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Pressure-Induced Bias in Gamma-Ray Radiometric Level Measurement under High-Pressure Nitrogen Blanketing: An Industrial Case Study and Physics-Based Screening Method

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Abstract- Radiometric level instruments are frequently selected for process vessels in which intrusive measurement is impractical because of high temperature, pressure, corrosive service, or severe fouling. Their non-contact nature, however, does not make the measurement immune to changes in the material located within the gamma-ray beam. This paper investigates an industrial case in which two continuous gamma-ray level transmitters were zero-adjusted on a confirmed-empty vessel at 0 barg nitrogen pressure and subsequently indicated false levels of approximately 40% and 43% after the vessel was pressurized to its normal 15 barg nitrogen blanket. Detector count rates decreased from 52,000 to 32,476 ct/s and from 36,011 to 24,540 ct/s, respectively. A first-principles screening model combining Beer-Lambert attenuation, ideal-gas nitrogen density, and NIST photon mass-attenuation data was applied to test whether compressed nitrogen could plausibly account for the observed signal change. The measured count losses of 37.55% and 31.85% correspond to effective nitrogen path lengths of approximately 3.70 m and 3.01 m under the stated assumptions. The analysis therefore supports pressure-dependent gas density as a credible contributor, while emphasizing that geometry, buildup, detector alignment, configuration, and radiation-system condition must be excluded before compensation is implemented. A controlled pressure-temperature validation protocol and an instrument-specific compensation framework are proposed for safe engineering application.

Indexed Terms- gamma-ray level measurement, nitrogen blanketing, radiometric instrumentation, Beer-Lambert law, pressure compensation, industrial process control

I. INTRODUCTION

Gamma-transmission and gamma-attenuation instruments are well established for non-contact measurement in industrial vessels where conventional wetted level technologies may be unreliable or impossible to apply. A sealed radionuclide source is mounted on one side of a process vessel and a detector is mounted on the opposite side. The detector converts received radiation into a count rate that changes with the total attenuation along the beam path. International Atomic Energy Agency (IAEA) guidance describes the use of nucleonic gauges for industrial measurement, while commercial radiometric systems commonly employ Cs-137 or Co-60 sources with scintillation-type detectors [1]-[3].

A practical consequence of the transmission principle is that the detector responds to all mass intersecting the radiation path, not only to the process liquid whose level is intended to be measured. Vessel walls, refractory or insulation, deposits, gas, and process composition can contribute to the measured attenuation. For many ambient-pressure level applications, gas-phase attenuation is negligible compared with vessel and liquid attenuation. In a large vessel operated under a high-pressure nitrogen blanket, however, the gas density may increase by more than an order of magnitude relative to atmospheric conditions. If the effective radiation path through that gas is several metres, the resulting attenuation may be measurable and may shift the apparent empty reference.

The industrial case examined here arose after an empty-vessel zero adjustment was performed while the vessel was depressurized. When nitrogen blanketing was subsequently restored to the normal operating pressure of 15 barg, two independent radiometric level channels indicated substantial

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positive level although the vessel remained operationally confirmed empty. The purpose of this study is to determine whether the magnitude of the observed count-rate reduction is physically consistent with pressure-induced nitrogen attenuation and to define a validation and compensation approach suitable for process instrumentation practice.

The work is intentionally presented as an anonymized engineering case study. Plant identity, equipment numbers, and instrument tag numbers are excluded. The numerical measurements relevant to the physics analysis are retained. The paper does not assert that nitrogen density is the sole root cause; rather, it quantifies its plausibility and identifies the additional verification required before any automatic correction is used.

II. RESEARCH OBJECTIVE AND CONTRIBUTIONS

The primary research question is: can the increase in nitrogen density between a depressurized empty-vessel condition and a 15 barg nitrogen-blanketed condition plausibly produce the 31.85-37.55% detector count-rate reduction observed in two independent gamma-ray level channels?

The contributions of this paper are fourfold: (1) documentation of a field-observed pressure-dependent bias affecting two radiometric level channels; (2) conversion of the field observations into normalized intensity ratios and optical-depth increments; (3) a first-principles screening calculation linking nitrogen pressure, density, photon mass attenuation, and effective beam path; and (4) a proposed engineering workflow for pressure-ramp validation, compensation, independent verification, and management-of-change controls.

III. MEASUREMENT PRINCIPLE AND THEORETICAL BASIS

A. Gamma-Ray Transmission Principle

For a narrow-beam transmission approximation, detected intensity can be represented using the Beer-Lambert relationship:

$$I = I_0 \exp[-\Sigma(\mu/\rho)_j \rho_j x_j] \quad (1)$$

where I is detected intensity or count rate, I_0 is the corresponding unattenuated intensity, μ/ρ is the mass attenuation coefficient, ρ is material density, and x is path length. Equation (1) is a screening representation rather than a complete detector model because industrial installations also include beam divergence, scattering, finite detector length, source collimation, background radiation, and electronic processing.

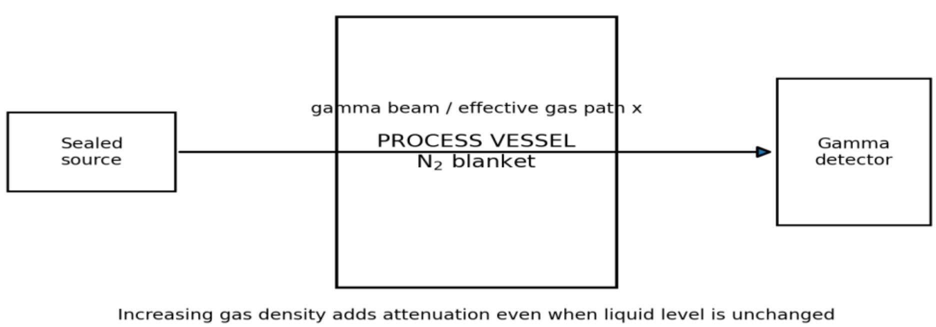

Fig. 1. Simplified radiometric level geometry and gas attenuation path.

B. Nitrogen Density as a Function of Pressure

For a first-pass estimate, nitrogen is treated as an ideal gas. Its density is therefore approximated by:

$$\rho = PM / RT \quad (2)$$

where P is absolute pressure, M is molar mass, R is the universal gas constant, and T is absolute

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temperature. Gauge pressure must therefore be converted to absolute pressure. At 25 °C, Eq. (2) gives approximately 1.13 kg/m³ at 1 bara and 18.08 kg/m³ at 16 bara, corresponding to an incremental density of about 16.95 kg/m³.

C. Incremental Pressure-Induced Attenuation

If all non-gas attenuation terms remain unchanged between two empty-vessel conditions, the incremental optical depth associated with the gas-density change may be isolated from the count-rate ratio:

$$\Delta\tau = -\ln(I_2/I_1) = (\mu/\rho)\,\Delta\rho\, x \quad (3)$$

NIST tabulates nitrogen mass attenuation coefficients of 0.08063 cm²/g at 0.6 MeV and 0.07081 cm²/g at 0.8 MeV [4]. For a Cs-137 photon energy near 0.662 MeV, a screening value of approximately 0.075 cm²/g (0.0075 m²/kg) is used here by interpolation. This value is not a substitute for a vessel-specific radiation transport calculation; its purpose is to test order-of-magnitude plausibility.

IV. INDUSTRIAL CASE AND METHODS

A. Operating Context

The case involved a large process vessel equipped with two continuous gamma-ray level instruments. The vessel normally operates with nitrogen blanketing at approximately 15 barg. During maintenance or commissioning activity, the vessel was confirmed empty and the instruments were zero-adjusted while nitrogen pressure was 0 barg. After restoration of the normal nitrogen blanket, the vessel remained empty but both channels indicated substantial positive level.

The instruments are treated as Unit A and Unit B to preserve confidentiality. The field evidence used in this paper consists of the raw detector count rates at the two stable pressure conditions, the corresponding indicated false level, and the revised empty reference later entered near the normal operating pressure. No intermediate pressure points are represented as measured data in this study.

B. Field Data Reduction

TABLE I. OBSERVED EMPTY-VESSEL FIELD DATA

Parameter	Unit A	Unit B
Empty count at 0 barg (ct/s)	52,000	36,011
Empty count at 15 barg (ct/s)	32,476	24,540
Count-rate loss	37.55%	31.85%
False indicated level	~40%	~43%
Revised empty reference (ct/s)	32,825	25,000
Level after revision	1.20%	1.38%

For each instrument, the normalized residual intensity was calculated as I_{15}/I_0. The pressure-associated optical-depth increment was then calculated as $-\ln(I_{15}/I_0)$. Finally, Eq. (3) was rearranged to estimate the effective nitrogen path length consistent with the measured attenuation under the screening assumptions.

C. Root-Cause Screening

Because a change in count rate can arise from mechanisms other than gas density, the engineering method includes competing hypotheses. These include a changed source-shutter or source-holder position, altered source-detector geometry, vessel residue or wall wetting, configuration or linearization changes, detector/electronics response, external radiation interference, and nitrogen composition or density. The gas-density calculation is therefore used as one branch of a broader diagnostic process rather than as a stand-alone proof of causation.

V. RESULTS

A. Observed Count-Rate Change

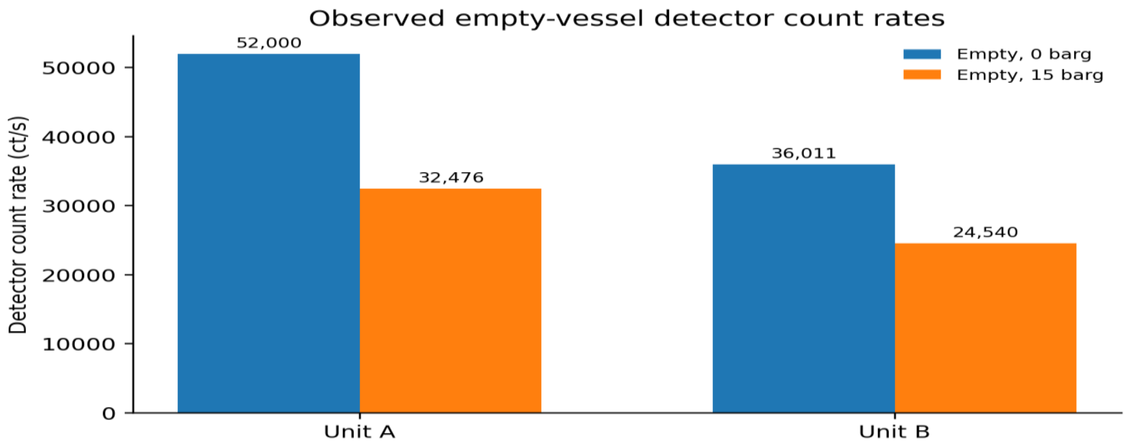


Fig. 2. Detector count rate before and after nitrogen pressurization.

Unit A decreased from 52,000 to 32,476 ct/s, a loss of 37.55%. Unit B decreased from 36,011 to 24,540 ct/s, a loss of 31.85%. The corresponding normalized intensities were 0.6245 and 0.6815. These ratios correspond to optical-depth increments of 0.4707 and 0.3835, respectively. The large magnitude of both changes is consistent with the false level indications because radiometric level calibration interprets lower received intensity as increased absorbing material along the beam path [2], [3].

B. Physics-Based Screening Result

TABLE II. INPUTS TO FIRST-PRINCIPLES SCREENING CALCULATION

Parameter	**Value**
Pressure at depressurized reference	1 bara
Pressure at normal blanket	16 bara
Temperature used for screen	298.15 K (25 °C)
N_2 density at 1 bara	1.13 kg/m³
N_2 density at 16 bara	18.08 kg/m³
Incremental density	16.95 kg/m³
Screening μ/ρ near Cs-137 energy	0.0075 m²/kg

Applying Eq. (3), Unit B's observed optical-depth increment corresponds to an effective nitrogen path of approximately 3.02 m. Unit A corresponds to approximately 3.70 m. Conversely, an assumed 3.0 m gas path predicts an incremental count loss of 31.71%, which is essentially the same magnitude as the Unit B observation. A path of approximately 3.7 m predicts the Unit A observation.

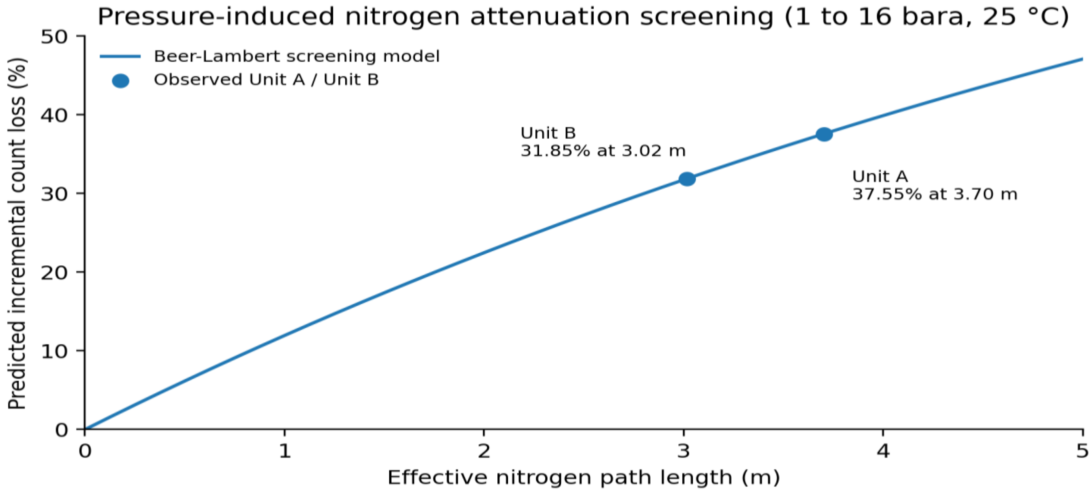


Fig. 3. Screening prediction versus effective nitrogen path length.

The agreement demonstrates physical plausibility: compressed nitrogen over a several-metre beam path can produce a count-rate change of the same order as the field observation. It does not prove that the actual beam path equals the inferred value or that nitrogen density explains all of the change. Actual source energy, gas temperature, gas composition, beam geometry, vessel internals, scatter, background treatment, detector response, and installation geometry can shift the relationship.

C. Effect of Re-Referencing at Normal Pressure

Following the event, empty references close to the 15 barg detector counts were entered. Unit A used an empty reference of 32,825 ct/s and then indicated approximately 1.20%; Unit B used 25,000 ct/s and indicated approximately 1.38%. This operationally restored a useful near-zero indication at the normal blanket condition. However, re-referencing at one pressure does not establish measurement accuracy during depressurization, pressurization, or intermediate pressure operation. It also cannot distinguish gas attenuation from other mechanisms that might coincidentally produce a similar count change.

VI. DISCUSSION

A. Interpretation of the Field Evidence

The two independent instruments changed in the same direction after the same process transition, which strengthens the case for a common process-dependent mechanism. The calculated attenuation magnitude is also compatible with compressed nitrogen over a plausible vessel-scale path length. Together, these observations justify treating nitrogen density as a high-priority hypothesis.

The unequal percentage changes between Unit A and Unit B are also informative. A single universal correction factor should not be assumed. Different source-detector chords, collimation, detector active lengths, background contributions, linearization curves, or shielding arrangements can lead to different sensitivity to the same process pressure. Consequently, any correction should be derived and validated separately for each measurement channel.

B. Competing Root Causes

TABLE III. COMPETING HYPOTHESES AND REQUIRED CHECKS

Hypothesis	Evidence / Test
Source shutter / holder	Verify lock, indication, authorized survey and mechanical condition.
Source-detector geometry	Inspect alignment, supports, dimensions and movement history.
Residue / condensation	Confirm drain, purge, temperature, independent empty condition and buildup evidence.
Configuration / linearization	Compare backups, background, damping, span, isotope and setup history.
Detector / interference	Review diagnostics, temperature, power, count stability and external radiation.
Gas density / composition	Record pressure, temperature and composition during controlled ramp.

The diagnostic order in Table III is not intended to imply that nitrogen density is least likely; rather, it prevents a mathematical correction from masking a mechanical, configuration, process, or radiation-system defect. Source hardware must only be inspected or operated under the site's approved radiation-protection controls.

C. Implications for Calibration Practice

For a pressure-sensitive radiometric installation, the concept of an 'empty count' is incomplete unless the thermodynamic state is specified. An empty reference established at 0 barg is not necessarily transferable to an empty vessel at 15 barg. The calibration record should therefore identify pressure, gas temperature, gas composition, source condition, detector condition, and any relevant vessel configuration associated with each reference point.

A conventional two-point level calibration implicitly assumes that non-level attenuation remains sufficiently constant over the operating envelope. The case presented here shows why that assumption should be verified for large, high-pressure gas-blanketed vessels. If pressure-dependent attenuation is repeatable and material, it should be treated as a measured disturbance variable rather than absorbed indiscriminately into a fixed zero adjustment.

VII. VALIDATION AND COMPENSATION FRAMEWORK

A. Controlled Pressure-Ramp Test

The proposed validation should be performed only on an empty, isolated vessel under approved operating and radiation-safety procedures. Raw detector counts, indicated level, absolute vessel pressure, gas temperature, detector temperature, instrument diagnostics, and an independent confirmation of the empty condition should be recorded at each stabilized step.

TABLE IV. PROPOSED PRESSURE-RAMP VALIDATION SEQUENCE

Pressure-ramp stage	Purpose
Baseline: 0 barg	Collect 10-15 min stable count statistics.
Ramp up: 1, 3, 5, 8, 10, 12, 15 barg	Hold each point until pressure, temperature and count rate stabilize.
Ramp down: reverse sequence	Check hysteresis and repeatability.
Repeat on another day if practical	Assess day-to-day repeatability and confidence band.

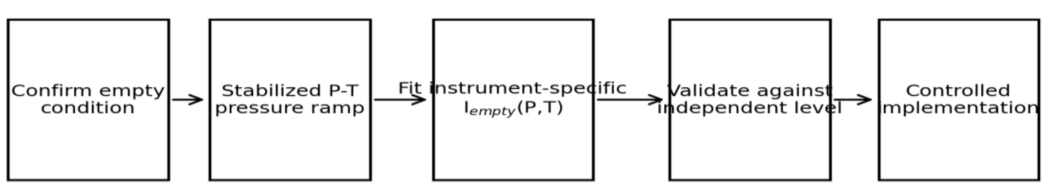
A pressure correction should only progress if the count response is monotonic, repeatable, physically explainable, and stable within statistical limits on both ascending and descending ramps. An unexplained discontinuity, large hysteresis, or instrument-specific anomaly should trigger root-cause investigation instead of curve fitting.

B. Instrument-Specific Compensation

If validation confirms a repeatable pressure-temperature effect, an empirical empty-count baseline Iempty(P,T) should be developed separately for each detector. A bounded lookup table or validated regression may then predict the empty-vessel count at the actual pressure and temperature. The measured count can be normalized to a defined reference condition before applying the established level calibration. This approach separates a demonstrable pressure-density disturbance from the level-dependent attenuation response.

Icorr = Imeas × Iempty(Pref,Tref) / Iempty(P,T)
(4)

Equation (4) is a conceptual normalization form. The final implementation must be matched to the transmitter's native calibration/linearization method and must not be introduced into a safety or trip function without appropriate functional-safety assessment. Input bad-quality handling, pressure and temperature range checks, interpolation bounds, rate limiting, alarming outside the validated envelope, and fail-safe behavior are required engineering considerations.



Any discontinuity, hysteresis, or failed independent check -> investigate root cause; do not mask mathematically

Fig. 4. Proposed validation and implementation workflow.

C. Independent Verification
After compensation is developed, corrected level should be checked against an independent level reference at several known levels and pressures. The verification should demonstrate that compensation does not conceal liquid ingress, buildup, source obstruction, detector degradation, external radiation, or abnormal process composition. Two empty points alone are insufficient to establish a compensation curve because interpolation between 0 and 15 barg would assume, rather than demonstrate, the functional relationship.

VIII. LIMITATIONS

This study is based on a limited but high-value industrial dataset consisting of two instruments at two stabilized pressure states. Intermediate pressure measurements, repeated cycles, direct gas-temperature histories, detailed source and detector geometry, and independent radiation-transport simulation were not available for the present analysis. The ideal-gas approximation and interpolated nitrogen mass attenuation coefficient are appropriate for a plausibility screen but should be replaced by measured operating data and installation-specific modelling for final design.

The inferred effective path lengths are not geometric measurements. They are equivalent path lengths that reproduce the observed optical-depth increment under the screening assumptions. Agreement between an equivalent path and a plausible vessel dimension supports, but does not prove, the nitrogen-density hypothesis. A controlled pressure-ramp experiment remains necessary for causal validation.

IX. CONCLUSION

Two gamma-ray continuous level instruments on a confirmed-empty process vessel experienced substantial detector count-rate reductions after nitrogen blanket pressure increased from 0 barg to 15 barg. The count losses were 37.55% and 31.85%, producing false level indications of approximately 40% and 43%. Re-establishing the empty reference near normal pressure restored near-zero indication but did not determine root cause or validate behavior across the pressure range.

A Beer-Lambert screening analysis using ideal-gas nitrogen density at 25 °C and NIST mass-attenuation data shows that the observed count losses are physically consistent with compressed nitrogen acting over effective paths of approximately 3.70 m and 3.01 m. Therefore, pressure-dependent nitrogen attenuation is a credible contributor in this case and warrants formal validation.

The principal engineering conclusion is that high-pressure gas blanketing should be treated as a potential disturbance variable in large-vessel radiometric level applications. Automatic compensation should only be implemented after controlled multi-point pressure-temperature testing demonstrates a repeatable channel-specific relationship and after mechanical, configuration, buildup, detector, and radiation-interference causes have been excluded. The proposed validation framework provides a practical path from field observation to a defensible compensation strategy without masking unresolved instrument or process faults.

DECLARATIONS
Conflict of Interest: The author declares no conflict of interest in the preparation of this manuscript. Funding: No external funding was received for this study. Data Availability: The numerical data required to reproduce the screening calculations are reported in Table I. Plant identity, equipment identifiers, and detailed site records are withheld for confidentiality. Safety Statement: This paper is an engineering analysis and is not a radiation-work authorization, calibration procedure, safety-instrumented-function design basis, or substitute for manufacturer instructions and approved site procedures.

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