Metrological prerequisites for determination of silage density compacted in a bunker silo using a radiometric method

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Abstract: It is particularly important to appropriately compact the chopped material upon storage to produce high quality silage feed. It was the objective of the research to understand the metrological prerequisites for online density measuring using a radiometric probe. Caesium 137 with an activity of 37 MBq was used as radiation source in the tests. Source and detector were hovered over the goods to be measured. The number of gamma photons reflected from the goods occurs to be proportional to the density of the silaged goods. The probe was tested in a compaction test arrangement on chopped grass and maize, as well as on different bulk goods. It could be shown that radiometric measuring devices are suitable to measure the density of agricultural goods, particularly ensiled goods, using back-scattering. The measuring built the basis for the development of a probe which shall be deployed on horizontal silos in the future.

Keywords: silage compaction, bunker silo, silage density, radiometric measuring device

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1 Introduction

Maize silage and wilted grass silage are both important basic feeds for ruminants. The provision of suitable silage requires adequate compaction of the ensiled goods. When storing silage goods in the bunker silo, compactor vehicles, i.e. tractors, wheel loaders or roller compactors used in road construction are used for compaction.

In recent years the performance of field choppers and transport technology has been improved significantly. Similar developments could not be noticed in development of compactor vehicles. Thus compaction in bunker silos must be considered a technological bottle neck in the processing chain. Inadequate compression of the chopped material causes increased loss in dry mass and undesirable fermentations as well as generation of mould funguses, subsequently leading to contamination with mycotoxins.

Richter et al. (2009) analysed that mould clusters especially can be found on the edge of silo walls and on the top of the silo. In these places the densities measured were lower than those in the middle and at the bottom of the silo. Schmerbauch (2000) reported that a higher mould infestation was found in a less compressed round-bale silages rather than in a highly compressed silage bales. He determined a silage compactness of at least 200-210 kg_{DM}/m^3 for green forage with a relatively high content of raw fiber.

A literature research Kressel (2008) found how mould in maize silage affects milk production and metabolism parameters of milk cows. Due to the contamination with mould, the milk production was reduced by nearly 5 kg milk per cow and day, and the proportions of fat, protein and milk glucose are going down. In turn, the cell content and the ammoniac content in the rumen secret are rising. Wichert, Kienzle and Bauer (1998) determined after feeding tests, that milk cows took in 10% to 20% less green feed when silage with higher contamination of bacteria, yeast, and mould fungus was

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offered.

The literature specifies densities for appropriate storage of grass silage with respect to dry mass (DM) at 160 - 225 kg_{DM}/m^3 (20% or 40% DM), and of maize silage at 225 - 265 kg_{DM}/m^3 (28% or 33% DM) (Honig, 1987).

Although these benchmarks for desirable densities are known, it was found out in density measuring of 210 bunker silos by Kleinmans et al. (2005) that in more than half of the silos the minimal densities were not achieved.

Dry mass content, raw fiber content, bending strength, leaf-stalk ratio, length of the chopped material, compacting pressure, compacting frequency and time as well as silo height have established as important impacting factors for compaction (Fürll, 1972; Dernedde, 1983; Savoie, Muck and Holmes, 2004; Wagner and Büscher, 2005; Holmes, 2006; Schemel, Idler and Fürll, 2007). However, farmers often lack the measuring technology and the processing techniques to react to all respective influencing factors. Processing decisions at storage and compaction must be made based on the experience and approximate values.

Various methods were developed for measuring the achieved silage density. In practice it has been established to take core samples with special drills (Muck and Holms, 2000; Kleinmans et al., 2005; Latsch and Sauter, 2011) from the silo, or to cut out silage blocks with a silage block cutter (Wagner, Leurs and Büscher, 2004; Latsch and Sauter, 2011). The silage density is established on the volume of the sample and the respective mass.

The disadvantage of both methods is that sampling is only established past the storage period. Therefore, there is a lack of parameter for control of the compaction process at the point of storage. A procedure of measuring the silage density on storage and extraction is the radiometric density measuring with so-called γ-scatter probes. Conventional γ-scatter probes are constructed as one-tube probes, i.e. the radioactive source, normally Caesium 137, and the radiation detector are arranged in one tube. An absorber with potentially high density shields the detector from direct radiation. The single-rod-probe entered via a drill hole into the silo stock for determination of silage density (Kuhn, 1976; Gläser and Kuhn, 1997). In the silo stock, the Caesium emits gamma photons that are absorbed depending on the density of the surrounding silage, or reflected to the detector. The gamma photons measured at the detector are a measure for the silage density. The radioactive density measuring requires trained operation personnel. The radiometric γ-scatter probe facilitates pointed measuring only.

In road construction, a so-called Troxler-probe is used for the measuring of density of the lower road bed or tarmac layers (Troxler, 2011). In this probe, source and detector are hovered over the measured material. The reflected gamma photons from the examined layers are measured in this procedure. The probe has been designed for densities of 1,200 – 2,500 kg/m^3. This range of density is clearly above the densities in a bunker silo. The Troxler-probe only facilitates pointed measuring.

In order to facilitate continuous compacting, roller compactors for road construction are fitted with distance sensors (ABG, 1997). Using this method, two sensors measure the distance of the roller compactor to the bottom in the lane and directly next to it. Information about the compaction effect is calculated from the difference in distance. Based on this method, roller compactors from road construction with several distance sensors were successfully used on bunker silos (Häbler, 2008; Tölle, Häbler and Römer, 2009). It is the disadvantage of this procedure that just the compaction effect is measured, but not the actual density of the compacted matter.

It can be summarized that there is currently no reliable method for farmers to measure the density of the silage continuously when we drive-compact it. Own research has the objective to develop such a measuring method and to develop the respectively required device. Radiometric density measuring was chosen as the most promising measuring principle following the preliminary evaluations. The evaluations are based on the density measuring by Gläser and Kuhn (1997) with a radiometric single rod probe. As opposed to their method, it is required for our own development to have the radiometric source and the detector remaining on the surface of the ensilaged material. Only by doing this it allows continuous density measuring while drive-compacting.

2 Materials and methods

2.1 Measuring principle and measuring arrangement

The measuring principle is based on the interaction of gamma photons with the electrons of the scattering material. The higher the density of electrons is, the higher the material density is. Scattering and absorption processes are overlapping in the measured material (Gläser and Kuhn, 1997). Both process are counteracting, and both cause the resulting impulse rate of the back-scattered gamma photons to show a maximum (Figure 1). It must be ensured that the density measuring is facilitated on one side of the maximum by choosing the suitable radiation source. Normally measuring takes place on the rising branch left to the maximum. The allocation of the impulse rate to density is thus distinct.

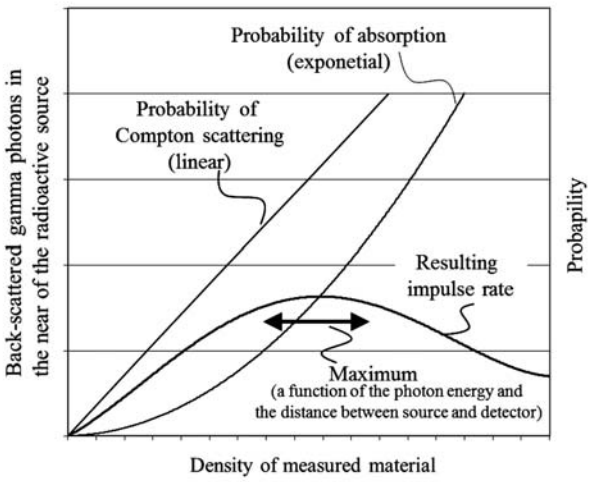


Figure 1 Development of basic form of impulse rate measured by backscatter probes as a function of density of surrounding material (Gläser and Kuhn, 1997, modified)

The expected densities for chopped grass and chopped maize are below 1,000 kg/m^3. Gläser and Kuhn (1997) specify the radionuclide Caesium 137 as radiation source for this density range.

A compaction test arrangement was built to identify metrological prerequisites (Figure 2). The test arrangement consists of a frame, a compaction box, a compactor stamp, and a hydraulic unit with 2 hydraulic cylinders. The compactor box has a volume of about 0.3 m^3 at 600 mm diameter and 1,000 mm bank height.

Located on the compactor stamp is a radiometric measuring unit (Figure 2) by RGI Industriemessgeräte GmbH (Bad Wildbad, Germany). This measuring unit consists of a Caesium radiator with an activity of 37 MBq and a natrium iodide scintillation detector.

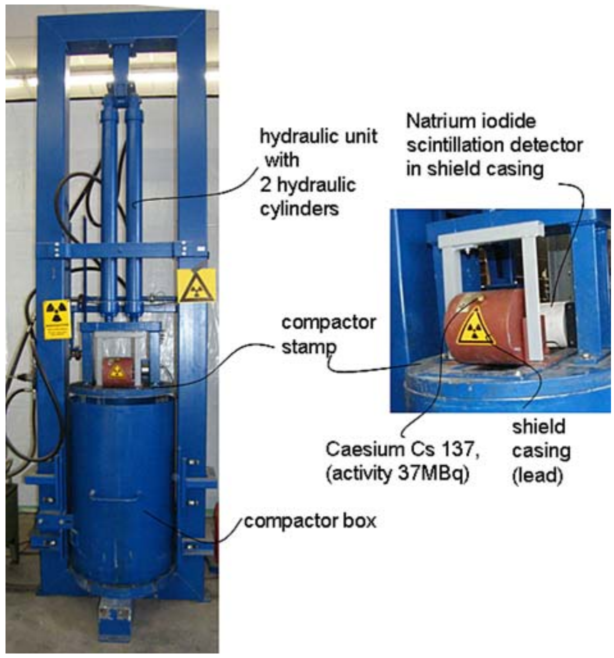


Figure 2 Compaction test arrangement with mounted radiometric measuring unit

The radioactive Caesium is located in the middle of a cylindrical, shielded container (Figure 3). From the middle of the shielded container, a bore hole leads to the outside. Photons emitted in the direction of this bore hole are passing through the bore hole to the outside, and hitting the material to be measured in the compaction box. The gamma photons enter the material to be measured until they collide with electrons of its atoms. A part of the gamma photons is absorbed as a consequence of the collision, while another part is scattered, i.e. the gamma photons change their trajectory and lose part of their initial energy in the process (Compton-scattering). Part of these scattered photons are coincidentally scattered in such way that they leave the material to hit the detector and to be measured.

The detector is also located in a lead shielded casing, fitted with a squared window to catch only photons from a certain direction. Both shielded containers can be rotated by given angles α and β respectively. The distance between the shielded containers is variable.

In order to have the 30 mm steel compactor stamp absorb only a minimum of gamma photons, a slot has been cut in the stamp in the approximate range of the emission trajectory. The slot is closed from down upside with a 5 mm aluminium plate to prevent silage material from being extruded through the slot.

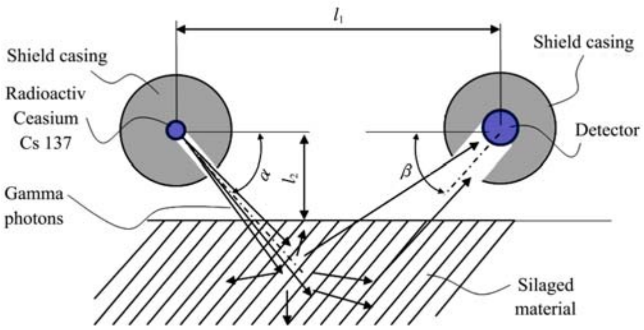


Figure 3 Drawing of principle of radiometric measuring probe

After filling, the compactor stamp compresses the chopped material to a defined volume. The material density is calculated by the remaining volume and the mass filled in. The calculated density represents the fresh matter bulk density. The compaction tests are way length controlled. The 0.282 m^2 compactor stamp is powered with a maximum of 100 kN press strength to facilitate the required compression length. Juice generated by compression is drained from the bottom of the compaction container.

2.2 Execution of tests

In the test, weighed volumes of chopped grass and maize were filled into the compaction container and were compressed. The dry matter content of chopped maize was 39.8%, the dry matter content of the three chopped grass samples used for compression tests were 37.3% (1), 27.4% (2) and 34.3% (3). In one case the material was filled in loose and compressed on the whole,; in the other case the material was filled one layer at a time, and each layer was pre-compressed. Various compression grades were generated by gradually lowering the compactor stamp. Geometrical parameters of the measuring probe were varied and respective impulse rates in the various compression stages were measured (Table 1).

Table 1 Parameters and variants in the tests in the compaction test facility

Parameters	Variants
Diameter of exit opening in shielded container d_{AO}	10 mm, 12 mm, 14.7 mm, 25 mm
Distance l_1 source – detector	20 cm, 25 cm, 30 cm, 35 cm
angle of entry α	70°, 65°, 60°, 55°, 50, 45°, 40°, 35°
Angle β of detector	90°, 70°, 45°
Distance l_2 from measured material	115 mm (80 mm +35 mm)
Measured goods	air (blank value) compressed differently: grass cut, chopped maize loose filling: shives (110 kg/m³), rye grain (760 kg/m³)
Material environment	aluminium, steel, plastic
Type of detector	NaJ/Tl crystal (DD50), BGO crystal (WD25)
Activity of source Cs 137 on 24. August 2010	37 MBq, half life 30 years

Shives and rye grains with established bulk densities were measured radiometrically for comparison and calibration. Shives are woody particles from the hemp stem core. The mean value of the impulse rates obtained at a measuring time of 40 seconds was used to determine the relation between the density ρ of the measured material and the impulse rate I.

In order to facilitate estimating the penetration depth of the gamma rays into the examined material, fillings with shives (bulk density 110 kg/m^3) and rye (bulk density 760 kg/m^3) with each 10 cm, 15 cm, 20 cm and 30 cm packed beds were made. It was assumed that back-scattered gamma photons form the same angle against the normal on the surface than the incident gamma photons. On the basis of this assumption, the distance and angles between source and detector were adjusted (Table 2).

Table 2 Parameter and variants in the tests for depth measuring

Searched measuring depth/cm	Filling material	Diameter d_{AO} of exit opening at the source/mm	Distance l_1 source to detector/cm	Angle α of entry /(°)	Angle β of detector/(°)	Type of detector
10	rye	25	25	70	70	DD 50
10	shives	25	30	70	70	DD 50
15	rye	25	25	70	70	DD 50
20	shives	25	30	70	70	DD 50
20	rye	25	25	70	70	DD 50
30	shives	25	30	70	70	DD 50

A lead body was moved along under the packed beds. The goal was to determine whether the impulse rate would change when the lead body was located under the measuring arrangement, absorbing the gamma radiation.

3 Results and discussion

Differently high impulse rates of the back-scattered gamma quanta are detected by varying angle of source and detector, the distance of both measuring bodies to each other, as well as the width of the exit opening of the radiation source. In order to facilitate establishing potentially sensitive density differences, the measuring arrangement must be adjusted in such way that the correlation line shows a sharp increase. The increase is sharper,

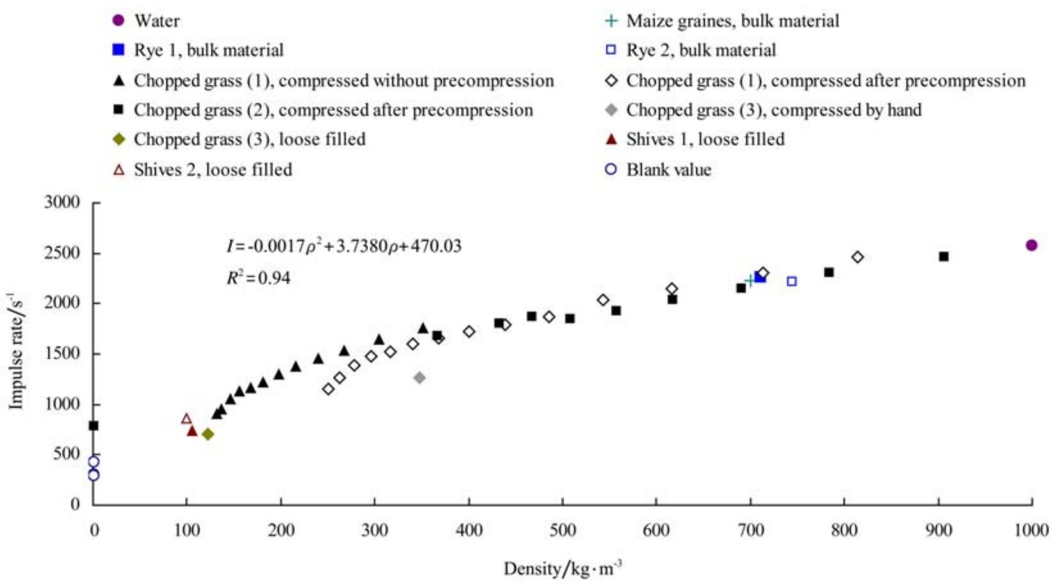
- the minor difference is between source and detector;
- the flatter the angles of source and detector are;
- the wider the exit opening is in the shielded container of the source;
- the more sensitive the detector is.

The rise of the correlation line is the lower,

- the higher the distance is between source and measured material; and
- the more material is located between the measuring arrangement and the measured material, e.g. by the compaction stamp.

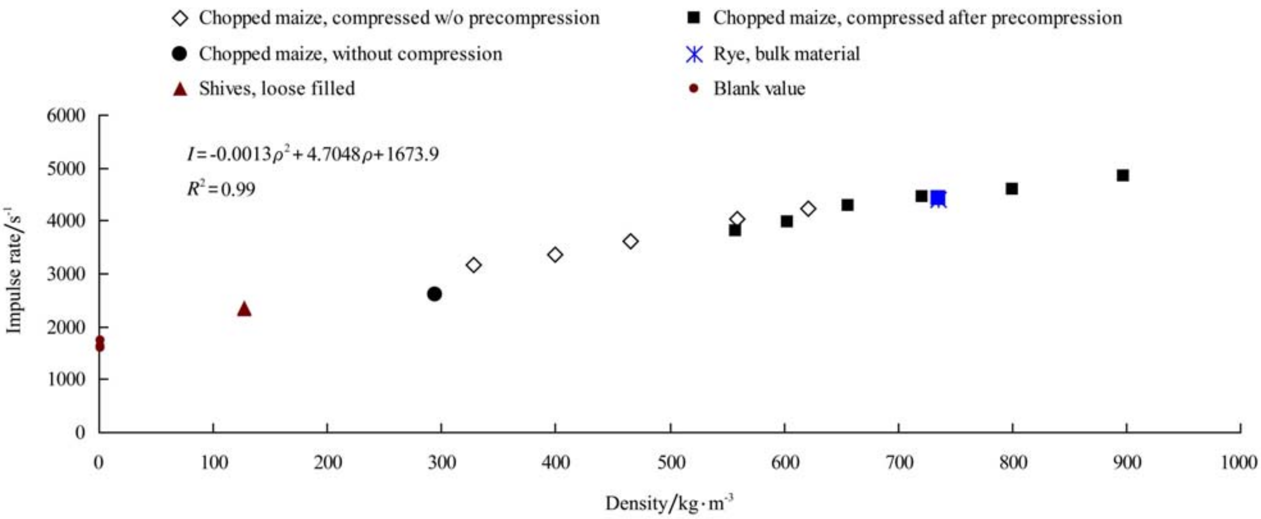
In an optimal arrangement the relation between the density ρ of the measured material and the impulse rate I can be shown. The measuring ranges from non-compacted to highly compacted chopped grass and chopped maize respectively as well as the bulk goods, shives, rye grain and maize grain. At the lower/upper scale end of the density range are impulse rates for air/water (Figure 4 and Figure 5). The heights of the measured impulse rates in both tests vary depending on the different diameter of the source opening. However, in any case the bulk goods shives, rye grain and maize grain fit very well into the nearly linear density trend of the chopped, compacted grass and maize. Taking the results of Gläser and Kuhn (1997) into account, the calculated R-squared values were relatively high for a quadratic regression curve.

Thus rye and shives for calibration of the measuring probe can be fairly well utilized for chopped grass and chopped maize. This procedure is generally based on the fact that plant materials are similar in their stoichiometric composition and thus as well in their mass attenuation coefficients (Gläser, 1992). Rye grains show a similar scattering and absorption behaviour as grass cut, which is compressed to a density of 760 kg/m^3.



Note: source opening d_{AO} = 14.7 mm, detector DD50, angle emitter α = 55°, angle detector β = 70°, distance source-detector l_1 = 20 cm, distance to measured goods l_2 =115 mm

Figure 4 Correlation between the density ρ of selected agricultural good, particularly chopped grass and the impulse rate I at the detector in back-scatter measuring



Note: source opening d_{AO} = 25 mm, detector DD 50, angle emitter α = 55°, angle detector β =70°, distance source-detector l_1= 20 cm, distance to measured goods l_2 = 115 mm

Figure 5 Correlation between the density (ρ) of selected agricultural goods, particularly chopped maize, and the impulse rate (I) at the detector in back-scatter measuring

Measuring shows that density determination according to the principle of back-scattering is possible. Thus source and detector can be driven over the goods. Drillings and single rod probes in the silo, as required in earlier measuring (Gläser, 1992; Gläser and Kuhn, 1997), can be omitted. Bulk goods like rye grain or shives are fairly suitable for calibration of the measuring arrangement for chopped grass and chopped maize.

When a lead body is moving along under shives with 10 cm and 20 cm packed bed height, the impulse rate is obviously reduced. When a lead body is moving along under the shives with 30 cm packed bed height, the impulse rate is still slightly reduced (Figure 6). The lead body is thus evident up to a maximum of a packed bed height of 30 cm.

It is also striking that the impulse rate measured at shives with a packed bed height of 10 cm is significantly higher in comparison to an impulse rate measured at shives with a packed bed height of 30 cm, even though the lead body is still far away from the measuring point. This means that at lower heights of packed bed, gamma quanta are not only scattered by the shives, but also from the immediate surrounding, in this case from the concrete floor with a density of 2400 kg/m^3. Furthermore, it is noticeable that the impulse rate is lower at the moment of measuring, when the lead body is passing the irradiated area. This result confirms the physical fact of Figure 1. The density of lead is 11 300 kg/m^3 high, and the resulting impulse rate is low because of the fact, that the adsorption of the gamma quanta is higher than their scattering. The measurement takes place on the right side of the maximum of resulting impulse rate curve.

In rye the impulse rate is reduced by the lead body at 10 cm packed bed height significantly and at 15 cm packed bed height still detectably (Figure 7). The entry depth of the gamma rays is thus lower in rye with higher density compared to shives. This finding is also supported by the fact that the distance between source and detector can be wider to detect scattered gamma quanta in a packed bed of shives up to 30 cm than in a packed bed of rye (Table 2).

The measured values show the principle-related disadvantages when measuring is made according to back-scattering instead of transmission principle. In view of the simultaneously proceeding of the adsorption process of gamma quanta the application of back-scattering for density determination of silage is applicable only in a defined area. However, taking into account all the factors relevant to the external circumstances the radiometric density measuring of silage is basically given and very promising.

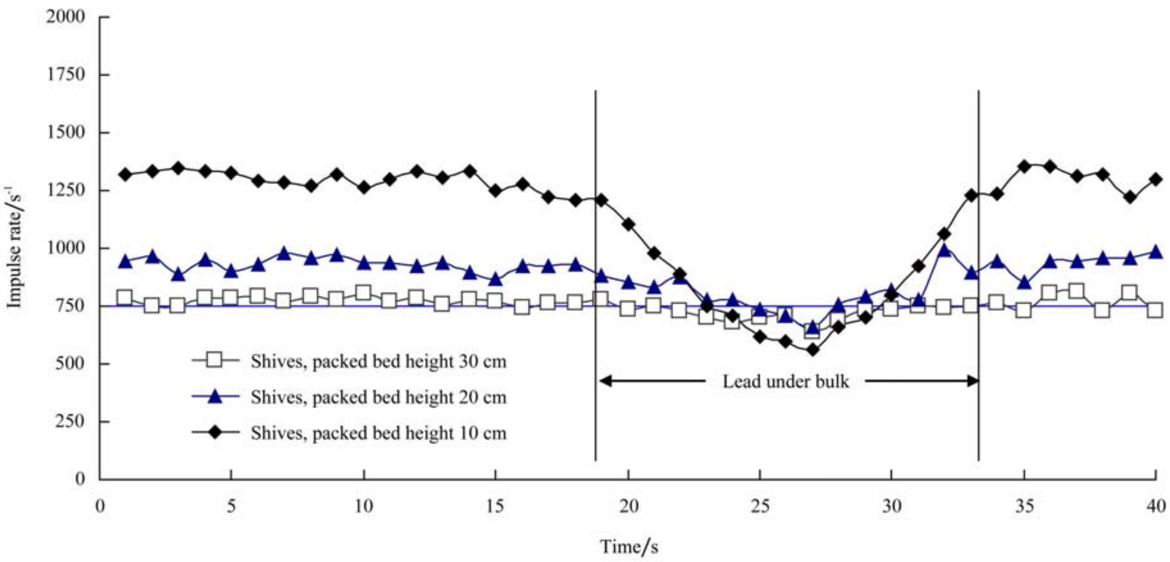


Figure 6 Impulse rate in shives with 10 cm, 20 cm, and 30 cm packed bed height and a lead body moved along under the measured material

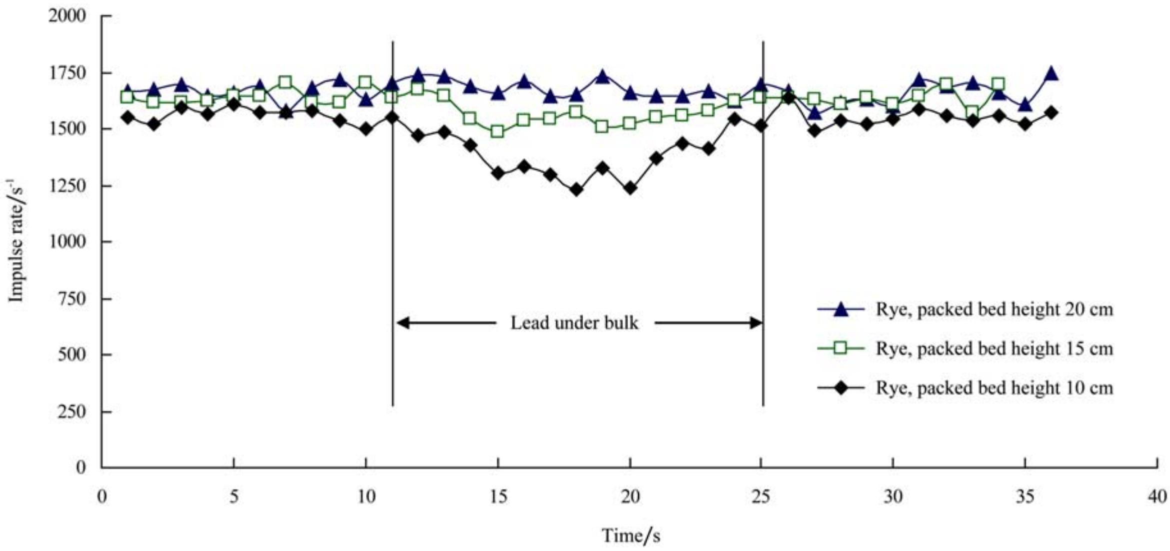
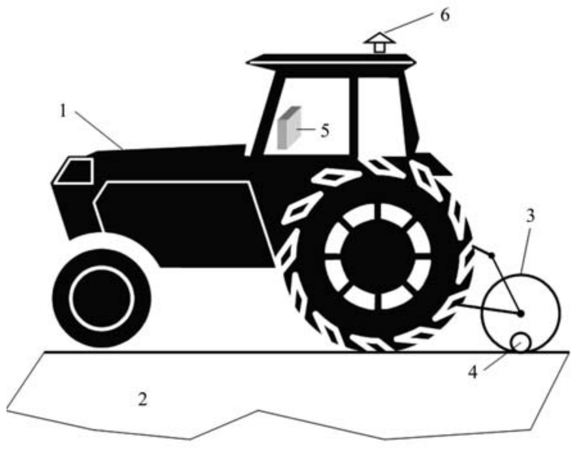


Figure 7 Impulse rate in rye with 10 cm, 15 cm, and 20 cm packed bed height and a lead body moved along under the measured material

The results support a concept by Fürll and Schemel (2006) for application of radiometric density measuring in the bunker silo (Figure 8). The concept envisions the radiometric measuring unit (Pos. 4) to be arranged in a trailing measuring wheel (Pos. 3). During driving in the silo the density is measured continuously and shown to the driver via display. In connection with a navigation system, the (Pos. 6) area distribution of the silage density can be displayed.

Particularly in times of nuclear disasters like Chernobyl and Fukushima, radioactive substances apparently raise concerns in the general perception. This applies explicitly when food or feed are brought in connection with radioactivity.



1. Compacting tractor 2. Storage goods 3. Measuring wheel
4. Density sensor 5. Evaluation unit 6. Navigation aerial

Figure 8 Concept for execution of online-density measuring at a tractor (Fürll and Schemel 2006, modified)

A radiation source with an activity of 37 MBq was used in the tests. Not any radiation was detected on the surface of the shielded container. On the surface of the transport container 40 µSv/h were measured (Table 3).

Table 3 Radiation doses at different locations

Criterion	Location/radiometric measuring device	Radiation dose
Radiometric density probe, 37 MBq	surface of lead shield container, when probe in shield container [1)]	0 µSv/h
	surface of transport container, when probe in container [1)]	40 µSv/h
Natural terrestrial radiation exposure (mean value)	Germany - Northern Germany (ZDF, 2011) - Hessen (ZDF, 2011) - Black Forest (ZDF, 2011)	 2.5 µSv/d 7 µSv/d 15 µSv/d
	India, Tamil Nadul[2)]	6 µSv/h
	Kenia, Mombasa[2)]	12 µSv/h
	Iran, Ramsar[2)]	30 µSv/h
Additional profession-related radiation exposure	return flight Frankfurt – New York (Bonath, 2010)	100 µSv
	operator at Portac detector (Bonath, 2010)	< 1 µSv/h
	Troxler probe, 185 to 3700 MBq (Troxler, 2011)	2 mSv/a
	14 m distance to Castor-transport on November 28, 2011 (ZDF, 2011)	4-5 mSv/h
Radiation protection requirements for individuals exposed to radiation in professional environment (Vogt and Schulz, 2011)	individual exposed to radiation	1 mSv
	total dose professional life	400 mSv
	category B (monitored area) [3)]	>1 - 6 mSv/a
	category A (control area) [3)]	>6 - 20 mSv/a
	off-limits area	> 3 mSv/h

Note: 1) data by RGI Industriemessgeräte GMBH; 2) J. Bittner, personal communication, Company RGI Industriemessgeräte GmbH, Bad Wildbad, GERMANY, 22.6.2010. 3) max. stay period: 40h/week, 50 weeks/year, individual older than 18 years

The radioactive radiation of the Caesium-137 source was only emitted at the exit opening of the shielded container. Upon application this was exclusively directed on the measured material. A transport container can be used when the radiation source after use is stored in a different place than the measuring arrangement. Otherwise, the exit opening must be covered with a shield respectively if the source is not used.

When radiation levels are determined, it must be considered that there is a natural terrestrial radiation exposure by gamma rays on earth, which differs according to the actual location (Table 3). Since radiometric measuring devices are dedicatedly shielded, the radiation levels emitted by such devices are normally very low compared to requirements for individuals exposed to radiation (Vogt and Schultz, 2011), or e.g. to radiation levels occurring at Castor transports.

Nevertheless if the contractor wants to be authorized to use a Cesium 137 source for density control he must have a valid handling license for radioactive substances as well as general knowledge about the use and handling of these. Basically all persons who are in direct contact with an unshielded radioactive source have to be informed about the general health risks that may arise from handling with ionizing radiation. If the three basic concepts, time, distance and shielding, of radiation protection receive attention there is no increase in hazard to human health. In order to avoid any health risks, the time near the source must be as short as possible, the distance to the source as far as possible and the shield of the source as thick as possible. The radiometric device used offers the basic concepts of radiation protection as the Cesium 137 source is placed in the middle of a shielded container made of lead and is only irradiating in direction of the agricultural good or the soil.

The kind and necessity of training of the persons using the radiometric method will depend on the technical design (locked or open design, removable or fix Cesium source, etc.) of the device.

4 Conclusions

The pilot plant tests with radiometric measuring arrangements show that a conversion of the measuring principle in practical applications appears promising. Therefore, a measuring wheel with integrated radiometric measuring unit for mounting at a tractor according to the concept (Figure 8) shall be developed and tested for the coming harvesting period. One key issue of the future research will be the potential measuring faults that can be achieved. It is not known what measuring fault may be produced by the measuring unit when driving, and how vibrations might affect the measuring.

The use of a radioactive measuring probe may expose humans and the environment to the radiation. According to legal requirements, it must be assessed for new occupations involving exposure to radiation, whether potentially occurring hazards to health are rectified by the economical, social, or other benefits. Since the radiometric density sensor shall lead to improved compaction of silage and consequently to less contamination with harmful mould funguses and mycotoxins, an approval by law for the deployment of the density probe can be expected. Details for the approval process have to be examined.

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