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Annual Users' Conference

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M Resort, Henderson, NV | June 15 – June 18

MIRION TECHNOLOGIES

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Radiation Detectors for RMS

Selection Criteria and Application Considerations

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Mirion Connect | Annual Users' Conference 2026

Henderson, NV

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Daily Check-In:

Tuesday

Please take a moment to check in for today's session.

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Agenda

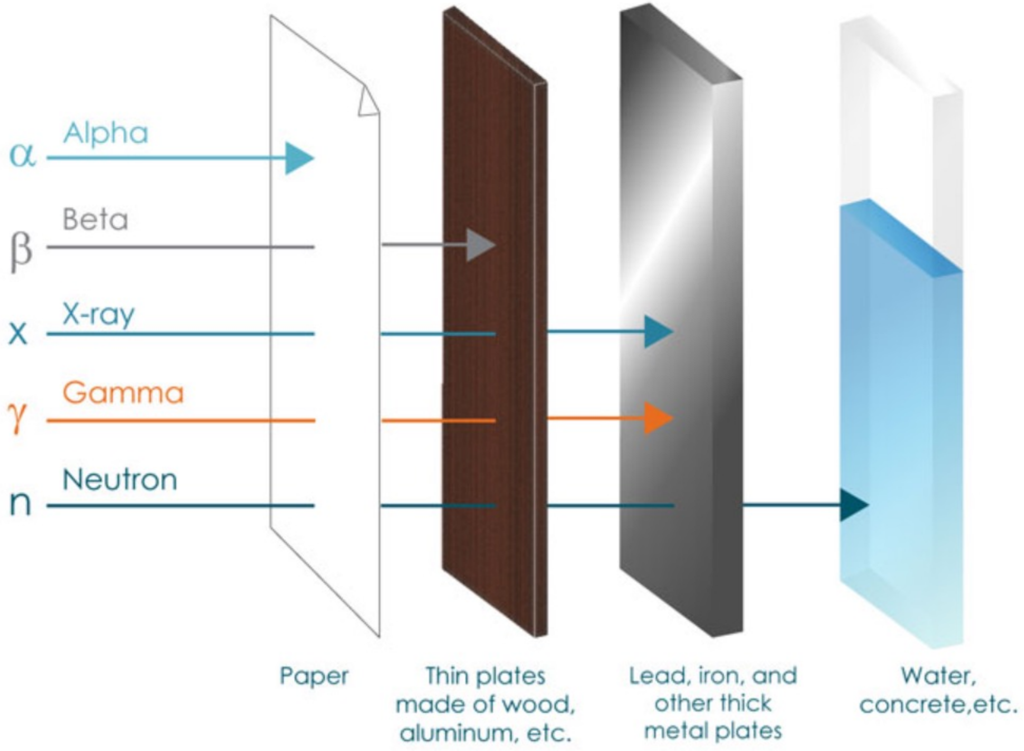
Agenda

Focus on Installed Radiation Monitoring System (RMS) Detectors

- *Types of radiation and their sources in NPPs*
- *Types of detectors, selection criteria, and applications in RMS*
- *Survey and Q&A*

Types of Radiation and Their Sources in NPPs

Radiation Types in NPP and Other Environments



Alpha Particles
- High mass (4 amu) & high charge (+2) (helium nucleus)
- Travel 1-2 inches in air
- Stopped by paper, skin

Beta Particles
- Low mass (0.0005 amu) & low charge (+ or -1) (electron)
- Travel 10 - 20 feet in air
- Stopped by book, cardboard, wood, plastic, etc.

Gamma Rays
- Electromagnetic waves produced in the nucleus
- No mass & no charge
- Travel many feet in air
- Lead or steel used as shielding

X-Rays
- Same characteristics as gamma rays but originate in the electron cloud, not the nucleus
- Typically lower energy vs. gamma rays

Neutrons
- Moderate mass (1 amu) & no charge
- Travel many feet in air
- Stopped by hydrogen, other low Z material (water, concrete)

Dose Rate Terms & Units (Area Monitoring)

- **Roentgen**
  - *Unit used to measure exposure to x-rays or gamma rays*
  - *Measure of charge created in dry air*
  - *Typical units: mR, mR/hr (SI: no equivalent)*

- **Rad**
  - *Unit used to measure a quantity of absorbed dose (Radiation Absorbed Dose)*
  - *Measure of energy deposited in dry air*
  - *Typical units: mrad, mrad/hr (SI: mGy, mGy/hr)*

- **Rem**
  - *Used to measure a quantity called equivalent dose;*
  - *Measure of the absorbed dose (energy deposited) in human tissue to quantify the effective biological damage of the radiation. Not all radiation has the same biological effect, even for the same amount of absorbed dose.*
  - *Typical units: mrem, mrem/hr (SI: mSv, mSv/hr)*

- *Common misconception: R = rad = rem; as seen above, these are different physical quantities*
  - *1 R = 0.877 rad*
  - *Rad/Rem relationship is energy dependent; 1 rad Cs-137 = 1.21 rem; 1 rad Co-60 = 1.17 rem; etc.*
    - *Based on rad in air (air kerma) to dose equivalent (rem – measure of biological dose)*

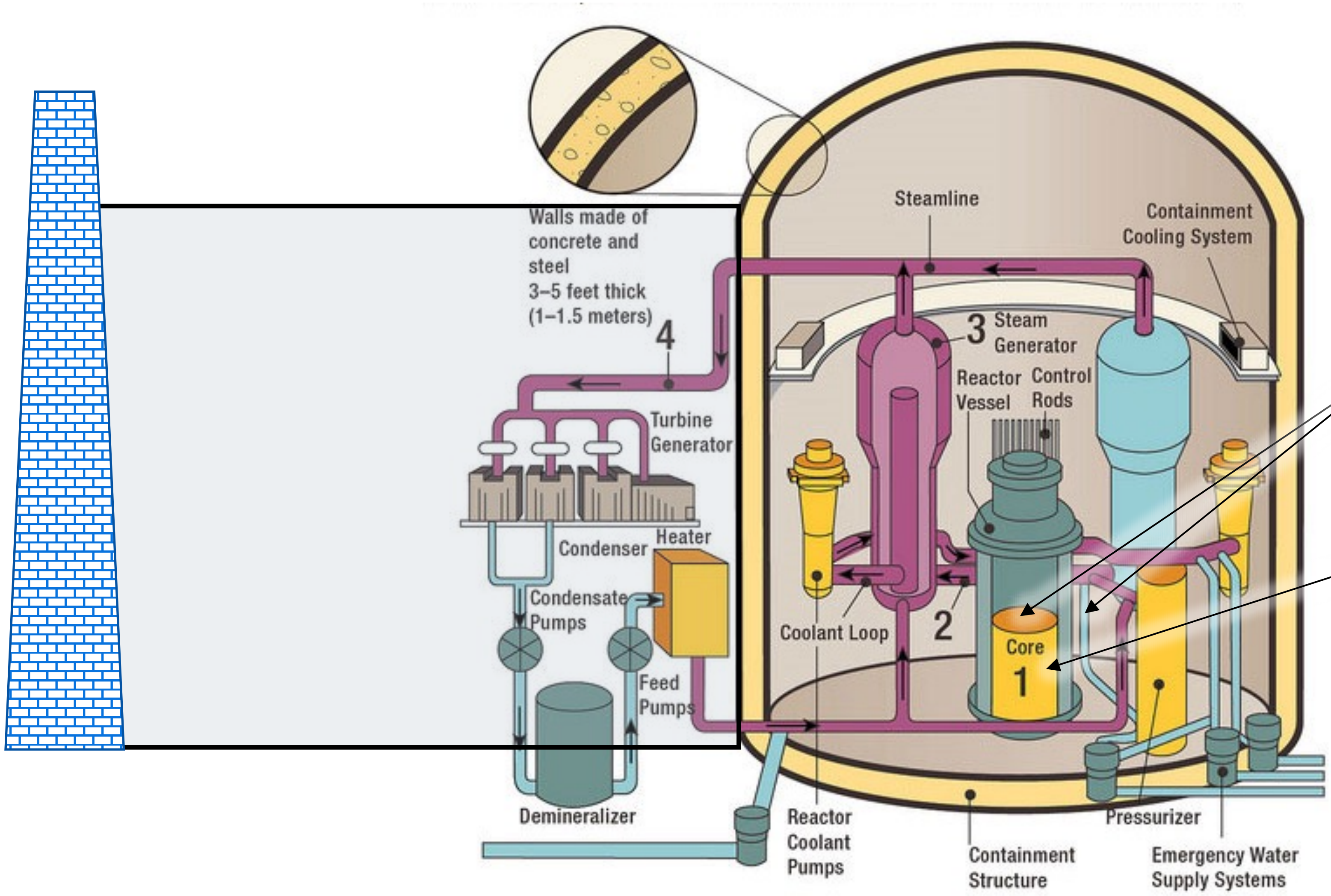
Process Monitoring Terms & Units

- **Volumetric activity**
  - *Measure of normalized (per unit volume) activity in gas or liquid*
  - *Typical units: μCi/cc, pCi/l, Bq/m^3*

- **Minimum Detectable Activity** *(MDA) (also Minimum Detectable Concentration, MDC)*
  - *Smallest amount of activity that can be detected in specified measurement conditions: background, measurement time, confidence level*
  - *Typical units are those of the parent system, e.g. μCi, μCi/cc, Bq, Bq/m^3, etc.*
  - *In many plant documents, MDA or MDC is often referred to as "Sensitivity" (see below)*

- **Sensitivity**
  - *Response factor that correlates the raw output of a detector (e.g. CPM or amps) to the quantity of interest. Determined empirically by primary calibration, or by modeling*
  - *Typical units: CPM/μCi, CPM/(μCi/cc), CPM/(mrad/hr), amp/(mrad)/hr, etc.*
  - *Caution: as mentioned above, sometimes "Sensitivity" is used in referenced to MDA*
  - *Also referred to sometimes as "Efficiency" or "Conversion Factor" (EUCF)*

Sources of Radiation (PWR Example)



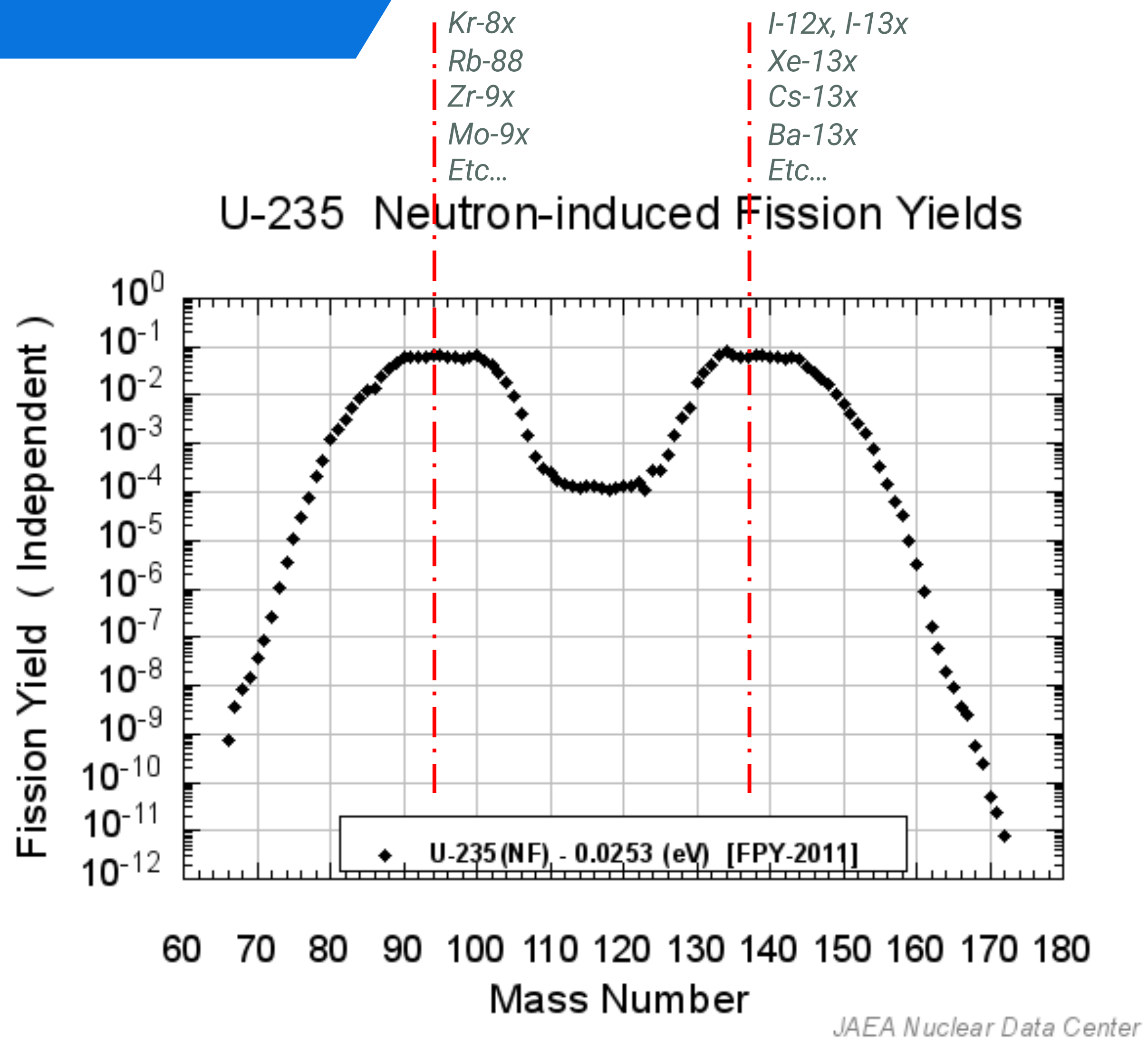
Activation products created in and around the reactor

Fission products created in the fuel

(nrc.gov/reactors/pwrs.html)

Sources of Radiation: Fission Products

- Direct byproducts of the nuclear fission process
- Generated when heavy nuclei (e.g., U-235) split into smaller fragments.
- Fission products can migrate through systems and structures, impacting:
  - Radiation safety
  - Containment design
  - Monitoring and decontamination strategies



Example shown for thermal neutrons; Yield profiles shift with fast neutrons

Sources of Radiation: Activation Products

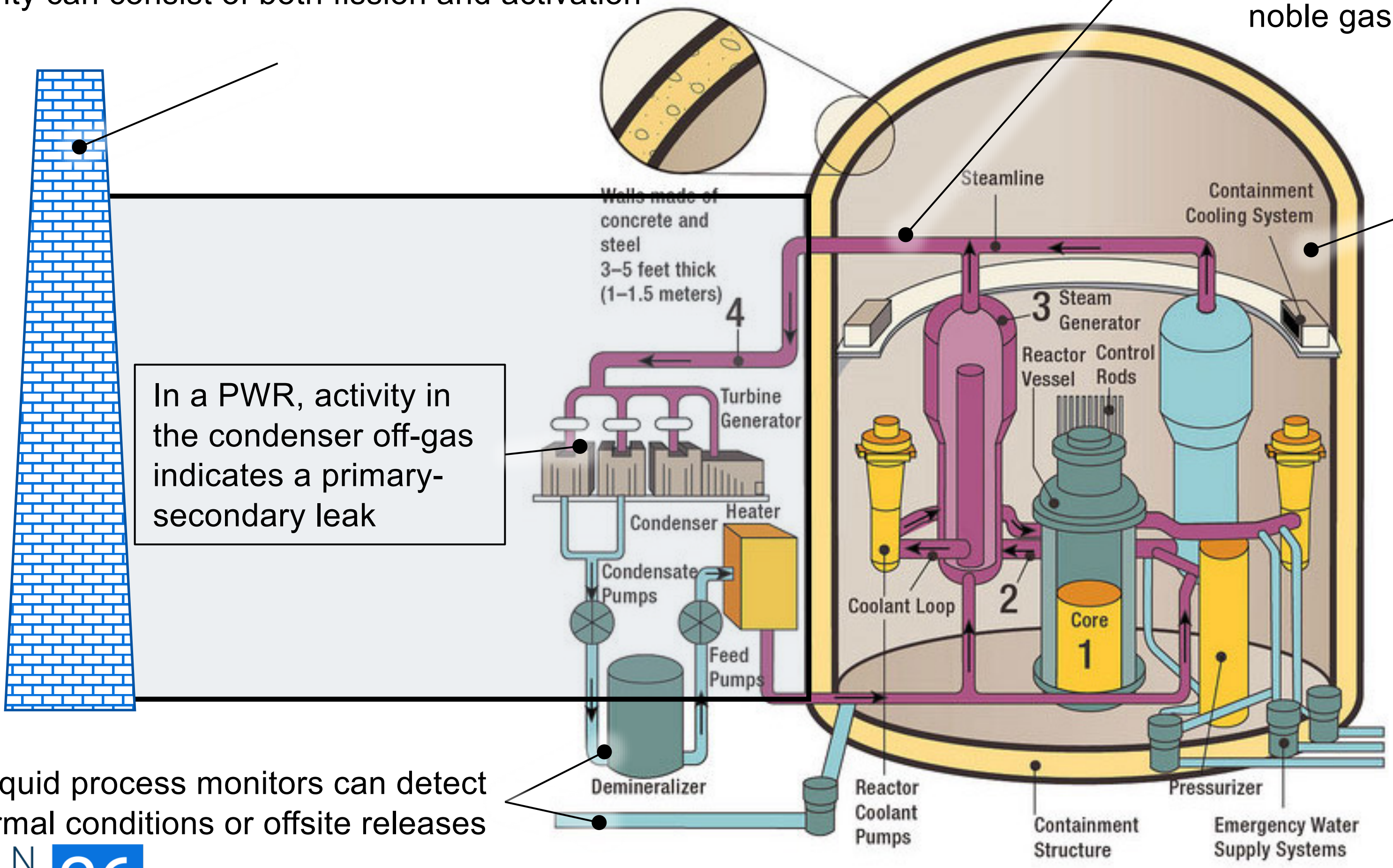
- *Formed when neutrons interact with materials in and around the reactor*
- *Influenced by:*
  - *Neutron flux profiles*
  - *Structural materials*
  - *Coolants and cover gases*
- *For advanced reactors, changes in traditional parameters above may result in non-traditional activation products in NPP environments.*
- *Coolants*
  - *^{13}N, ^{16}N, ^{18}F from water*
  - *^{41}Ar from argon entrained in water*
  - *^{24}Na from sodium*
  - *Helium effectively immune to activation, but impurities such as air or water (moisture) could activate as shown above*
- *Vessels and internal structures*
  - *^{51}Cr, ^{54}Mn, ^{58}Co, ^{59}Fe, ^{60}Co, etc.*

Radiation Monitoring Examples

Effluent release points (e.g. plant vent, fuel pool vent, containment purge) are monitored for airborne activity.
Activity release results in offsite dose to the public which must be quantified
The activity can consist of both fission and activation products

In a PWR, activity in the steam line indicates a primary-secondary leak
- N16 detectors can identify a small leak
- Area monitors adjacent to the steam line quantify a catastrophic leak / environmental release (mixed noble gases in steam line)

A sample drawn from containment can be monitored for airborne radioactivity to detect a small primary coolant leak
- Typ. Rb-88 or Cs-137 particulate
- Typ. Kr-85, Xe-133 noble gas



In a PWR, activity in the condenser off-gas indicates a primary-secondary leak

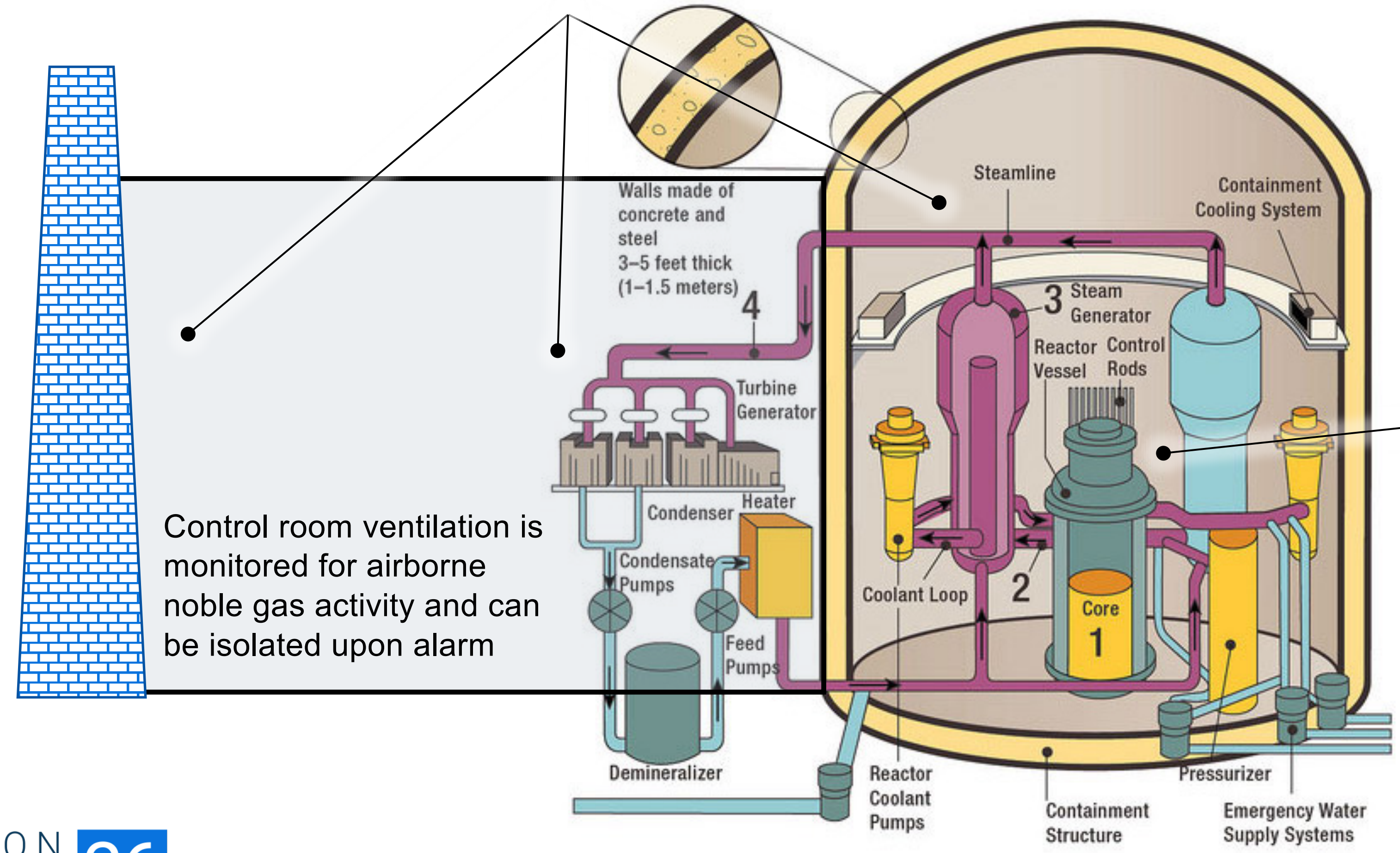
Various liquid process monitors can detect abnormal conditions or offsite releases

(nrc.gov/reactors/pwrs.html)

Radiation Monitoring Examples (Cont'd)

Gamma area monitors placed throughout the plant, including in containment, alert operators to high dose rates

Area and/or airborne monitors at the plant boundary provide an indication of release to the environment and surrounding public
(typically a separate system from the RMS)



Control room ventilation is monitored for airborne noble gas activity and can be isolated upon alarm

During a severe accident, a LOCA-qualified gamma detector inside containment is used to track the magnitude of the accident
(this is not a personnel protection ARM)

(nrc.gov/reactors/pwrs.html)

Types of Detectors, Selection Criteria, and Applications in RMS

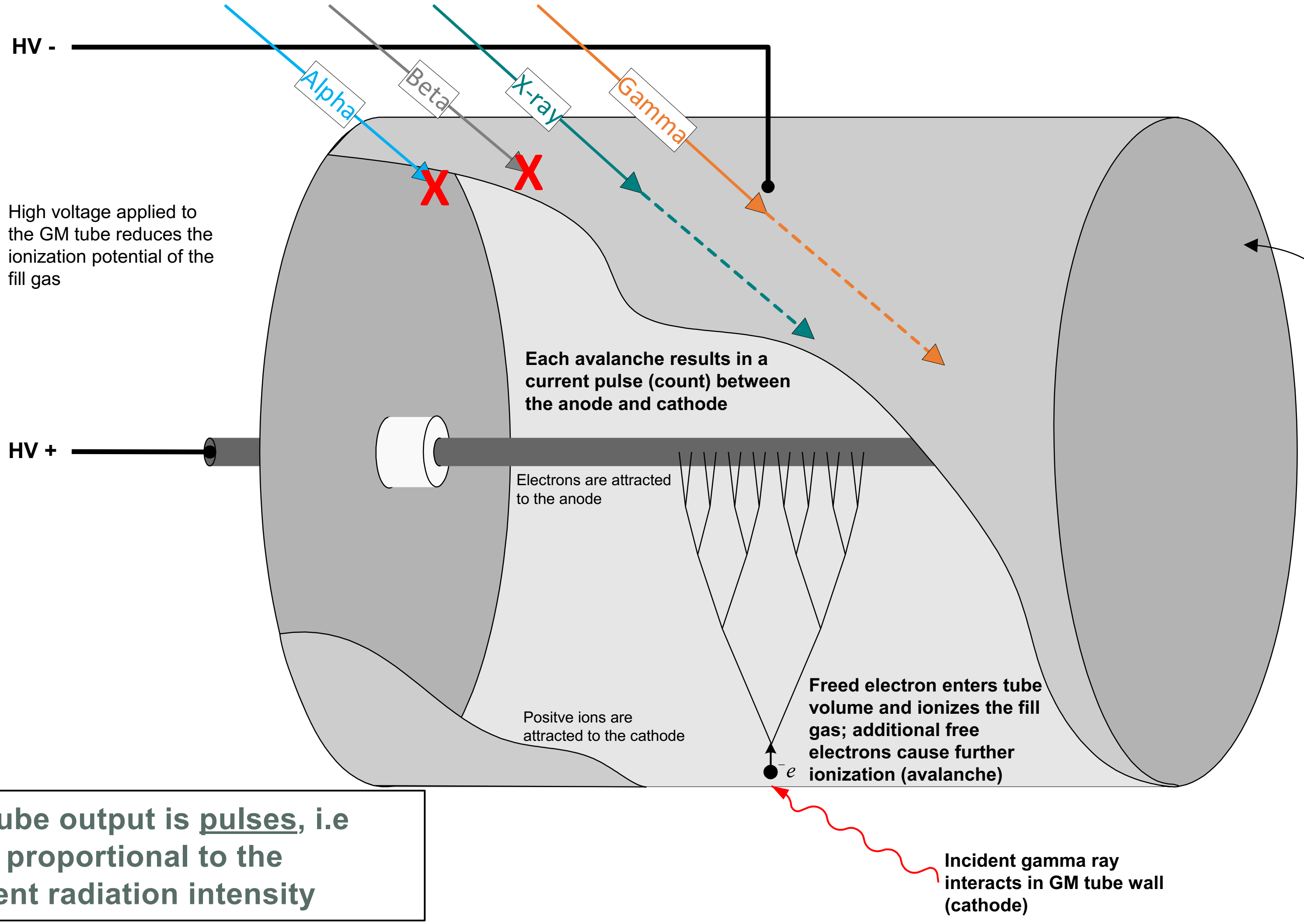
Measuring Radiation

	Sources	How measured – airborne
Alpha emitters	Fuel (^{235}U, ^{238}U)	N/A - Not typical in NPP, but for other nuclear facilities monitor by collecting particles on filter paper and measuring with PIPS detector (aluminized passivated surface allows alphas through but not light)
	Radon daughters	N/A -- but can interfere with beta particulate detectors
Beta and/or Gamma/x-ray emitters	Noble gas fission & activation products e.g. Kr-85, Xe-133	Normal range: Offline monitor with sample chamber viewed by beta scintillation detector, or beta GM tube, or PIPS detector Accident range: GM tube or ion chamber adjacent to sample chamber, or flow-through ion chamber
	Particulate fission & activation products e.g. Co-60, Cs-137, Rb-88	Offline monitor with filter paper viewed by beta scintillation detector, or beta GM tube, or PIPS detector
	Gaseous or molecular iodine (activation product)	Gamma scintillation detector viewing offline sample cartridge
	Radon daughters (particulates)	Naturally occurring but interferes with beta particulate measurement – can be compensated with alpha (PIPS) detector

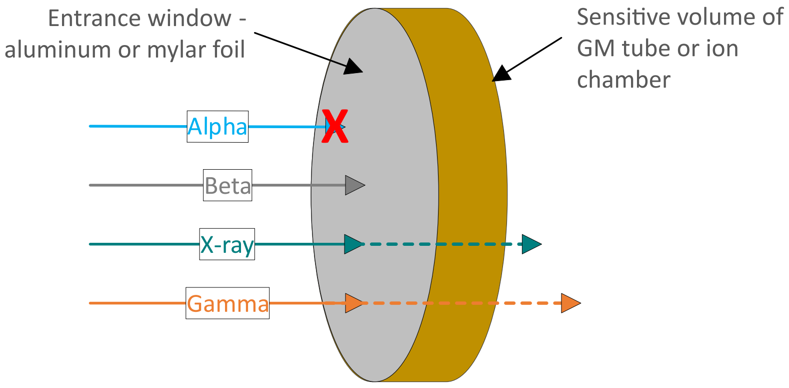
Measuring Radiation (Cont'd)

	Sources	How measured – entrained in process
Alpha emitters	Fuel (^{235}U, ^{238}U)	N/A
	Radon daughters	N/A
Beta and/or Gamma/x-ray emitters	Noble gas fission & activation products	In steam line: Adjacent to line area monitor (GM tube, Ion chamber, scintillation detector) In liquid process: N/A – low entrainment of NG in water
	Particulate fission & activation products	Adjacent to line gamma scintillation detector (depends on concentration). For best sensitivity, extract process to offline sample chamber / sample media and actively monitor with detector.
	Gaseous or molecular iodine (activation product) e.g. I-131, I-135	Adjacent to line gamma scintillation detector (depends on concentration). For best sensitivity, extract process to offline sample chamber / sample media and actively monitor with detector.
	Radon daughters (particulates)	N/A
Gamma/x-ray dose rate	Contaminated process streams, filter banks, etc; reactor, RCS, steam lines	GM Tubes Ion chambers Si diode detectors

Geiger Mueller Tube Detection Principle



A thin entrance window, e.g. aluminum or mylar, will allow beta detection ("pancake GM tube")



Thin-window GM tube or ion chamber

- **GM Tube output is <u>pulses</u>, i.e <u>CPM</u>, proportional to the incident radiation intensity**

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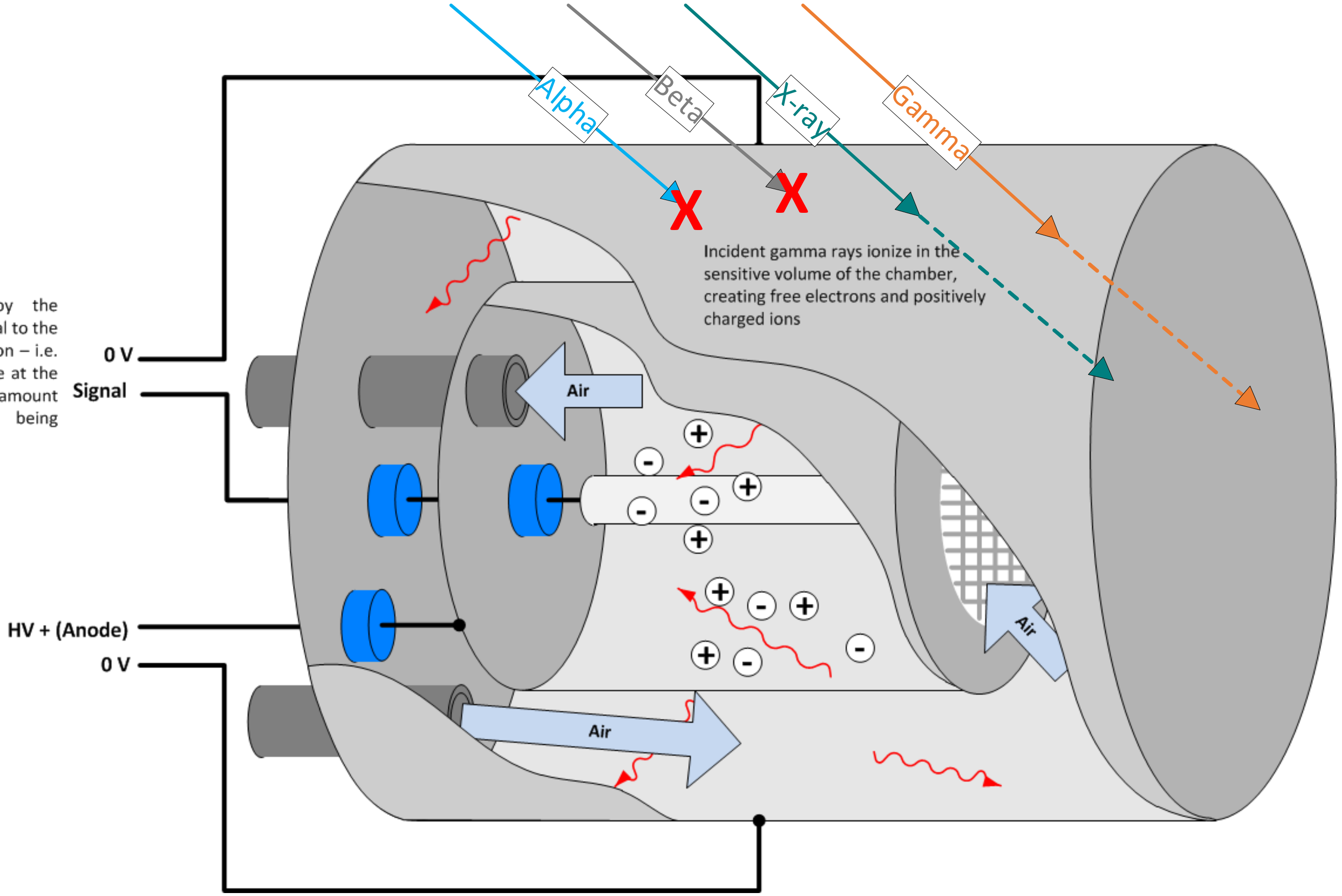
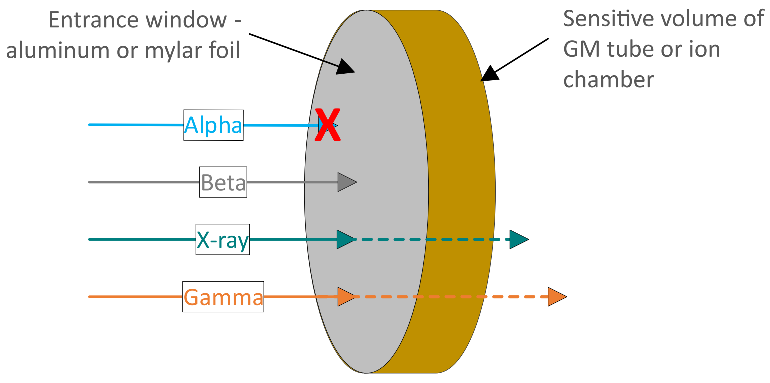
Ionization Chamber Detection Principle

The current measured by the processing unit is proportional to the intensity (amount) of radiation – i.e. proportional to the dose rate at the detector location and to the amount of activity in the pipe being monitored.

High voltage is applied to the ionization chamber, drawing electrons to the anode and positive ions to the cathode.



Flow-through ion chamber shown; sealed chamber is conceptually similar except all radiation originates from the outside.



Thin-window GM tube or ion chamber

- **Ion chamber output is <u>current</u>, i.e <u>Amps</u>, proportional to the incident radiation intensity**

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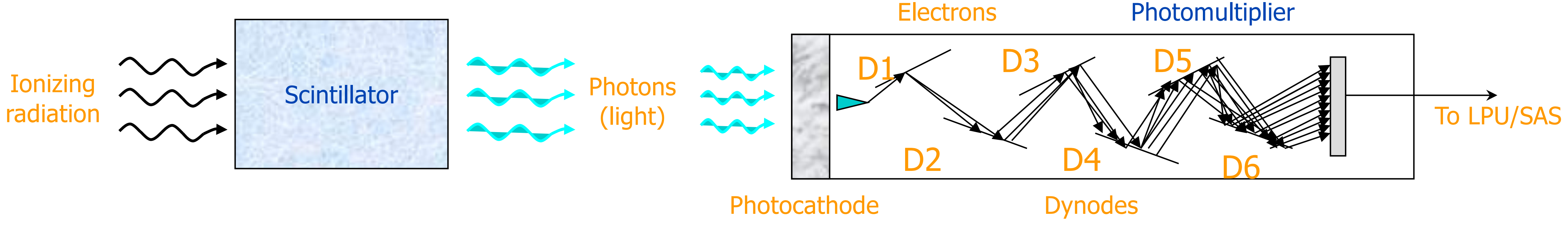
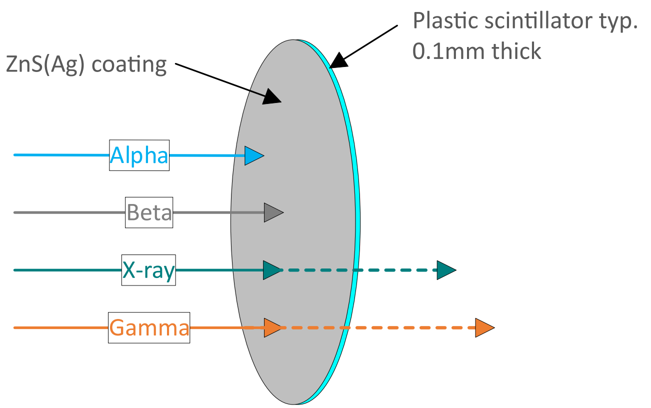
Scintillation Detection Principle

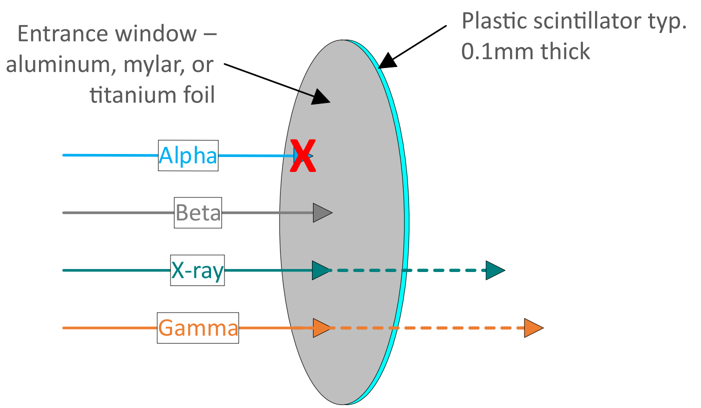
- Scintillation detector output is <u>pulses</u>, i.e <u>CPM</u>, proportional to the incident radiation intensity
- Additionally, pulse amplitude is proportional to the radiation energy



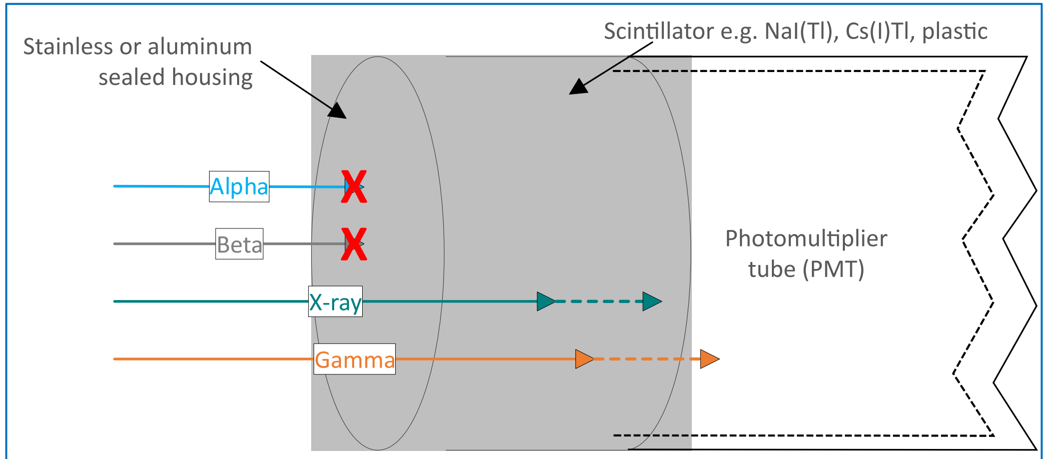


Alpha/Beta plastic scintillation detector

(not commonly used in RMS applications)



Beta plastic scintillation detector



Gamma scintillation detector

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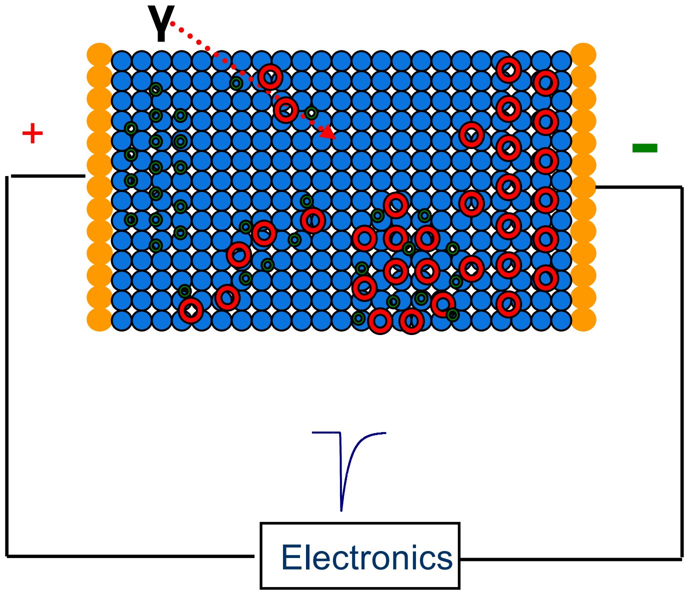
PIN Diode (Utilized in GIM 204K)

- PIN diode detector output is pulses, i.e CPM, proportional to the incident radiation intensity
- Additionally, pulse amplitude is proportional to the radiation energy

PIN Diode



In a GIM 204K, each low-range PIN Diode is 2.65mm x 2.65 mm.

Eight (8) of these PIN Diodes are arranged in a ring to provide more uniform angular response and enhanced sensitivity of the detector assembly around the detector radially.

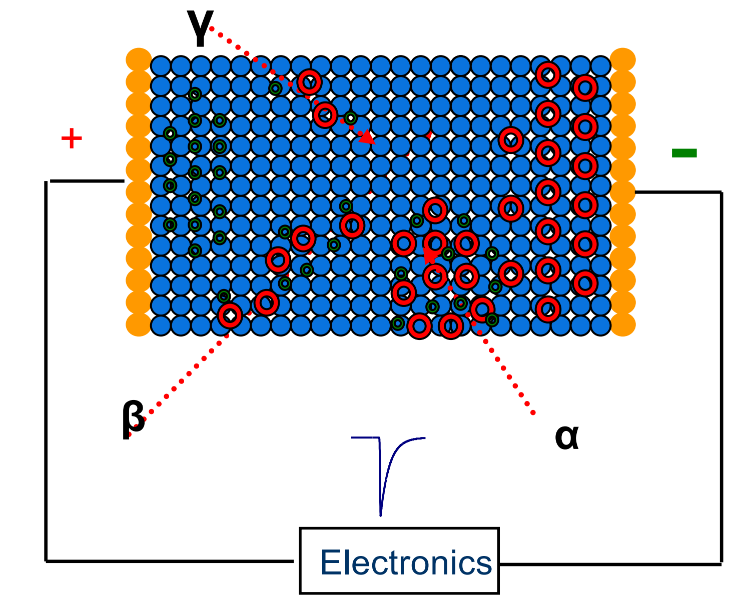
There is also a smaller HR PIN diode.

- p-type and n-type silicon layers sandwich a lightly-doped intrinsic (i) layer, which is the active detection volume
- Applied bias voltage depletes the i-layer of free carriers, creating a charge-free electric field across the detector
- Ionizing radiation entering the depletion layer deposits energy via Coulombic interactions with the silicon lattice
- Energy deposited liberates electron-hole pairs
- Number of pairs is directly proportional to the deposited energy (~3.6 eV per pair)
- Bias voltage sweeps electrons to the p-contact and holes to the n-contact before recombination occurs
- Charge movement induces current pulse measured by detector electronics (preamplifier and signal conditioning circuitry)
- Amplitude of the resulting voltage pulse is the basis for dose rate measurement and pulse height analysis for spectroscopy

PIPS Detection Principle

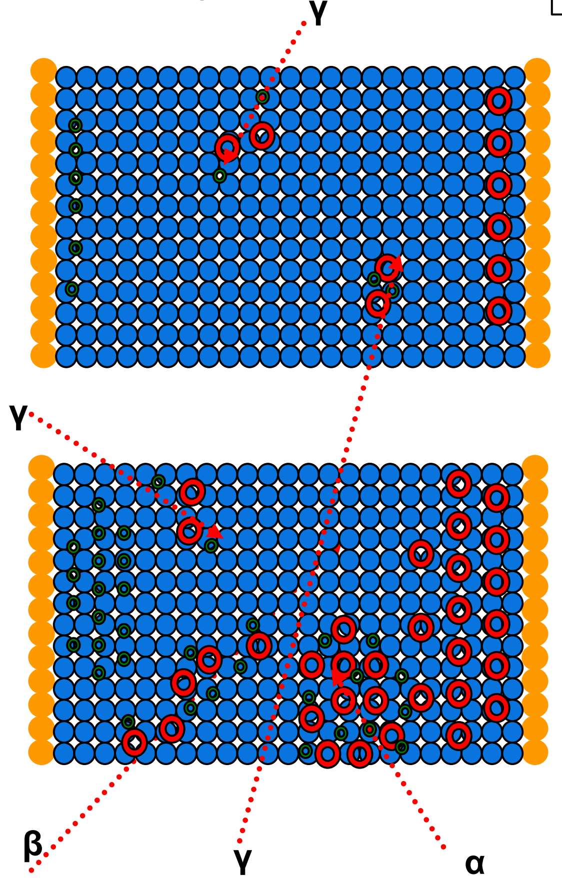
- PIPS detector output is <u>pulses</u>, i.e <u>CPM</u>, proportional to the incident radiation intensity
- Additionally, pulse amplitude is proportional to the radiation energy

<u>PIPS Solid State Silicon Diode:</u>
(PIPS = Passivated Implanted Planar Silicon)

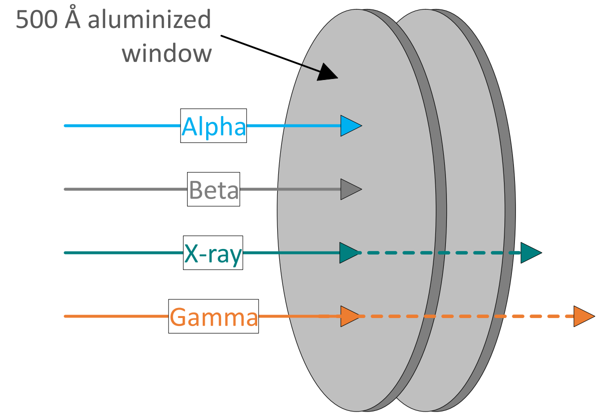


Ionizing radiation entering the PIPS diode creates free electrons and corresponding "holes" in the diode.
A bias voltage (~80 V) is applied to the diode to collect the electrons and holes, generating a pulse (count).
Because the active layer of the diode is thin and not very dense, the diode is more sensitive to charged particles (alpha & beta) than to photons (gamma).

<u>Background Subtraction:</u>



By "stacking" two PIPS diodes together, the 2nd diode is shielded from alpha & beta radiation. Both diodes will detect gamma radiation.
The response of the 2nd diode is subtracted from that of the 1st diode for gamma compensation.



PIPS Diodes
(2X stacked configuration)

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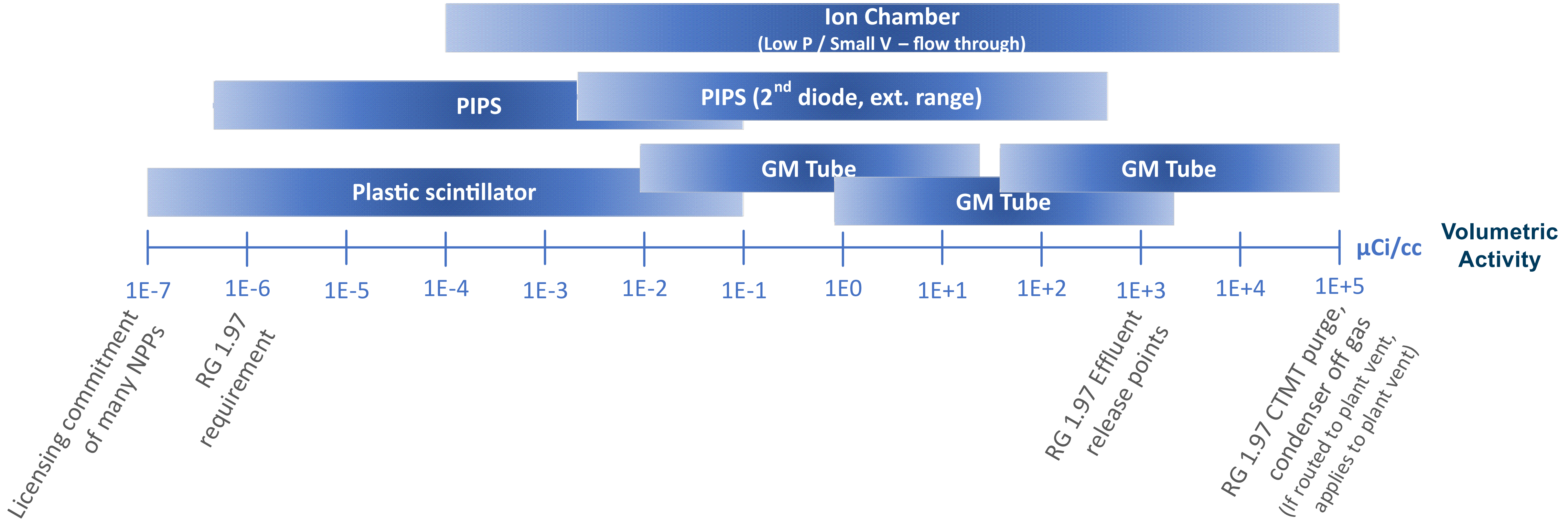
Detector Selection – Process Monitoring

Scale shown below for noble gas since it is always monitored, including accident range:



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Monitor Selection – RAMSYS Product Line

Process airborne monitors (plant vent, CTMT atmosphere, CTMT purge, etc.)

Model	Channel Name	Detector	Typical Measurement Ranges
PING 206S	ABPM 201 IM 201 NGM 204	A/B Particulate (Dual Silicon) Iodine NaI (Tl) 1¼" x 1" Noble gas (large area silicon)	Alpha: 2.7×10^{-13} to10^{-4} µCi/cc Beta: 2.7×10^{-11} to10^{-4} µCi/cc Iodine: 10^{-10} to10^{-4} µCi/cc Noble gas: $<1\times10^{-6}$ to $2\times10^{+3}$ µCi/cc
PING 207S	PM 205 IM 201 NGM 216	Beta Particulate (scintillator) Iodine NaI (Tl) 1¼" x 1" Noble gas (plastic scintillator)	10^{-12} to 10^{-7} µCi/cc 10^{-10} to 10^{-4} µCi/cc 10^{-7} to 10^{-2} µCi/cc
PING 209L	ABPM 205 IM 203 NGM 209	Beta Particulate (scintillator) Iodine NaI (Tl) 1¼" x 1" Noble gas (large area silicon)	Alpha: 2.7×10^{-13} to10^{-4} µCi/cc Beta: 2.7×10^{-11} to10^{-4} µCi/cc Iodine: 10^{-10} to10^{-4} µCi/cc Noble gas: $<1\times10^{-6}$ to $2\times10^{+3}$ µCi/cc
BIM 201K	BIM 201K	Noble gas	Noble gas: $<1\times10^{-6}$ to 10^{-2} µCi/cc
NGM 203S	NGM 203S	Noble gas high/accident range	10^{-4} to 10^{+5} µCi/cc

NGM 203S

LM 212S

PING 209L

BIM 201K
Beta Induct Monitor

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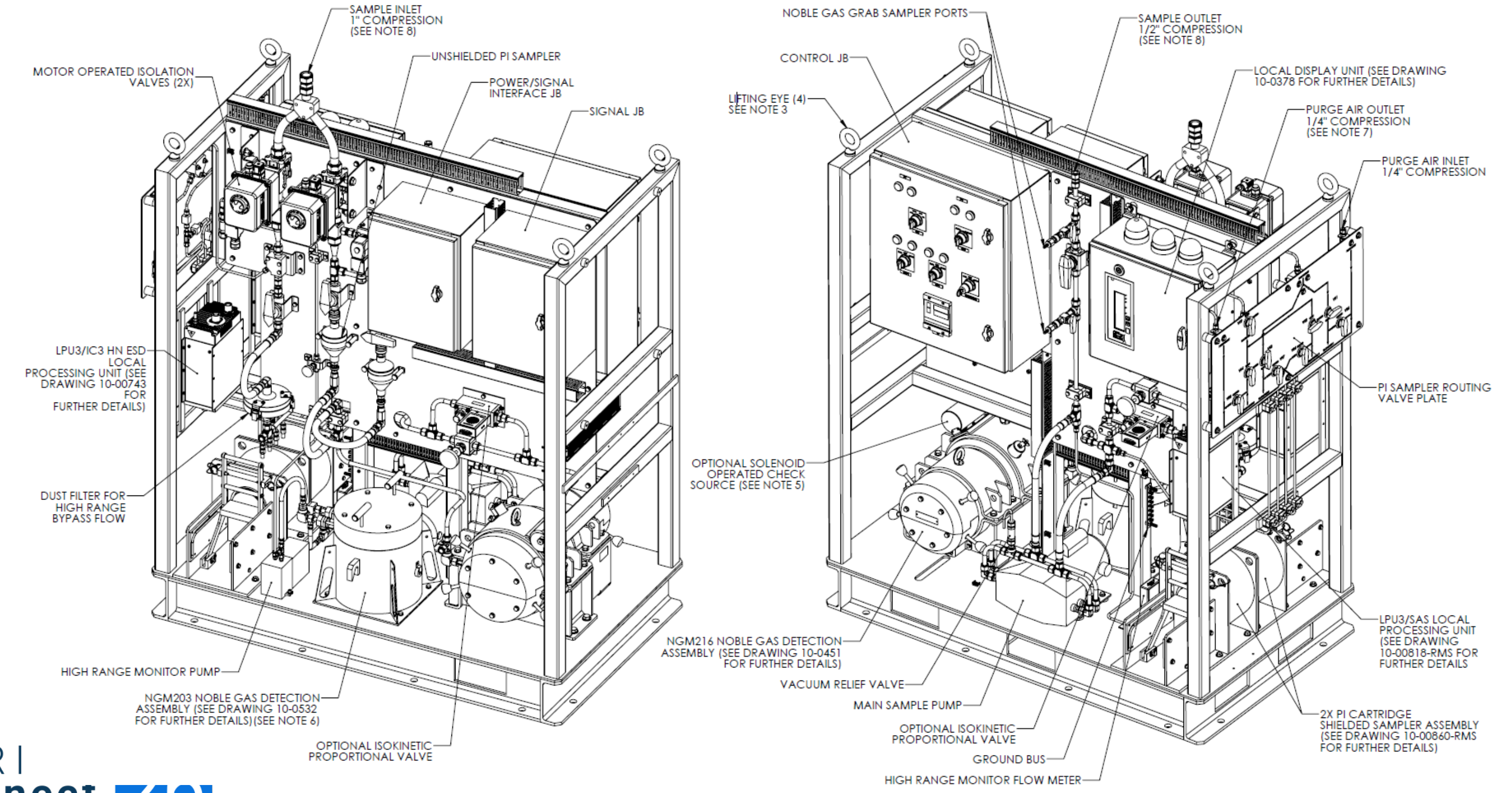
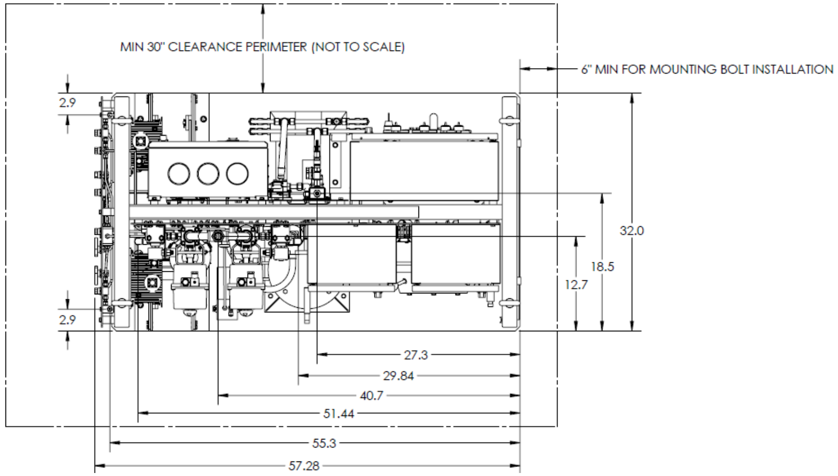
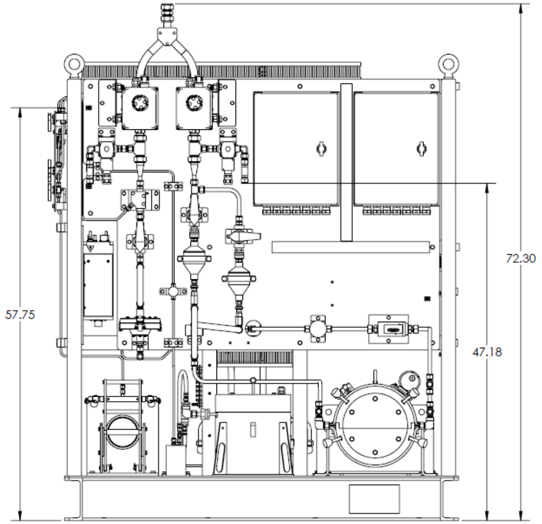
Monitor Selection – RAMSYS Product Line

Process airborne monitors (Combined / RG 1.97 plant vent/stack monitor skid)

Model	Channel Name	Detector	Typical Measurement Ranges
NGM 221S	NGM 216 NGM 203	Noble gas (plastic scintillator) Noble gas high/accident range	10^{-7} to 10^{-2} µCi/cc 10^{-4} to 10^{+5} µCi/cc







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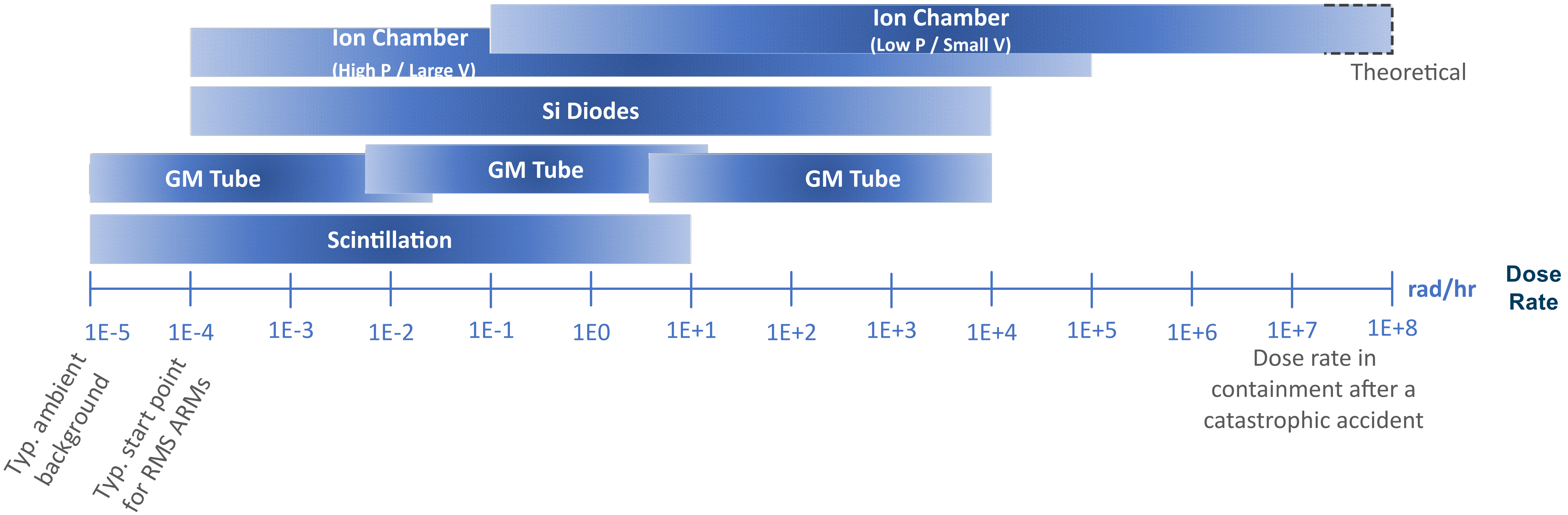
Detector Selection – Area Monitoring



Monitor Selection – RAMSYS Product Line

Area Monitors

Model	Detector	Typical Measurement Range	Comments
GIM 201K	Ion chamber	10^{-6} to 10 Sv/h 10^{-4} to 10^{3} rem/h	Low range
GIM 202K	Ion chamber	10^{-7} to 10^{2} Gy/h 10^{-5} to 10^{4} rad/h	Wide range for harsh environment
GIM 203K	Ion chamber	10^{-6} to 10^{3} Sv/h 10^{-4} to 10^{5} rem/h	Wide range
GIM 204K/M	Silicon diode	10^{-8} to 10^{3} Gy/h or Sv/h 10^{-6} to 10^{5} rad/h or rem/h	Very wide range
GIM 205K	Ion chamber	10^{-5} to 10^{3} Gy/h 10^{-3} to 10^{5} rad/h	Waterproof, high temperature
GIM 206K	Ion chamber	10^{-3} to 10^{5} Gy/h 10^{-1} to 10^{7} rad/h	Very high range for harsh environment
GIM 207K	Geiger Muller	10^{-6} to 10^{-3} Gy/h or Sv/h 10^{-4} to 10^{-1} rad/h or rem/h	Low range
GIM 208K	Geiger Muller	10^{-4} to 1 Gy/h or Sv/h 10^{-2} to 10^{2} rad/h or rem/h	High range
GIM 209K	Geiger Muller	10^{-6} to 1 Gy/h or Sv/h 10^{-4} to 10^{2} rad/h or rem/h	Wide range
GIM 210K	Geiger Muller	10^{-6} to 1 Gy/h or Sv/h 10^{-4} to 10^{2} rad/h or rem/h	Dual detector

GIM 201K

GIM 202K

NIM 201K

GIM 205K

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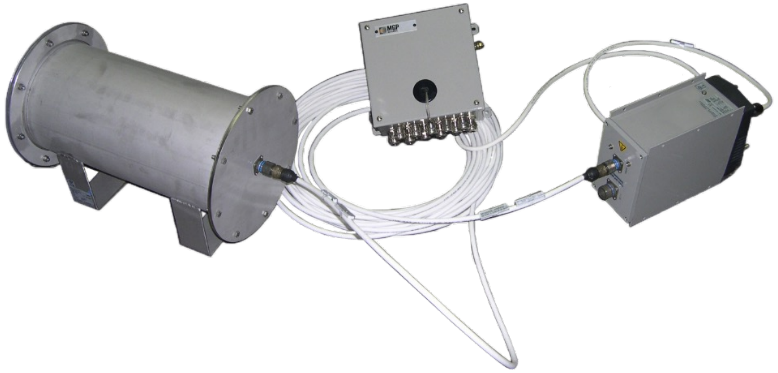
Area & Process Monitors

Ion Chamber Detector with Local Processing & Display Unit (LPDU) field unit

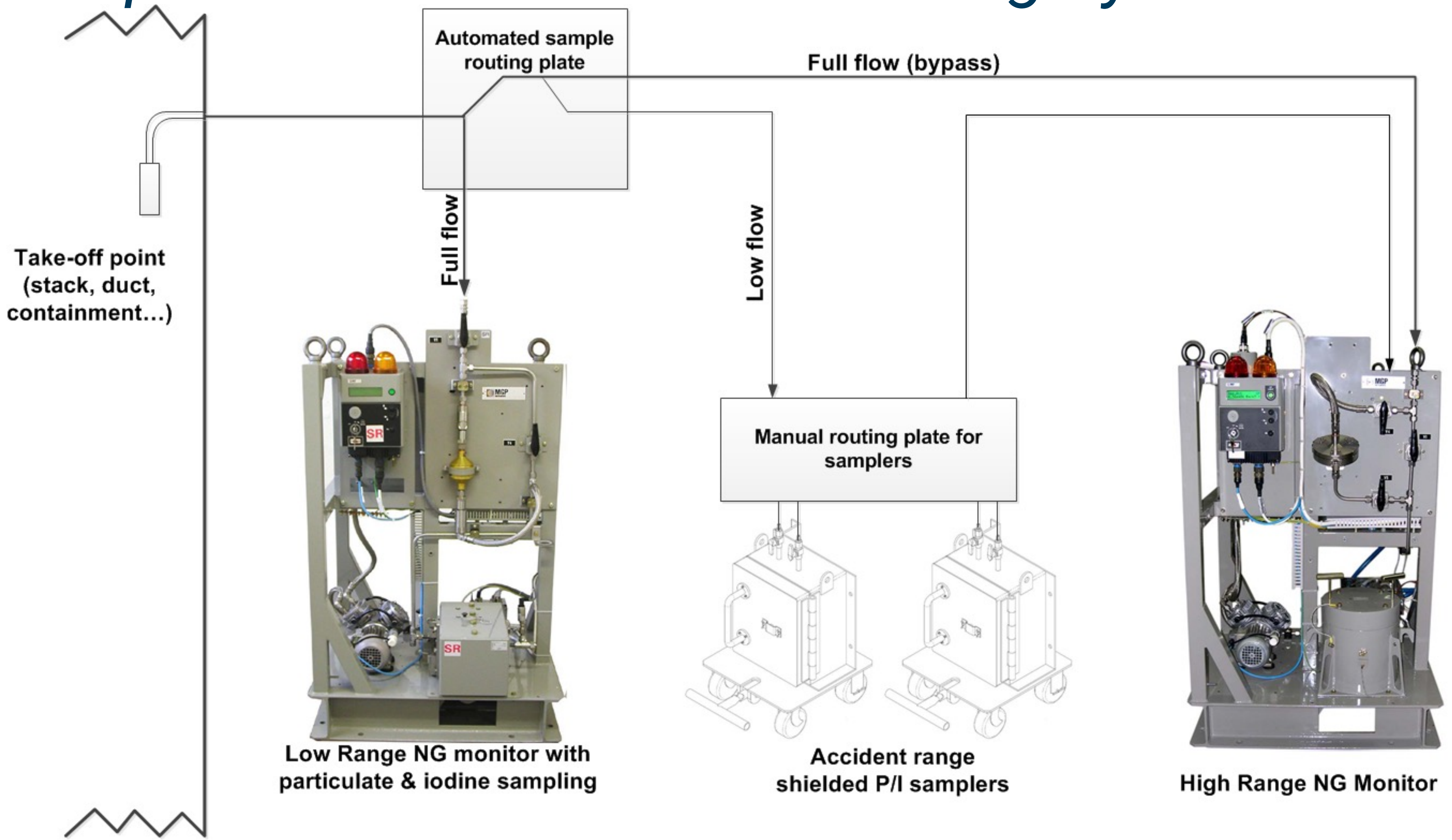
N16 detector with Local Processing Unit (LPU) field unit & signal junction box



Si Diode Detector & LPDU field unit

Adjacent to line (ATL) shielded liquid process monitor

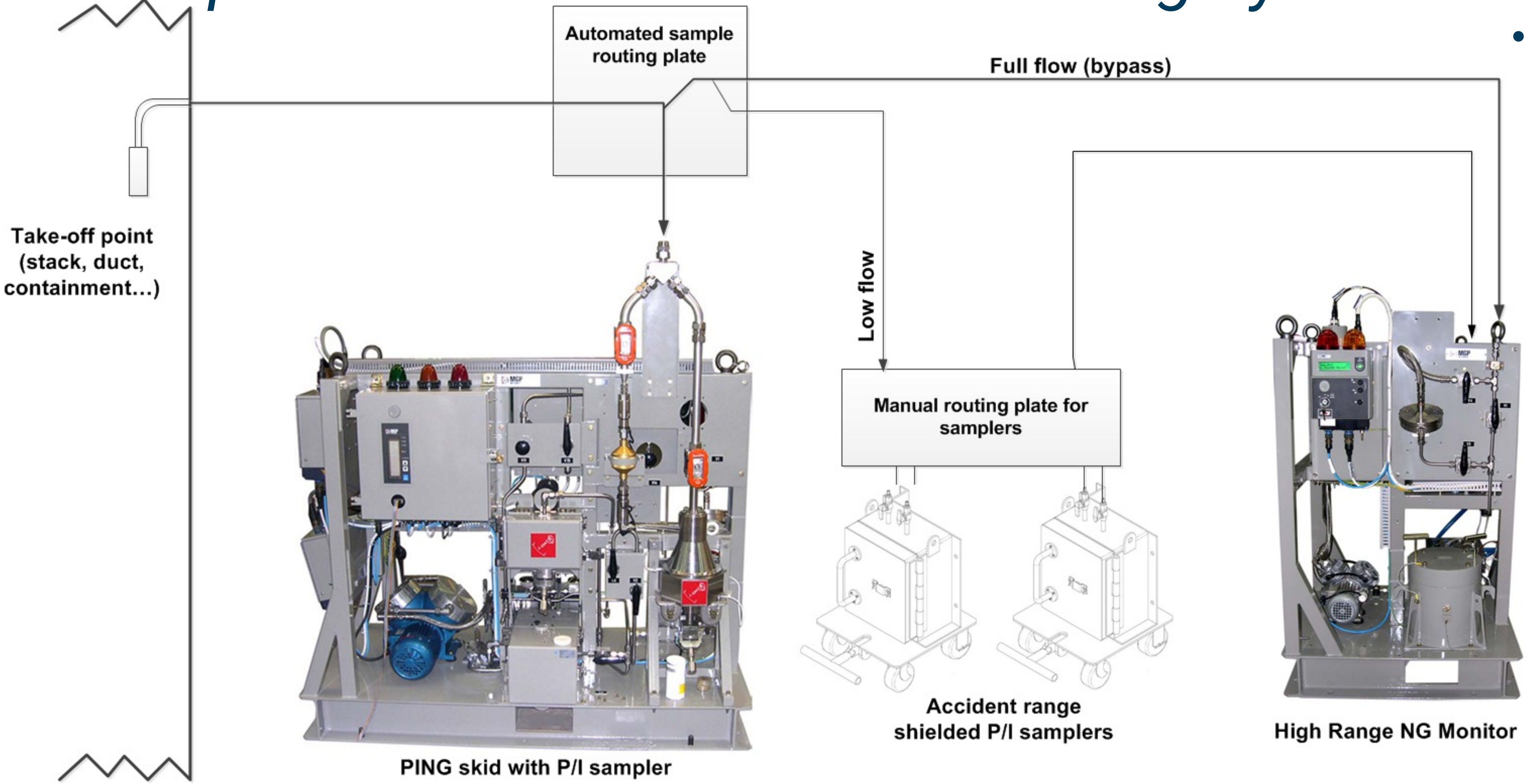
Simple Offline Airborne Monitoring System



- *Other options are possible:*
  - *Stack/vent process flowmeter 4-20 mA signal input*
  - *On-skid heat trace (off-skid as well but not Mirion scope)*
  - *Sample Routing Plate Options (Dual inlet vs. single inlet)*
  - *Accident P/I Samplers with area monitoring for personnel protection*

- *Simple normal + accident range configuration*
- *Normal and accident range NG monitoring, P/I sampling*

“Complete” Offline Airborne Monitoring System



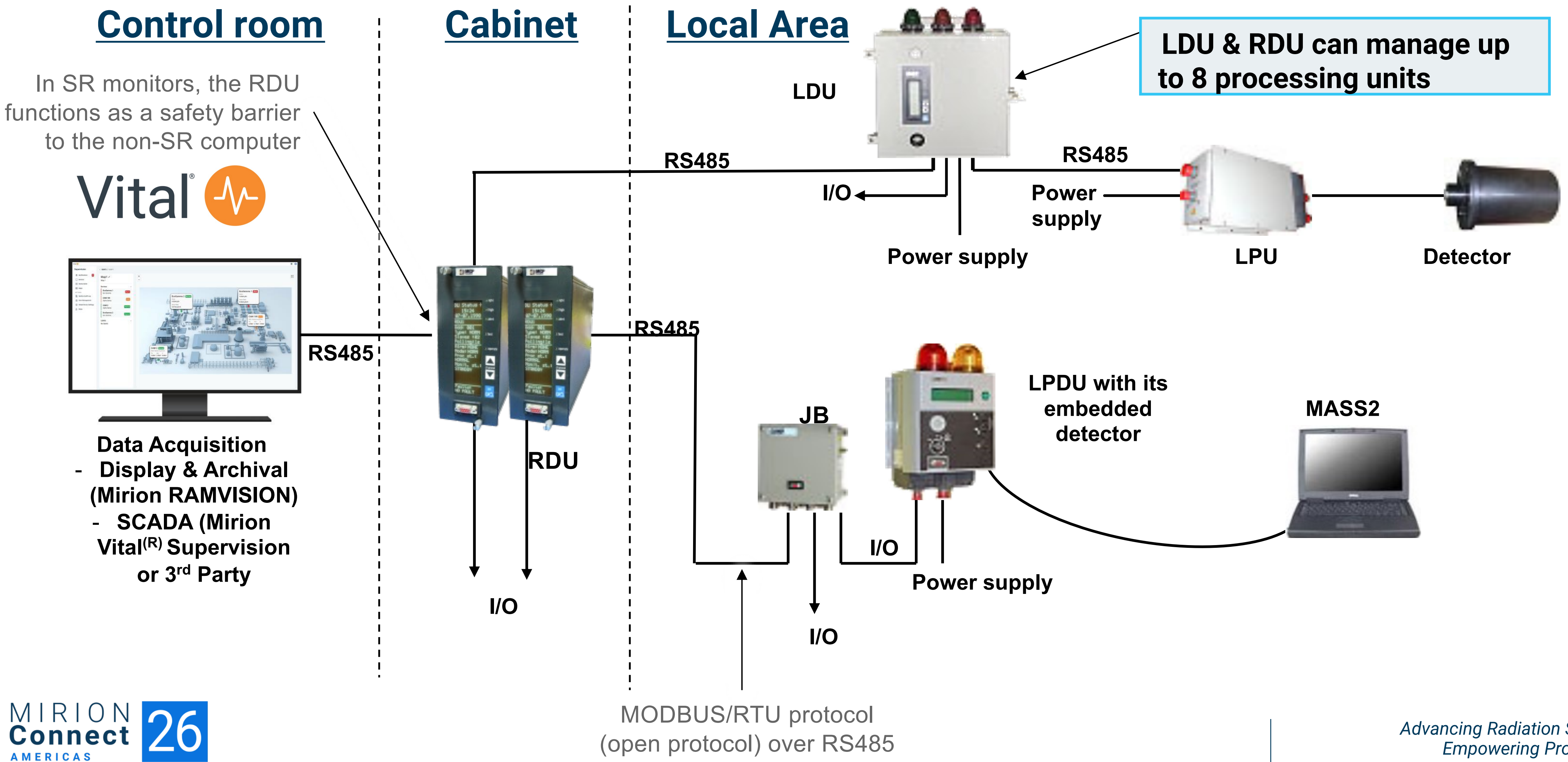
- *Other options are possible:*
  - *Stack/vent process flowmeter 4-20 mA signal input*
  - *On-skid heat trace (off-skid as well but not Mirion scope)*
  - *Sample Routing Plate Options (Dual inlet vs. single inlet)*
  - *Accident P/I Samplers with area monitoring for personnel protection*

- *Normal range PING skid + high range noble gas monitor & samplers*
- *Presence or absence of P&I detectors determined by plant licensing docs – regs only require sampling*

A Note About Offline Sampling

- *To effectively sample or monitor particulate, the particulate reaching the sample collector or detector must be representative of what was drawn in at the sample point.*
- *Particulate size can range from 0.002 to 100 µm*
- *Examples: Dust, cloud, fume, haze, fog, smog, smoke, spray, etc…*
- **The main challenge in particulate monitoring is to ensure that the aerosol distribution / concentration at the source (i.e., stack) does not change by the time it gets to the monitor.**
- *This requires:*
  - *Specific flow regime (Reynolds number between laminar and turbulent)*
  - *Vertical line with very smooth transitions / bends*
  - *Shortest possible sample line, specifically shortest possible horizontal runs*
- *Otherwise, the majority of the particulate / aerosol may deposit on the inner surfaces of the sample lines and the measurement is rendered irrelevant.*
- *Simple concepts apply to transport of radioiodine, though sample transport time and material selection play a more significant role due to the chemical activity.*
- *Requirements:*
  - *Operating NPPs: ANSI N13.1-1969*
  - *New NPPs / non-NPP facilities: ANSI/HPS N13.1-1999, 2011, or 2021 (Licensing basis defines)*
  - *Internationally: ISO 2889*

Communication & Networking



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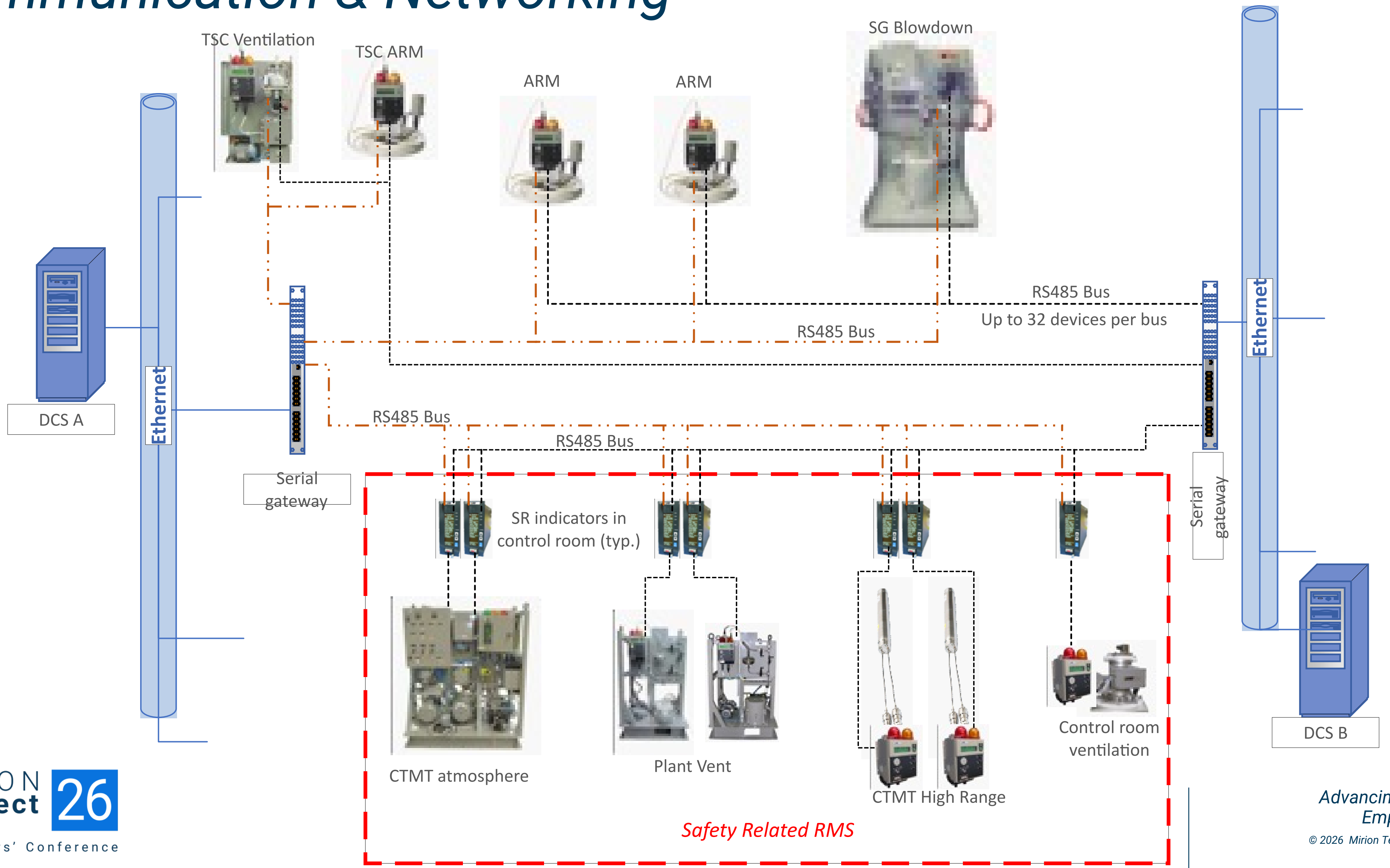
Communication & Networking



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User References

- *Glenn F. Knoll, Radiation Detection & Measurement*
- *Area and Process Radiation Monitoring System Guide, Rev. 3, EPRI, Dec. 2017*
- *Calibration of Radiation Monitors at Nuclear Power Plants: Revision 2 of TR-102644, EPRI, Dec. 2017*
- *Instrumentation For Light-water-cooled Nuclear Power Plants To Assess Plant And Environs Conditions During And Following An Accident, Regulatory Guide 1.97, Rev. 2 or Rev. 3 for US NPPs*
- *Guide to Sampling Airborne Radioactive Materials in Nuclear Facilities, ANSI N13.1, 1969 (Existing / Legacy US NPPs)*
- *ANSI/HPS N13.1-1999/2011/2021 (New Nuclear Facilities)*

Survey and Q&A

Survey for:

Instrumentation and Control (I&C) Forum

Please take a moment to fill out a short survey on this session.

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