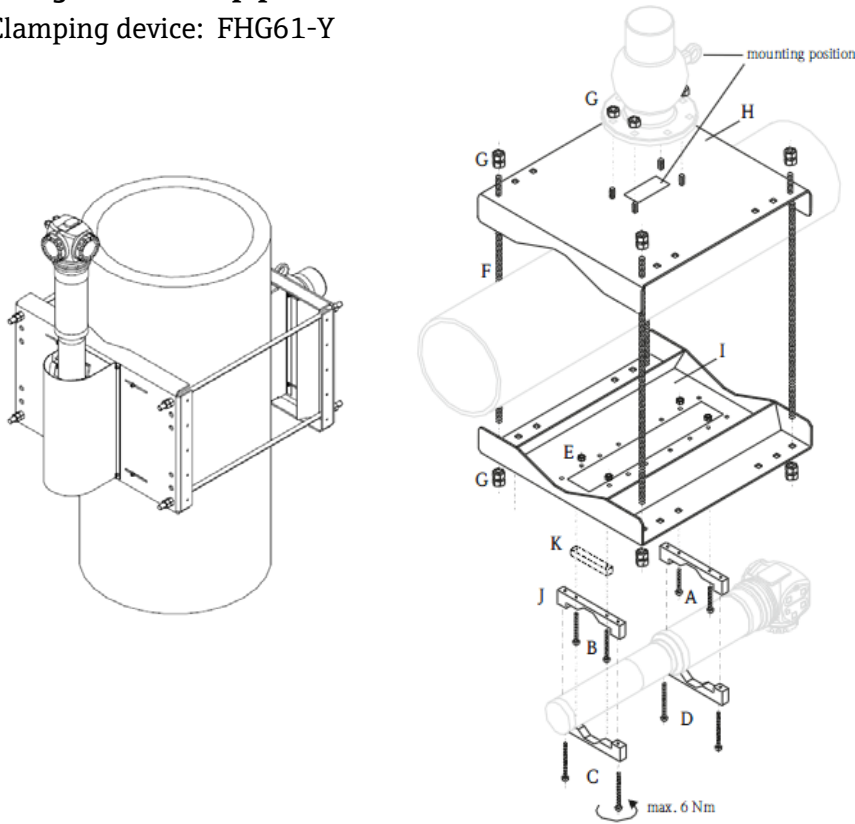**Straight beam for pipes DN 50 – 200**
Clamping device: FHG61-A
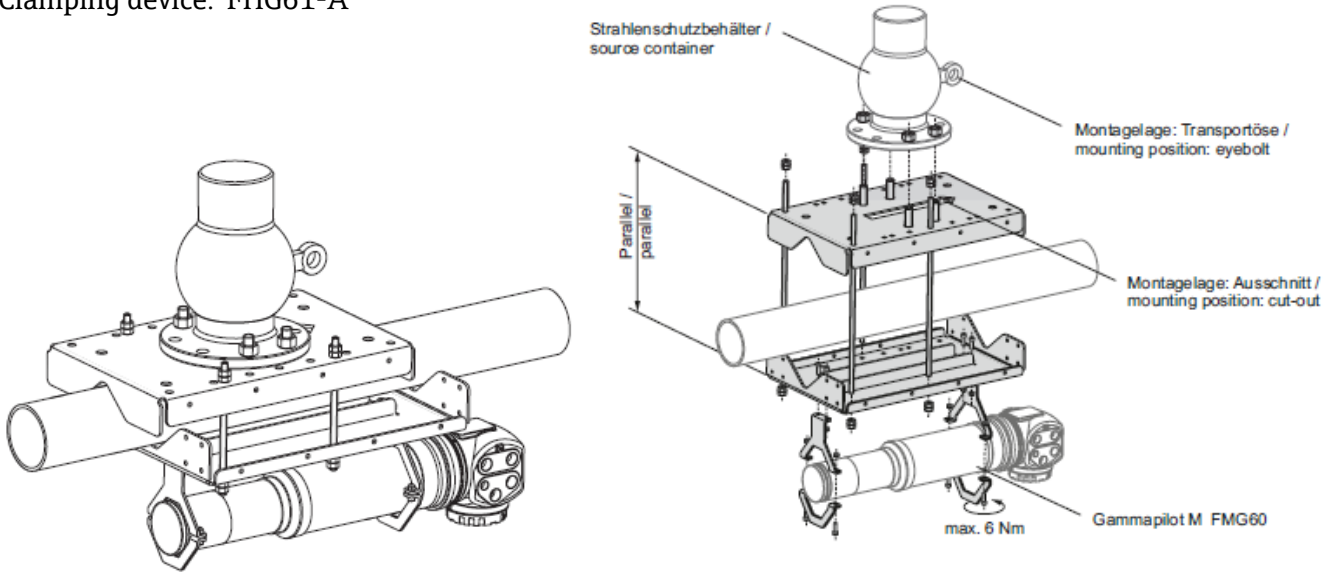
Straight beam for pipes DN 200 – 400
Clamping device: FHG61-B

Straight beam for pipes DN 400 – 1000
Clamping device: FHG61-Y

mounting position

max. 6 Nm

Diagonal beam for pipes DN 50 – 200
Clamping device: FHG61-C

Montagelage: Transportöse /
mounting position: eyebolt

Modulator (optional) /
modulator (option)

Strahlenschutzbehälter /
source container

Position Strahlerkasten /
position emitter box

Montagelage: Ausschnitt /
mounting position: cut-out

Parallel /
parallel

max. 6 Nm

Gammapilot M FMG60

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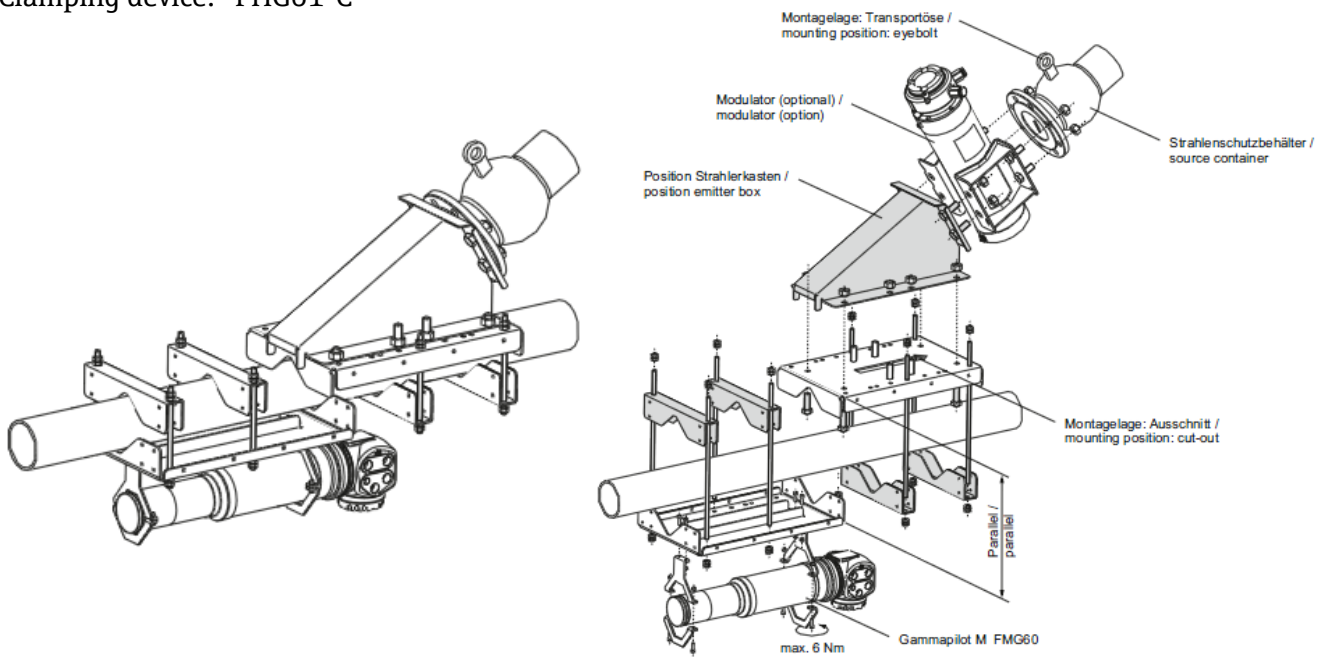
3.5   Clamping device with source container FQG60

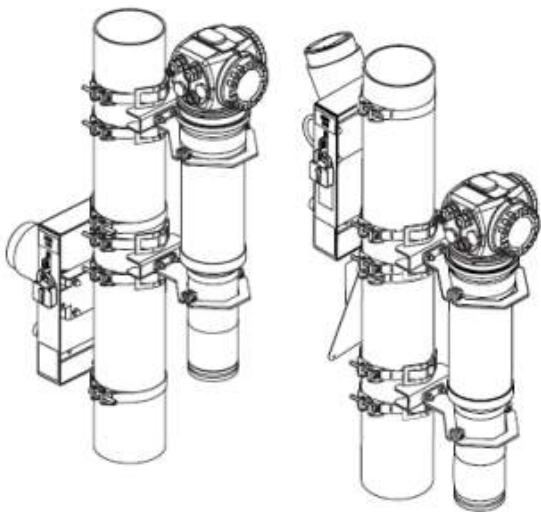**Straight and diagonal beam for pipes with diameter 48-77mm (1.89-3.03in)**
Clamping device: FHG61-E
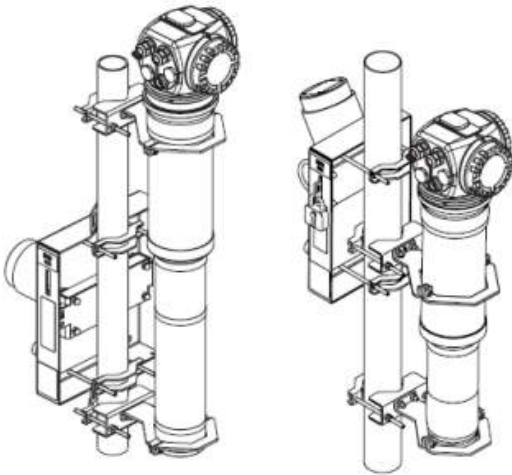
Straight and diagonal beam for pipes with diameter 80-273mm (3.15-10.7in)
Clamping device: FHG61-F

4   Accuracy of system

The accuracy is defined to be the sum of the temperature stability of the detector and the statistical noise out of the source. But there can be also external influences.

Parameters that define the accuracy:

- **Stability of detector** (with NaI-crystal ±0.1% / PVT plastic ± 0.5%)
- **Statistical variation of the radioactive decay** (depends mainly on the integration time)
- Calibration (important for the linearity of the measurement)
- During process: Temperature change / Build up / Abrasion

4.1   Stability of detector

The stability of a detector influences the repeatability of a signal over time and temperature changes.

Scintillator	Temperature range	Influence of ambient temperature
PVT	-40 ℃ to +60 ℃	±0.5 %, typical long-term stability < 1% / a
NaI	-40 ℃ to +60 ℃	±0.5 %
NaI	0 ℃ to 50 ℃	±0.1 %

Stability [c/s]: $\pm 0.1\% \cdot I_N$

I_N = average pulse rate

Stability [%]: $\dfrac{\pm 0.1\% \cdot I_N}{\Delta I}$

$\Delta I = I_{max} - I_{min}$

$\Delta \rho$ = Density difference

Stability [kg/m3]: $\dfrac{\pm 0.1\% \cdot I_N \cdot \Delta\rho}{\Delta I}$

Increasing the stability is possible with an enlarging of the penetration length, thus creating a higher count rate difference $\Delta I.$

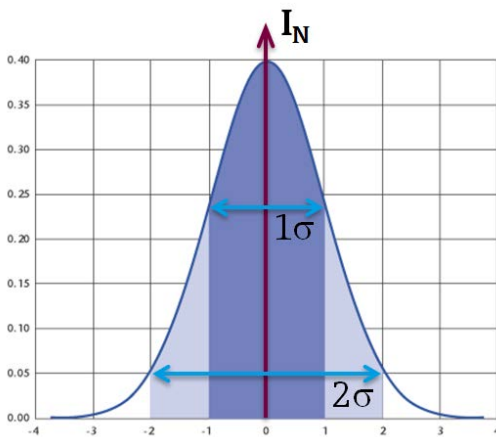## 4.2 Statistical variation of radioactive decay

The radioactive decay is subject to statistical fluctuations. Therefore, the pulse rate fluctuates about its average value. The standard deviation σ is a measure for these fluctuations. It can be calculated in the following way:

Stability [c/s]:

$$\pm\sigma = \pm \frac{\sqrt{I_N}}{\sqrt{\tau}}$$

- σ = Standard deviation (sigma)
- I_N = average count rate (c/s)
- τ = integration time (output damping)

Confidence level:

$$\pm\sigma = \pm\sqrt{I_N} = 68.28\ \%$$

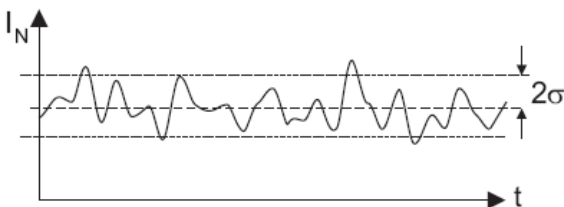$$\pm2\sigma = \pm2\sqrt{I_N} = 95.45\%$$

$$\pm3\sigma = \pm3\sqrt{I_N} = 99.74\%$$

Generally confidence level 2σ is used.

Stability [c/s]:

$$\pm2\sigma = \pm2 \frac{\sqrt{I_N}}{\sqrt{\tau}}$$

- σ = Standard deviation (sigma)
- I_N = average count rate (c/s)
- τ = integration time (output damping)

Statistical variation of the radioactive decay depends mainly on the integration time.
The statistical variation can be reduced by enlarging the integration time.

Time constant should be as long as possible and as short as required by the dynamic of the process.

5   Calibration of the system

The radiometric measurement system has to be calibrated on site due to the influence of the geometrical changes of the installation. A complete calibrated system cannot be shipped because of radiation safety regulations, which request to transport the source container in a specified Type-A package. Therefore the source container and the detector can only be mounted on site, with a clamping device on the pipe.

The calibration is important for the linearity of the measurement.

5.1   One-point calibration

For many applications a one-point calibration is sufficient. Apart from the background calibration, only one further calibration point is used. This calibration point should be located as near as possible to the actual operating point. Densities in the proximity of this operating point are measured fairly precise, whereas the precision may decrease with increasing distance to that operating point.

In a one-point calibration, the detector FMG60 only calculates the reference pulse rate I_0. The slope of the exponential function of the absorption isn't defined, therefore the standard value for the absorption coefficient is used, μ = 7.7 mm2/g.

5.2   Two-point calibration

With a two point calibration the slope of the exponential function is completely defined. Each calibration point consists of a density value and the associated count rate.

In a two-point calibration, the detector FMG60 calculates the reference pulse rate I_0 and the absorption coefficient μ of the material measured.

The initial calibration starts typically with water in the pipe, as it is the support medium for the solids and it has the lowest density. Herewith the first calibration point will be determined.

For the second point we recommend the maximum density of the slurry or a density value close to this point. This density value has been determined by taking a sample, e.g. by Marcy measurement or in a laboratory.

If there is no possibility to take a sample of the slurry density, calibration plates can be used instead. With the specific thickness and density of those plates, you can simulate a density change of the process medium inside the pipe. The available thickness of the plates, offered by Endress+Hauser, is 3mm steel or lead. To simulate a density value, several plates can be necessary. The needed number of calibration plates will differ for various pipe diameters.
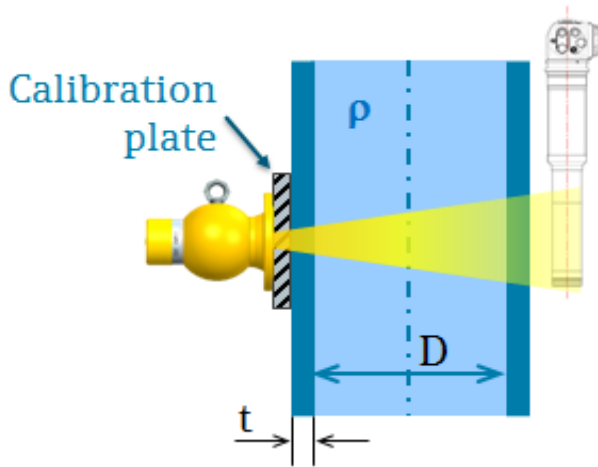
$$\Delta\rho = \frac{t_{plate} \cdot \rho_{plate}}{D}$$

- $\Delta\rho$ = density difference of medium
- D/(t) = path length through medium/plate
- $\rho_{medium/plate}$ = density of medium/plate

Calibration plates
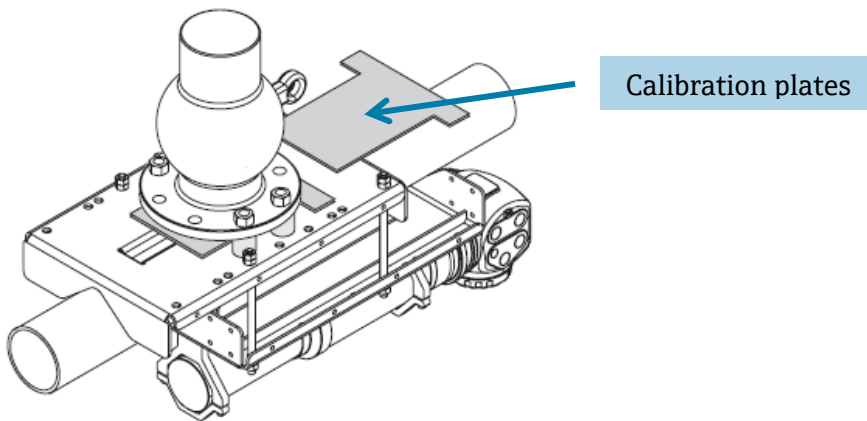
Example:
Pipe diameter 500mm; Density range 1 - 2.4 g/cm^3.
Calibration point 1: pipe filled with water
Calibration point 2: using calibration plates

Density range: $\Delta\rho$= 2.4 g/cm^3 − 1 g/cm^3 = 1.4 g/cm^3

$$\Delta\rho = \frac{t_{plate} \cdot \rho_{plate}}{D} \quad \rightarrow \quad t_{plate} = \frac{\Delta\rho \cdot D}{\rho_{plate}} = \frac{1.4\frac{g}{cm3} \cdot 500mm}{7.89\frac{g}{cm3}} = 88.72\text{mm steel}$$

Endress+Hauser offer plates with a thickness of 3mm steel.
88.72 mm / 3mm ~ 30 Plates of steel → 90mm steel

$$\Delta\rho = \frac{t_{plate} \cdot \rho_{plate}}{D} = \frac{90mm \cdot 7.89\frac{g}{cm3}}{500mm} = 1.42 \text{ g/cm}^3$$

Calibration point 2: 1.42 g/cm^3 + 1 g/cm^3 = 2.42 g/cm^3

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6 Recalibration

Recalibration is necessary if the measuring conditions have changed, e.g. by increasing build up in the pipe or due to abrasion.

For the recalibration only one point of the density value is necessary. As in total nine calibration points can be used for a density measurement, the calibration point 10 is used with the reference pulse rate I_0 and the overall calibration is recalculated according to the current measuring conditions and the absorption coefficient μ is kept unchanged from the original calibration. That means the exponential function will only be shifted up or down.
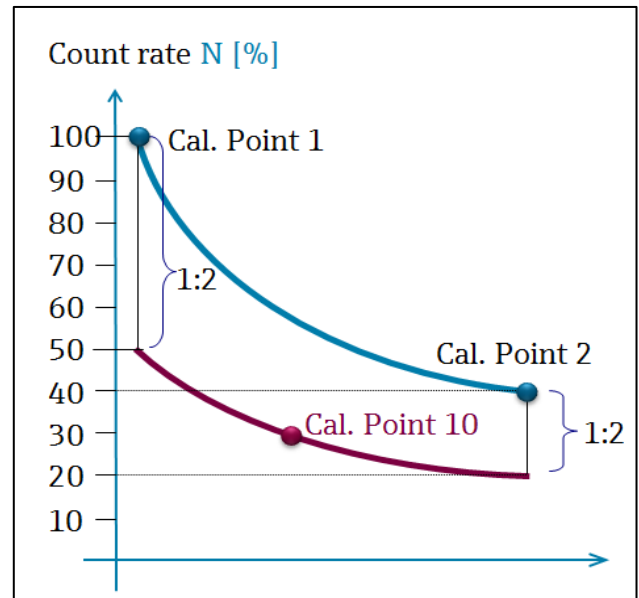
6.1 Re-calibration with calibration plates

To recalibrate a radiometric density system, calibration plates can be used. Typically the achieved accuracy is in a range of 1-2%. However, first an initial calibration with values from the laboratory is essential. If the system is calibrated, the pipe can either be drained off (diameter <200mm) or filled with water. The calibration plate needs to be inserted and the shown density value has to be marked on the calibration plate. Later, whenever it is required, the density plate can be inserted again, considering the same conditions as during the time the calibration plate was marked (pipe empty for <DN200 or filled with water).

If the density gauge shows a not acceptable variation, calibration point 10 can be used to recalibrate the density gauge.

6.2 Is Re-calibration necessary in case of detector exchange?

In case a detector needs to be exchanged, the calibrated values from the defective detector can be uploaded. Due to tolerance reasons of the detectors and their new installation position, a small error needs to be considered.

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7 Reference system for calibration

7.1 Marcy calibration

On site the Marcy calibration is being used very often. By using this technology, typically an uncertainty of 2-3% needs to be considered.

Typical content of a bucket 1000 cm³ (1 liter)

Pulp density scales are accurate to +/- 10g
→ max deviation: 20 g → max error = 2%

Each Marcy scale needs to be calibrated as well, which can cause an additional error of 1%.

In some samples the real density in a pipe is different to the sampled one. Reason is mainly a different slurry density at the pipe wall compared to that in the center of the pipe. For a good Marcy sampling, at least 5-10 samples should be taken.

When using a Marcy scale for a radiometric density calibration, the typically achieved accuracy is in a range between 2-5%.

7.2 Laboratory sample calibration

The most common and accurate calibration is carried out with the samples being measured in the laboratory. In that case the accuracy can be as good as 0.5 g/cm³ and there will be no real additional error during the calibration.