Accident-Range Gaseous Effluent Monitoring Calibration and Time-Dependent Instrument Response Factors

Steve Garry, CHP

Sr. Health Physicist

Office of Nuclear Reactor Regulation

U.S. Nuclear Regulatory Commission

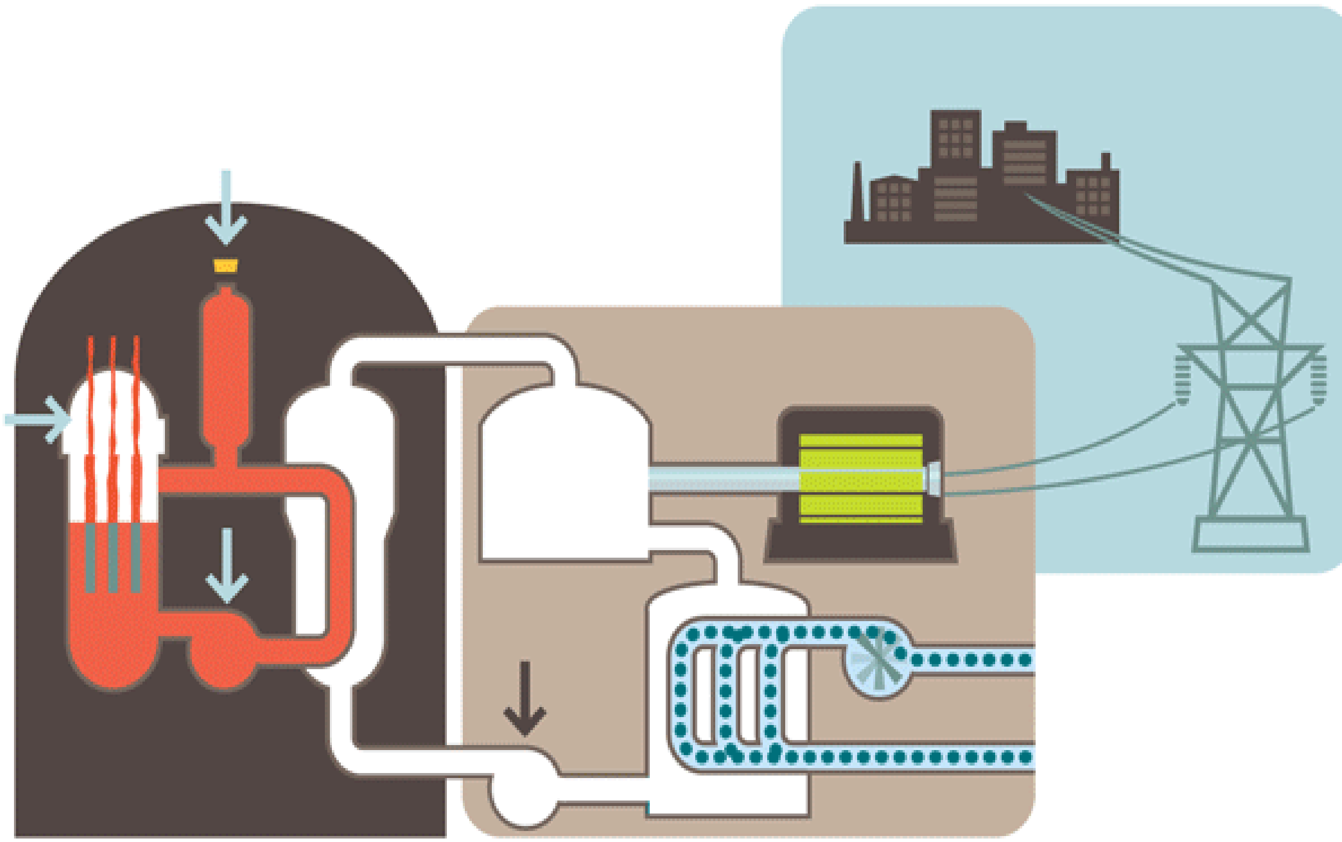
Radiological Effluents and Environmental Workshop
June 27, 2018
New Orleans, LA

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

- This presentation:
  - provides basic information on calibration of accident-range gaseous effluent monitors
  - is based on proposed guidance for calibration of accident-range effluent monitors given in HPPOS-001 and HPPOS-040
- Other calibration methods may be acceptable

TMI Accident

Wednesday, March 28, 1979



TMI Lessons Learned Task Force Status Report and Short-Term Recommendations NUREG-0578

- March 28, 1979, TMI Accident occurred
- July, 1979, NUREG-0578, TMI Short Term Report, was issued 3 months later, in
- May, 1980, NUREG-0660, NRC Action Plan, was issued in and submitted to Commission for approval
- Nov, 1980, NUREG-0737, TMI Action Plan Requirements, was approved by Commission, & issued in
- RG 1.97, Rev. 2, Instrumentation for Emergencies, was revised in Dec, 1980

NUREG-0737

(November, 1980)

NUREG-0737

Clarification of (NUREG-0660)
TMI Action Plan Requirements

Manuscript Completed: November 1980
Date Published: November 1980

NRR Calibration Guidance

HPPOS-001

- August 16, 1982, memo from NRR to Regional Administrators
  - NRR proposed calibration guidance
  - **Now known as Health Physics Position HPPOS-001**

Proposed Guidance for Calibration and Surveillance Requirements to Meet Item II.F.1 of NUREG-0737

HPPOS-001 PDR-9111210074

See the memorandum from D.G. Eisenhut to Regional Administrators dated August 16, 1982. This memo includes "Proposed Guidance for Calibration and Surveillance Requirements for Equipment Provided to Meet Item II.F.1,
*** prepared by the Division of Systems Integration, NRR.**

Revision 3
May 1983

U.S. NUCLEAR REGULATORY COMMISSION

REGULATORY GUIDE

OFFICE OF NUCLEAR REGULATORY RESEARCH

REGULATORY GUIDE 1.97

INSTRUMENTATION FOR LIGHT-WATER-COOLED NUCLEAR POWER PLANTS TO ASSESS PLANT AND ENVIRONS CONDITIONS DURING AND FOLLOWING AN ACCIDENT

A. INTRODUCTION

Criterion 13, "Instrumentation and Control," of Appendix A, "General Design Criteria for Nuclear Power Plants," to 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities," includes a requirement that instrumentation be provided to monitor variables and systems over their anticipated ranges for accident conditions as appropriate to ensure adequate safety.

B. DISCUSSION

Indications of plant variables are required by the control room operating personnel during accident situations to (1) provide information required to permit the operator to take preplanned manual actions to accomplish safe plant shutdown; (2) determine whether the reactor trip, engineered-safety-feature systems, and manually initiated safety systems and other systems important to safety are performing their intended functions (i.e., reactivity control, core

RG 1.97 Instrumentation for Nuclear Power Plants to Assess During an Accident

- Rev 0 (1975) provided general guidance
- Rev 1 (1977) provided general guidance
- **Rev 2 (1980) & Rev 3 (1983) provided specific guidance for radiation monitoring design and performance specifications**
- Rev 4 (2006) provides guidance on new digital instrumentation systems

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Noble Gases

RG 1.97, Rev. 2 & Rev. 3

- Footnote 9: Monitors should be capable of detecting and measuring radioactive effluent concentrations with **compositions ranging from fresh equilibrium noble gas fission product mixtures to 10-day-old mixtures, with overall system accuracies within a factor of 2.**

- Effluent concentrations may be expressed in terms of Xe-133 equivalents, in terms of noble gas nuclides, or in terms of integrated gamma MeV per unit time.

NEI 99-01 [Revision 6]

Development of Emergency Action Levels for Non-Passive Reactors

November 2012

Emergency Classifications
NEI 99-01, Rev 6 (endorsed by NRC)

- Unusual Event = 2x ODCM release rate limit
- Alert (1% EPA PAG)
  - 10 mrem TEDE, or
  - 50 mrem CDE (thyroid)
- Site Area Emergency (10% EPA PAG)
  - 100 mrem TEDE
  - 500 mrem CDE (thyroid)
- General Emergency (100% EPA PAG)
  - 1 rem TEDE
  - 5 rem CDE

Emergency Action Levels

- Establish EALs based on pre-calculated effluent monitor values corresponding to EPA PAG doses for a 1 hr exposure

- X/Qs based on ODCM annual average meteorological data

Instrument Manufacturers

- Older Models
  - Victoreen (GM and Ion Chambers)
  - Eberline (GM and Ion Chambers)
  - Kaman (GM and Ion Chambers)
  - General Atomics (Cd/Te)
- Newer Models
  - Mirion flow-through ion chambers

Instrument Response Factors (IRFs)

➢ Monitor "Outputs" and Dose Code "Inputs"

- Noble gas effluent monitor outputs are in:
  - cpm, or mR/hr, and converted to Ci/sec, or µCi/cc
- Dose Assessment Computer code inputs are:
  - Ci/sec (of a mix of radionuclides), or
  - µCi/cc (mix) and stack flow rate (CFM)

Dose Assessment Computer Codes

- URI, MIDAS, RADDOSE-V, RASCAL, others
- Dose code input is in units of µCi/cc or Ci/sec **of a mix of noble gases**
- **The dose assessment computer codes calculates the adjusted radionuclide "mix" based on decay of the T = 0 source term**
- So the input needs to be Ci/sec or µCi/cc **of the total MIX** of noble gas radionuclides at each time step

Detector measurements

- Detectors **DO NOT measure the "concentration of the mix,"** instead, they measure "ionizations" in **cpm, or mR/hr**
- Dose assessment codes input is the "**concentration of the mix"** (and flow rate); e.g., uCi/cc or Ci/sec
- So we need an "**Instrument Response Factor**" to convert from cpm or mR/hr into concentration uCi/cc or Ci/sec

Time Dependent Instrument Response Factors

- Detector signal (cpm or amps) is converted by microprocessor to µCi/cc or Ci/sec
- Vendor Detector Calibration
  - Primary calibration is based on Xe-133 gas; e.g., cpm // µCi/cc of Xe-133 (81 keV with 36.5% yield)
- Instrument Response Factors should be based on the calculated isotopic mix
- Isotopic mix changes as a function of time after Rx shutdown

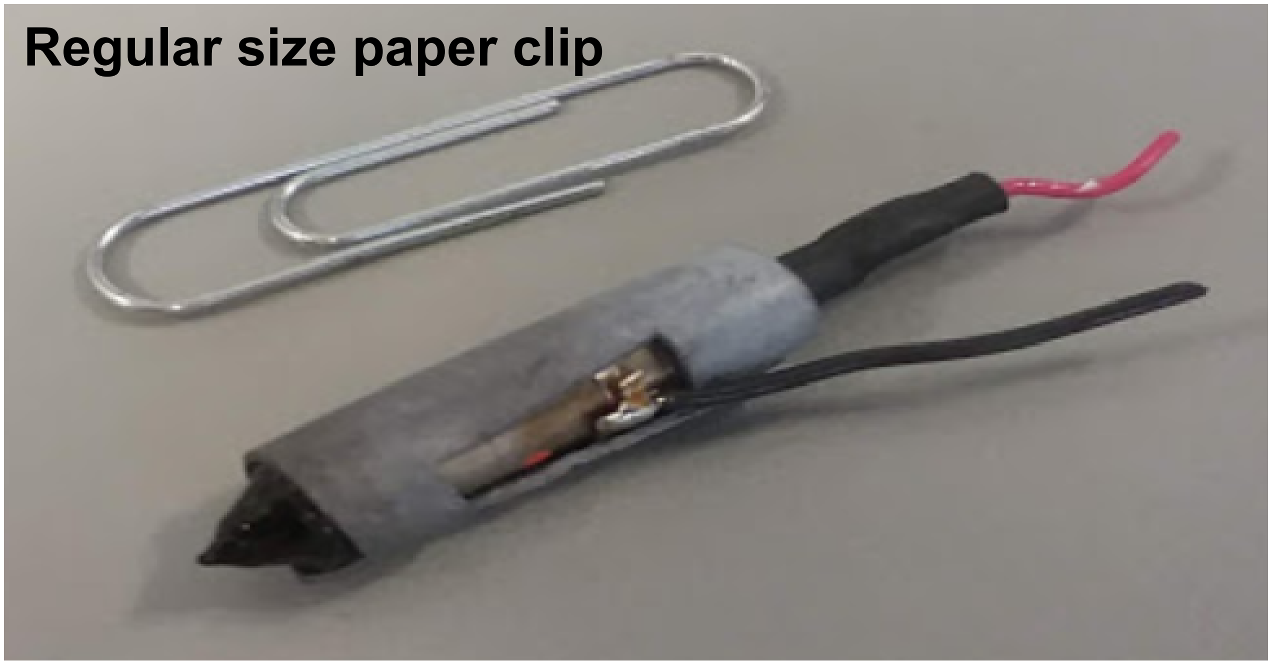
Isotopic Mix

- The isotopic mix has a significant effect on the instrument response factors (conventional detectors)
- **Use of only Xe-133 calibrations will generally over-estimate the total μCi/cc of a mix**
- **Use of Xe-133 calibration w/o correction could lead to premature EAL and ECLs declarations**
- Can lead to unnecessary protective actions such as sheltering or, more importantly, **or unnecessary evacuation**

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

GM Detectors

- GMs are energy compensated (e.g., lead shield)



- Energy compensated GMs have a strong energy dependency, under-responding at low energy

Ion Chambers

- Measures electrical "current" (amps) caused by radiation exposure
- Detector output is electrical current (e.g. milliAmps);
  - current is directly proportional to exposure rate
- Programmable microprocessor converts milliAmps to mR/hr or µCi/cc or Ci/sec

Instrument Response Factors

- Detectors based solely on a Xe-133 calibration (81 keV gamma), at T = 0
- Exposed to a core melt mix of noble gas:
  - GM detectors could over-respond by a factor ~30
  - Ion Chambers could over-respond by a factor of ~ 10
  - Cd/Te detectors could over-respond by a factor of ~ 5
  - Flow-through ion chambers may be within factor of ~ 2

Mid-Range and High Range Monitors

- Main Issues with GM or Ion Chambers:
  - GM response factors that are based only on Xe-133 will over-estimate the release: e.g.,
    - 0 to 8 hours
      - Gas Gap - T = 0 high estimate by a factor of ~ 5
      - Core Melt - T = 0 high estimate by a factor of ~ 30
    - 8 – 12 hours
      - Gas Gap - much better estimate
      - Core Melt - much better estimate
    - > 24 hours – under estimate

Potential for Unnecessary Evacuations

- Fukishima
  - the estimated number of directly-related evacuation caused deaths were more than 50
  - includes hospital patients and elderly people at nursing facilities who died from causes such as hypothermia, deterioration of underlying medical problems, and dehydration.
  - for long-term displacement, many people (mostly sick and elderly) died at an increased rate while in temporary housing and shelters.

Calibration & Surveillances (HPPOS-001)

NUREG 0737, Item II.F.1 Additional Accident-Monitoring Instrumentation (pdf pg 6,7)

- ANSI N323 – 1978 calibration methods are NOT applicable
  - ANSI N323 applies to portable instrument calibration only and requires portable instruments be:
    - Calibrated to the radiation type, geometry, intensity and energy spectrum of intended use
    - Un-calibrated scales or ranges should be identified on instrument as not being verified
    - Periodic performance tests

Calibration Process

Step 1. Vendor Calibrations

– Step 1.1 Gas calibration
– Step 1.2 Linearity check
– Step 1.3 Transfer calibration
– Step 1.4 Energy response characterization

Step 2. Secondary Calibrations at Plant

Step 3. Energy Response Factors

Step 4. Instrument Response Factors

Xe-133 and Kr-85

HPPOS-001, pdf pg 9

- In general, only 2 gas calibration sources that can be purchased
  - Xe-133 with 81 keV gamma (yield = 36.5%)
  - Kr-85 beta source (0.5% gamma emission)
    - Kr-85 not useful for gamma detection because of low gamma yield, and the sample is in a sample chamber and beta radiation is stopped by the sample chamber wall

cpm & mR/hr

(HPPOS-001, pdf 17)

- "cpm, or mR/hr, **is not** a good measure of "activity" or "concentration" because of detector energy dependence; i.e., different gamma energies and different gamma yields

- Example:
  - 1 µCi of Xe-135 (250 keV) produces **7.6 times** the dose as Xe-133
  - 1 µCi of Kr-88 (~2 MeV) produces **48 times** the dose as Xe-133

GM Detectors

- GM detectors measure "gamma flux" in cpm (or mR/hr derived from cpm)
- Unshielded GM detectors over-respond to low energy gammas
- Energy compensated, (e.g., lead shielded) GM detectors under-respond to low energy gammas
- Energy compensated GM detectors were designed as a dose-rate monitor for gamma energies > 100 keV

Energy-Compensated GM Detectors

- Characteristics:
  - Shielding “over-compensates” for low energy gammas
  - Significantly decreases GM response to our primary calibration gas (81 keV gamma from Xe-133)
  - Results in inaccurate scaling off the 81 keV response to high energies gammas

Ion Chambers

- Ion chambers measure “dose” & “exposure,” not “activity”
  - A “dose rate” instrument (i.e., ion chamber) is being used to measure “activity concentrations” (µCi/cc of a mix of nuclides)
  - Ion chambers are great for “dose-rate measurements,” but are not a good tool to measure “activity”
  - Mass energy absorption coefficients (i.e., probability of gamma interaction) are about the same for 100 keV as 1 MeV
  - However, 10 times the energy is absorbed, so the ion chamber response is 10X higher for 1 MeV vs. 100 keV
  - Difficult to measure “concentrations” of a mix of nuclides
  - Requires knowledge of gamma flux (gamma #s and energies) and the detector’s response to different gamma energies

Cd/Te Solid State Detectors

- General Atomics sold Cd/Te solid state detectors to ~ 20+ sites
- Calibration Report No. E-255-0961, (1984) "RD-72, Wide-Range Gas Monitor, High and Mid-Range Detectors"

Detector Terminology

HPPOS-001

- "**Prototype**" – hereafter referred to as a "Golden detector";
  e.g., a Model (V) 847 ion chamber

- "**Production Unit**" – A detector identical to the Golden detector sold to power plants

Primary Calibration

HPPOS-001, pdf pg 8

- Radioactive gas of a NIST traceable concentration is injected into the system to determine detector response:
  - At low, medium, & high concentrations
  - Measure instrument response factors (cpm // µCi/cc) or (mR/h//µCi/cc) **of Xe-133**
- Note: re-calibrations at plant, using Xe-133 gas at the plant are not practical, because too much gas would be released: e.g., 1E4 uCi/cc ~ 100 curies

Step 1. Primary Calibration

HPPOS-001, pdf pg 8 - 11

- Do a rigorous and comprehensive calibration
- Golden (Prototype) detector calibration:
  - **Step 1.1** **GAS CAL**: Xe-133 gas at low, medium, and high concentrations
  - **Step 1.2** **LINEARITY Check**: Low, medium and high doses
  - **Step 1.3** **TRANSFER Calibration (check)**:
    - Use a “reference” Cs-137 source
    - Use a “secondary” “transfer” Cs-137 source (for plants to use for in Secondary Calibration)
  - **Step 1.4** **ENERGY Characterization**: To solid sources in a wide energy range from 81 keV to ~ 2 MeV

Geometries

- We have two calibration geometries:
  - Gas geometry for Xe-133 in the sample chamber/detector geometry
  - Solid source geometry in a calibration jig

Step 1.1 Primary Calibration

Determine the detector's response to a NIST traceable gas source, e.g.,

Xe-133 gas source:

- GM detector's # of cpm // µCi/cc <u>of Xe-133</u>; or
- Ion Chamber's # of mR/hr // µCi/cc <u>of Xe-133</u>

<u>Why Xe-133?</u> It's the <u>**only**</u> readily-available gamma emitting gas source!

Xe-133 Primary Gas Calibration

RM-A1/A2 - MID RANGE　　　　　　　　　　　　ATTACHMENT 16

(8.9) DETECTOR RESPONSE--Xe-133 GAS

Date 7-19-85　　Detector Model 857-10　　Readout Module 856-10

Detector S/N 1490　　Readout Module S/N 1656

Type of Monitor: G-M Area Monitor

Text Ref.	Xe-133 Gas Concentration (μCi/cc)	c/m Gross	Readout Module (mR/hr) Gross	.041	Readout Module (mR/hr) Net	c/m Net	DVM Reading (V) Gross	-.607	DVM Reading (V) Net N/A.	Efficiency (mR/hr)/(μCi/cc) 24 MB	Initial
(8.9.6) [illegible] 1.	0.34 (7-19-85)	2203	2.5		2.46	2198	2.48		1.873	7.688	[illegible]
(8.9.8) [illegible] 2.	106.4 (7-24-85)	726902	925		924.96	726897	4.976		4.369	7.754	[illegible]
[illegible] 3.	42.85 (7-31-85)	366142	350		349.96	366137	4.591		3.99	8.168	[illegible]

See next page for remaining gas data.　　　NR.

(8.9.7) Ambient temperature 86.2 °F　　　[illegible]

Xe-133 Primary Gas Calibration

repeat gas calibration

RM-A4 /A2 - MID RANGE

(8.9) DETECTOR RESPONSE--Xe-133 GAS

Date 8-9-85 Detector Model 857-10 Readout Module 856-10

Detector S/N 1490 Readout Module S/N 1656

Type of Monitor: G-M Area Monitor

Text Ref.	°F		Xe-133 Gas Concentration (μCi/cc)		c/m Gross	Readout Module (mR/hr) Gross	0.041	Readout Module (mR/hr) Net	c/m Net	DVM Reading (V) Gross	.607	DVM Reading (V) Net	Efficiency (mR/hr)/(μCi/cc)	Initial
(8.9.6)	76.5	1.	4.55	(7-31-85)	43482	35		34.96	43477	3.587		2.980	7.6835	[illegible]
(8.9.8)	77.5	2.	0.287	(" ")	1470.9	1.85		1.809	1465.5	2.348		1.746	6.303	[illegible]
	77.5	3.	0.064	(8-1-85)	424	0.535		0.494	418.6	1.835		1.228	7.72	[illegible]

N/A
NB

$\bar{x}$ 7.477 mr/hr/μCi/cc

σ 0.65 " " "

(8.9.7) Ambient temperature SEE ABOVE °F

MB

Summary of Calibration Data: GM (V) Detector, Response to Xe-133

uCi/cc	cpm	cpm // uCi/cc	gps/cc*	cpm // gps/cc
4.55	43,482	9,556	6.06E+04	7.17E-01
0.287	1,470	5,122	3.82E+03	3.85E-01
0.064	424	6,625	8.52E+02	4.97E-01
0.34	2,203	6,479	4.53E+03	4.86E-01
106.4	726,902	6,832	1.42E+06	5.13E-01
42.85	366,142	8,545	5.71E+05	6.41E-01
	Average =	7,193		5.40E-01

* gps/cc = # of uCi x (3.7E4 dps/uCi) x Y (g/dis)

Remember this number

Xe-133 Gas Calibration

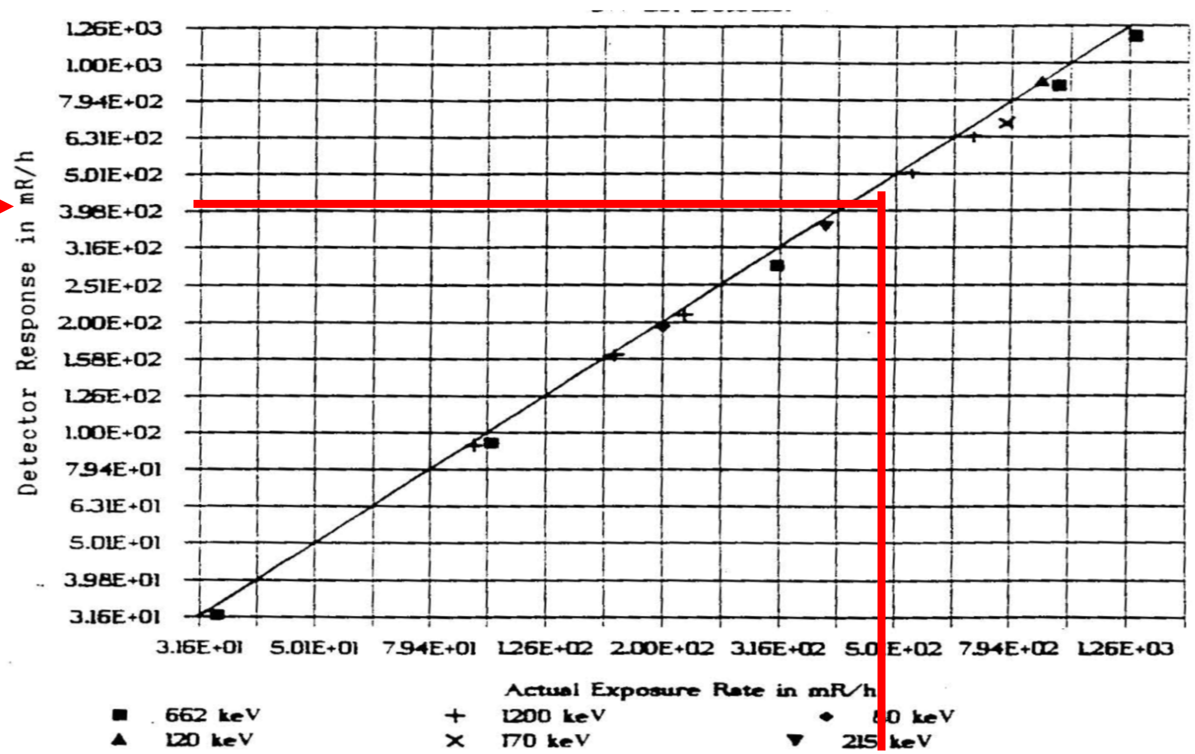
(Example)

- The "**instrument response factor**" to Xe-133
  - **7,193 cpm // µCi/cc of Xe-133**
  - **0.54 cpm / gps of Xe-133**
- The "**dose assessment code conversion factor**"
  - **1.39E-4 µCi/cc (Xe-133) // cpm**

Step 1.2 Linearity Check (Cs-137)

Detector Measurements

500 mR/h measurement



500 mR/h

Source dose rates

Step 1.3 Vendor Transfer Calibration

- Vendor does a transfer calibration
  - A Reference source is used to validate that each Production detector's response matches the prototype (Golden) detector's primary calibration
  - A Secondary transfer source calibration is performed for later use at the plant

2015 Transfer Calibration Check

Isotope	active Data Current µCi	Display III cpm	As Found Efficiency	Primary Calibration Efficiency	Primary Calibration Efficiency Tolerance –20%	+20%
Cs-137	49.7	6.58E3	132.3	1.18E2	94.4	141.6
Cs-137	553	6.13E4	110.8	9.25E1	74	111
Am-241	2,222	289	1.27 E-1	1.13E-1	9.04E-2	1.36E-1

6.585E3 cpm // 49.7 uCi = 132.3 cpm // uCi

Step 1.4 Golden Detector Energy Characterization (at vendor)

- The accident source term is composed of various 60 gamma energies from ~0 keV to ~2 MeV
- We need to know how the detector responds to each of those different gamma energies
- In a solid source geometry, determine the Golden detector's response to various energy gammas

Step 1.4 Energy Characterization

- Factory builds a solid-source calibration jig so that they have a fixed geometry
  - Calibration jig holds the Golden detector
  - Calibration jig has a solid source holder

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Solid Source Cal Jig

- Place the Golden detector in the jig at a fixed distance (e.g., 6 inches) from the source holder

- Expose the detector to various gamma energies in a solid source geometry

GM (V) Energy Characterization

end on

TABLE 2. ENERGY RESPONSE: MID RANGE STACK MONITOR
(DETECTOR MODEL 857-10, S/N 1490)
(READOUT MODULE 856-10, S/N 1656)

(d) End on; 0.035" steel plate between source and detector

9/18/85

Isotope	Energy (keV)	Activity (γps)	DVM Reading (mR/hr) equiv.	Gross Count Rate (cpm)	Detector Response net mR/hr / γps
Cd-109	88	2.997 E06	0.27 ± 0.08	164	6.7 ± 2.7 E-08
Co-57	124*	6.711 E06	0.84 ± 0.18	567	1.15 ± 0.27 E-07
Ba-133	81 342	3.022 E06 8.335 E06	2.8 ± 0.3	2732	(6.0 ± 2.4 E-08)** 3.06 ± 0.37 E-07
Cs-137	662	2.953 E06	3.8 ± 0.4	4188	1.26 ± 0.14 E-06
Mn-54	835	3.479 E06	5.2 ± 0.4	6450	1.47 ± 0.11 E-06
Y-88	898 1836	2.625 E06 2.775 E06	14.0 ± 0.7	17880	(1.6 ± 0.3 E-06)** 3.53 ± 0.35 E-06
Co-60	1253*	4.387 E06	10.4 ± 1.0	13210	2.35 ± 0.23 E-06

* Average energy (combined intensity).

Vendor (V) Solid Source Energy Characterization

end-on geometry

Nuclide	Gamma Energy	End-on cpm/gps	End-On Ratio to 81 keV
Ba-133	81 keV	4.87E-05	1.0
Cd-109	88 keV	5.47E-05	1.1
Co-57	124 keV	8.45E-05	1.7
Ba-133	342 keV	3.28E-04	6.7
Cs-137	662 keV	1.42E-03	29.1
Mn-54	835 keV	1.85E-03	38.1
Co-60	1253 keV	3.01E-03	61.8
Y-88	1.836 MeV	3.31E-03	68.0

GM (V) Energy Characterization

Side on

TABLE 2. ENERGY RESPONSE: MID RANGE STACK MONITOR
(DETECTOR MODEL 857-10, S/N 1490)
(READOUT MODULE 856-10, S/N 1656)

(c) 0.035" steel plate between source and detector; side on

9/17/85

Isotope	Energy (keV)	Activity (γps)	DVM Reading (mR/hr) equiv.	Gross Count Rate (cpm)	Detector Response net mR/hr / γps
Cd-109	88	3.002 E06	0.49 ± 0.10	302	1.42 ± 0.33 E-07
Co-57	124*	6.728 E06	1.7 ± 0.3	1197	2.44 ± 0.45 E-07
Ba-133	81 342*	3.022 E06 8.337 E06	4.8 ± 0.6	5408	(1.2 ± 0.3 E-07)** 5.25 ± 0.71 E-07
Cs-137	662	2.953 E06	5.0 ± 0.5	5740	1.67 ± 0.17 E-06
Mn-54	835	3.487 E06	6.4 ± 0.4	3895	1.82 ± 0.11 E-06
Y-88	898 1836	2.642 E06 2.794 E06	15.4 ± 1.3	18880	(1.9 ± 0.3 E-06)** 3.7 ± 0.5 E-06
Co-60	1253*	4.389 E06	11.4 ± 0.7	14040	2.58 ± 0.14 E-06

* Average energy (combined intensity).

Vendor Solid Source Energy Characterization
side-on geometry

Side-On Geometry Nuclide	Energy keV	Source ERF cpm/gps	Relative Response
Ba-133	81	8.55E-05	**1.0**
Cd-109	88	1.01E-04	**1.2**
Co-57	124	1.78E-04	**2.1**
Ba-133	342	6.49E-04	**7.6**
Cs-137	662	1.94E-03	**22.7**
Mn-54	835	1.12E-03	**13.1**
Co-60	1,253	3.20E-03	**37.4**
Y-88	1,836	3.50E-03	**40.9**

← **Outlier**

Vendor Mid-range GM (E) Detector

Model E Mid-Range Detector					
Solid Source Energy Characterization					
	keV	cpm// uCi	Gamma Yield	cpm/gps	Relative Response to 88 keV
Cd-109	88	0.33	0.036	2.48E-04	1
Ba-133	342	66.4	0.62	2.89E-03	12
Cs-137	662	131	0.85	4.17E-03	17
Co-60	1253	517	2	6.99E-03	28

High-range GM (E) Detector

GM (E) High Range Detector

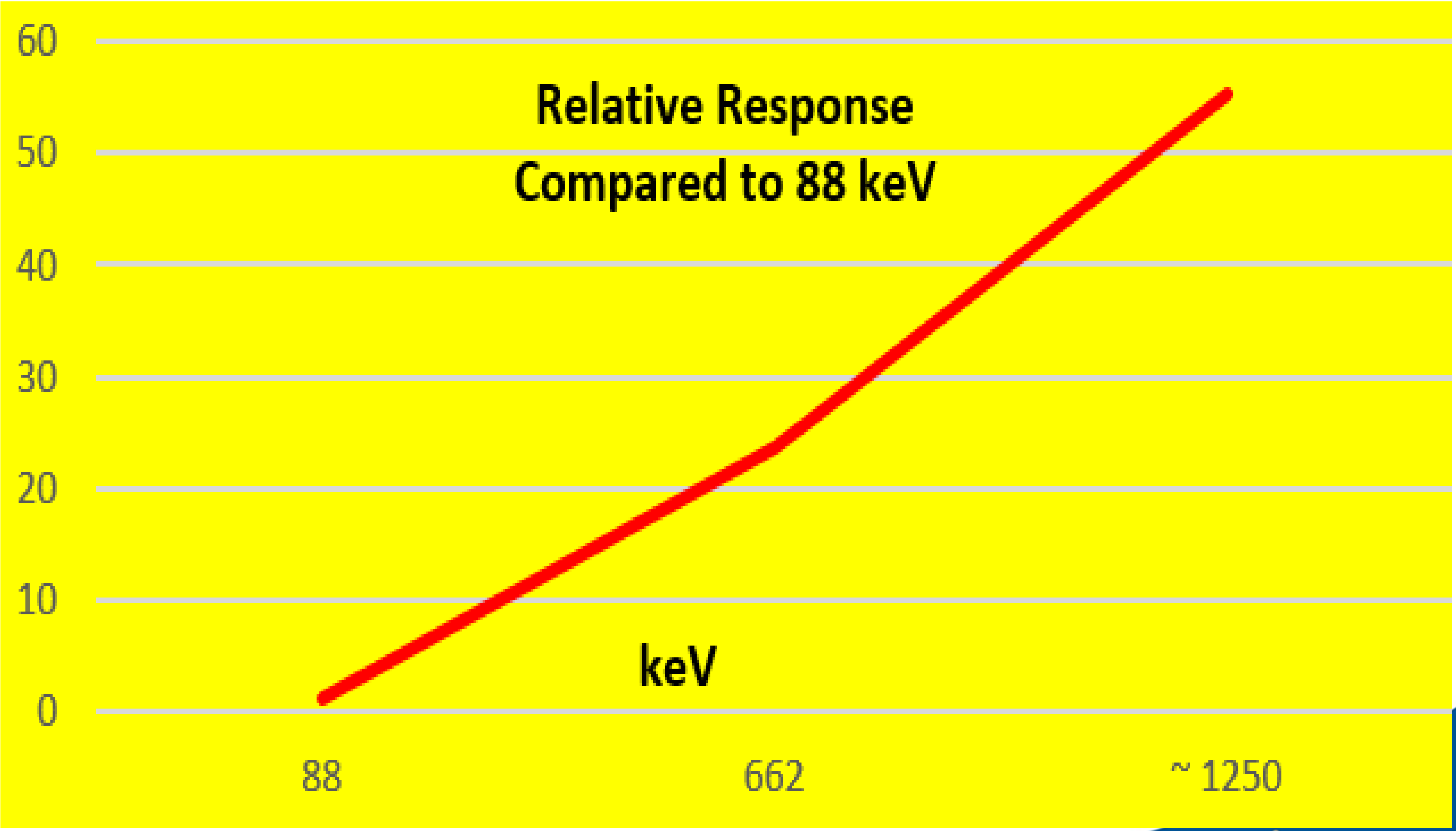
Solid Source Energy Characterization

	keV	cpm// uCi	Gamma Yield	cpm/gps	Relative Response to 81 keV
Cd-109	88	0.653	0.0361	4.9E-04	1
Cs-137	662	186	0.85	5.9E-03	24
Co-60	~ 1250	896	2	1.2E-02	55

gps/uCi = (cpm // ~~uCi~~) / [3.7E4 ~~dis~~/sec // ~~uCi~~ Yield (g/~~dis~~)]

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Model (E) High Range GM Detector
Solid Source Energy Characterization



Transfer to Plant

- The vendor is finished with Calibration Step 1
  - Step 1.1 Gas calibration
  - Step 1.2 Linearity check
  - Step 1.3 Transfer Calibration
  - Step 1.4 Solid source energy characterization
- The equipment and primary calibration data are sent to the plant
- Likely without further instruction on what to do with the energy characterization data

Step 2. Plant Secondary Calibration (check)

- Basic Method:
  - Use the calibration jig
  - Use the transfer source
  - Set the detector in the calibration jig
  - Mount the transfer source in the calibration jig
  - Measure the detector's response
  - Compare the results to the factory transfer source results
  - Tweak as needed
- Repeat periodically

Calibration Step 3
Energy Response Factors

- Objective: calculate the detector's energy response factors (ERF) to each of 60 different gamma energies in a gas geometry

- Analogous to doing an energy efficiency calibration on a gamma spectroscopy system

Source Term: 13 Noble Gases

6 Kryptons

- 1. Kr-83m
- 2. Kr-85m
- 3. Kr-85
- 4. Kr-87
- 5. Kr-88
- 6. Kr-89

7 Xenons

7. Xe-131m
8. Xe-133m
9. Xe-133
10. Xe-135m
11. Xe-135
12. Xe-137
13. Xe-138

There are **60 different gamma energies** from 13 noble gas nuclides

60 Gamma Energies

Nuclide	Half Life (hours)	gamma energy keV
Kr-83m	1.9	9
Kr-85m	4.5	150
	4.5	305
Kr-85	94,000	514
Kr-87	1.3	403
	1.3	674
	1.3	845
	1.3	1,175
	1.3	1,740
	1.3	2,010

	Half Life	keV
Kr-88	2.8	166
	2.8	196
	2.8	362
	2.8	835
	2.8	986
	2.8	1,000
	2.8	1,140
	2.8	1,180
	2.8	1,530

	Half Life	keV
Kr-89	0.053	197
	0.053	221
	0.053	345
	0.053	369
	0.053	411
	0.053	498
	0.053	586
	0.053	696
	0.053	738
	0.053	776
	0.053	836
	0.053	867
	0.053	904
	0.053	1,108
	0.053	1,117
	0.053	1,274
	0.053	1,324
	0.053	1,473
	0.053	1,501
	0.053	1,532
	0.053	1,694
	0.053	1,903

	Half Life	keV
	0.053	1,903
Xe-131m	288	164
Xe-133m	55	223
Xe-133	127	81
Xe-135m	0.25	527
Xe-135	9.2	250
	9.2	608
Xe-137	0.065	455
	0.065	1,491
Xe-138	0.3	153
	0.3	242
	0.3	258
	0.3	396
	0.3	401
	0.3	434
	0.3	1,114
	0.3	1,768
	0.3	1,851
	0.3	2,005
	0.3	2,016

Step 3. Energy Response Factors

- What is an Energy Response Factor (ERF)?
- At each specific energy, the ERF is the detector's response **in a gas geometry** to a gamma flux; i.e., (# of cpm // gps // cc)
- ERFs are gamma energy dependent
- Acronyms
  - "ERF" – Energy response factor
  - "gps" = gammas per second

Energy Response Factors (ERFs)

- **Objective:**
  - Calculate ERFs in a gas geometry **(# of cpm // gps / cc**)
  - For each of 60 different gamma energies

Basic Method

1. **<u>In a Gas Geometry</u>**
   - Measure the detector's response to the Xe-133's 81 keV gamma (# of cpm // µCi/cc)
   - Normalize (convert) from uCi to gps (# of cpm // gps // cc)
2. **<u>In a Solid Geometry</u>**
   - Measure the detector's response to a wide range of gamma energies (# of cpm // gps) at each solid source energy
   - Calculate the relative ratios of the solid source ERFs
3. **<u>In a Gas Geometry</u>**
   - Multiply the Xe-133's 81 keV ERF by the solid source ratios
   - Calculate the ERFs for 60 gamma energies

Detector Response Depends on the Gamma Energy

(HPPOS-001, pdf pg 17)

- Detector response (cpm or amps) // µCi/cc depends on each gamma energy and nuclide's yield at each gamma energy
  - For example, compare 1 µCi/cc (Xe-133) to 1 µCi/cc (Xe-138)
    - Xe-133 (127 hour half-life)
      - 81 keV
      - 36.5% yield
    - Xe-138 (18 min half-life)
      - 1.77 MeV energies with 17% yield
      - 2.02 MeV with 12% yield (29% combined yield)
  - **On a uCi //cc basis, Xe-138 produces 80 times more dose rate than Xe-133**

If Xe-133 was the only effluent

- In a gas geometry, we could calibrate to Xe-133 and be finished
- Example: 7,193 cpm // µCi/cc Xe-133

  = 7,193 cpm // µCi/cc = 1.39E-4 µCi/cc // cpm

  – RMS output reads 14,000 cpm

  – We then multiply 14,000 cpm x 1.39E-4 µCi/cc // cpm
- **= 1.95 µCi/cc of Xe-133**
- **We input the value 1.95 µCi/cc into the dose code (e.g., RASCAL, MIDAS, RADDOSE)**

Only 1 gamma emitting calibration gas is available

HPPOS-001 (pdf pg 9)

- Xe-133 (81 keV with a 36.5% yield)
  - Exception: Kr-85 (beta emitter) (0.5% gamma)
- Our best calibration method:
  - Characterize detector energy response using solid sources
  - Calculate ERFs in a solid source geometry
  - Convert ERFs from a "solid source" geometry to "gas source" geometry

Xe-133 and Solid Sources

- What we have:
  - We have the vendor calibration to Xe-133 in a gas geometry (# of cpm // µCi/cc)
  - We have the vendor detector energy characterizations <u>in a solid geometry</u> for 9 gamma energies

Example:

- A GM effluent detector is calibrated to Xe-133 gas (81 keV)
- The detector read-out is 7,193 cpm // µCi/cc of Xe-133
- The gamma yield is 0.365 gammas per disintegration
- 1 µCi = 3.7E4 dps
- Gamma emission rate (gps // µCi) =

  = (3.7E4 dps // µCi of Xe-133) x 0.365 gamma/dis

  = 13,320 gps // µCi of Xe-133 (81 keV)
- ERF (81 keV) = (7,193 cpm // µCi/cc) // 13,320 gps // µCi Xe-133
- ERF (81 keV) = 0.54 cpm //gps //cc of Xe-133

Example

➢ Assume the plant has received from the factory:

- 1) a rad monitor,
- 2) a transfer source,
- 3) a calibration jig, and
- 4) calibration data as follows:
  - Xe-133 gas calibration (# of cpm // µCi of Xe-133)
  - A solid source transfer calibration factor
  - Energy characterization data for 9 gamma energies <u>in a solid source geometry</u>

Primary Gas Calibration - Response to Xe-133

GM (V) Mid-Range Detector,

uCi/cc	cpm	cpm // uCi/cc	gps // cc *	cpm // gps/cc	cpm // gps/cc
4.55	43,482	9,556	6.06E+04	0.72	0.72
0.287	1,470	5,122	3.82E+03	0.38	0.38
0.064	424	6,625	8.52E+02	0.50	0.50
0.34	2,203	6,479	4.53E+03	0.49	0.49
106.4	726,902	6,832	1.42E+06	0.51	0.51
42.85	366,142	8,545	5.71E+05	0.64	0.64
	Average :	**7,193**		**0.54**	**0.54**

* gps/cc = # of uCi x (3.7E4 dps/uCi) x 0.365 (g/dis)

Remember this number

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Convert ERFs from solid geometry to gas geometry

- We have the solid source gamma energy calibration data from the factory
- Assumption: The ratios of ERFs in a solid geometry is the same as the ERF ratios in a gas geometry

Example Energy Calibration

- There are 7 <u>solid</u> calibration sources that were purchased, with 9 gamma energies
- In a solid source geometry, the vendor measured the detector's response to each of 7 solid sources
- Vendor provided the solid source activity in gps and detector response in cpm to each source
- Plant staff calculates the # of cpm // gps for each gamma energy (in a solid source geometry)

Solid Source Energy Response

GM (V) orientation "end-on"

TABLE 2. ENERGY RESPONSE: MID RANGE STACK MONITOR
(DETECTOR MODEL 857-10, S/N 1490)
(READOUT MODULE 856-10, S/N 1656)

(d) End on; 0.035" steel plate between source and detector

9/18/85

* Steel plate simulates sample chamber wall

Isotope	Energy (keV)	Activity (γps)	DVM Reading (mR/hr) equiv.	Gross Count Rate (cpm)	Detector Response net mR/hr / γps
Cd-109	88	2.997 E06	0.27 ± 0.08	164	6.7 ± 2.7 E-08
Co-57	124*	6.711 E06	0.84 ± 0.18	567	1.15 ± 0.27 E-07
Ba-133	81 342	3.022 E06 8.335 E06	2.8 ± 0.3	2732	(6.0 ± 2.4 E-08)** 3.06 ± 0.37 E-07
Cs-137	662	2.953 E06	3.8 ± 0.4	4188	1.26 ± 0.14 E-06
Mn-54	835	3.479 E06	5.2 ± 0.4	6450	1.47 ± 0.11 E-06
Y-88	898 1836	2.625 E06 2.775 E06	14.0 ± 0.7	17880	(1.6 ± 0.3 E-06)** 3.53 ± 0.35 E-06
Co-60	1253*	4.387 E06	10.4 ± 1.0	13210	2.35 ± 0.23 E-06

* Average energy (combined intensity).

GM Solid Source Energy Calibration

Detector Orientation is "End-On"

Nuclide	Gamma Energy	End-on cpm/gps	Ratio to 81 keV
Ba-133	81 keV	4.87E-05	1.0
Cd-109	88 keV	5.47E-05	1.1
Co-57	124 keV	8.45E-05	1.7
Ba-133	342 keV	3.28E-04	6.7
Cs-137	662 keV	1.42E-03	29.1
Mn-54	835 keV	1.85E-03	38.1
Co-60	1253 keV	3.01E-03	61.8
Y-88	1.836 MeV	3.31E-03	68.0

Solid Source Energy Response

GM (V) – orientation "side on"

TABLE 2. ENERGY RESPONSE: MID RANGE STACK I
(DETECTOR MODEL 857-10, S/N 1490)
(READOUT MODULE 856-10, S/N 1656)

(c) 0.035" steel plate between source and detecto

9/17/85

* Steel plate simulates sample chamber wall

Isotope	Energy (keV)	Activity (γps)	DVM Reading (mR/hr) equiv.	Gross Count Rate (cpm)
Cd-109	88	3.002 E06	0.49 ± 0.10	302
Co-57	124*	6.728 E06	1.7 ± 0.3	1197
Ba-133	81 342*	3.022 E06 8.337 E06	4.8 ± 0.6	5408
Cs-137	662	2.953 E06	5.0 ± 0.5	5740
Mn-54	835	3.487 E06	6.4 ± 0.4	3895
Y-88	898 1836	2.642 E06 2.794 E06	15.4 ± 1.3	18880
Co-60	1253*	4.389 E06	11.4 ± 0.7	14040

* Average energy (combined intensity).

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Solid Source Energy Calibration

GM (V) Orientation "side on"

Side-On Geometry Nuclide	Energy keV	Solid Source ERF cpm/gps	Relative Response
Ba-133	81	8.55E-05	**1.0**
Cd-109	88	1.01E-04	**1.2**
Co-57	124	1.78E-04	**2.1**
Ba-133	342	6.49E-04	**7.6**
Cs-137	662	1.94E-03	**22.7**
Mn-54	835	1.12E-03	**13.1**
Co-60	1,253	3.20E-03	**37.4**
Y-88	1,836	3.50E-03	**40.9**

OUTLIER

Average Solid Geometry ERF Ratio's

Radio-nuclide	Gamma Energy keV	Side-on Solid Source Geometry ERFs cpm // gps	End-on Solid Source Geometry ERFs cpm // gps	Average Solid Source Geometry ERFs cpm // gps	Solid Geometry Ratio to 81 keV	
Ba-133	81	8.55E-05	4.89E-05	**6.72E-05**	1.0	
Cd-109	88	1.01E-04	5.47E-05	**7.77E-05**	1.2	
Co-57	124	1.78E-04	8.45E-05	**1.31E-04**	2.0	
Ba-133	342	6.49E-04	3.28E-04	**4.88E-04**	7.3	
Cs-137	662	1.94E-03	1.42E-03	**1.68E-03**	25.0	
Mn-54	835	1.12E-03	1.85E-03	**1.49E-03**	22.1	Outlier
Y-88	898	2.00E-03	2.50E-03	**2.25E-03**	33.5	
Co-60	1253	3.20E-03	3.01E-03	**3.11E-03**	46.2	
Y-88	1836	3.50E-03	3.31E-03	**3.41E-03**	50.7	

GM (V) Solid Source Relative Response

GM (E) Energy Dependence

A	Stick Source Isotope	Cd-109	Ba-133	Cs-137	Co-60
B	Activity (uCi)	251	103.8	10.71	12.25
C	Count rate	82.9	6,890	14,000	63,300
D	Solid Source Eff. (cpm/uCi)	0.33	66.4	131	517

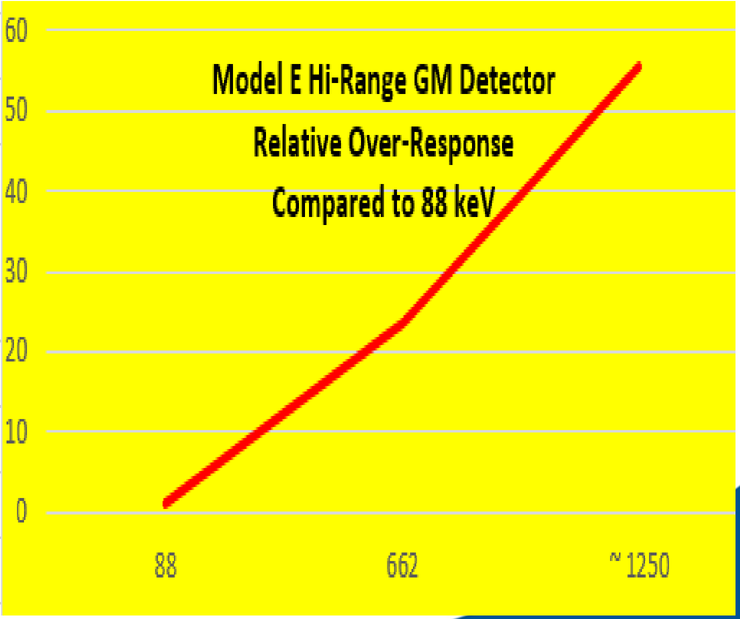
Eberline GM Solid Source Response Factors

High Range Detector

	keV	cpm// uCi	Gamma Yield	cpm/gps	Response to 88 keV
Cd-109	88	0.653	0.0361	4.9E-04	1
Cs-137	662	186	0.85	5.9E-03	24
Co-60	~ 1250	896	2	1.2E-02	55

gps/uCi = (cpm // ~~uCi~~)

3.7E4 ~~dis~~/sec // ~~uCi~~ Yield (g/~~dis~~)



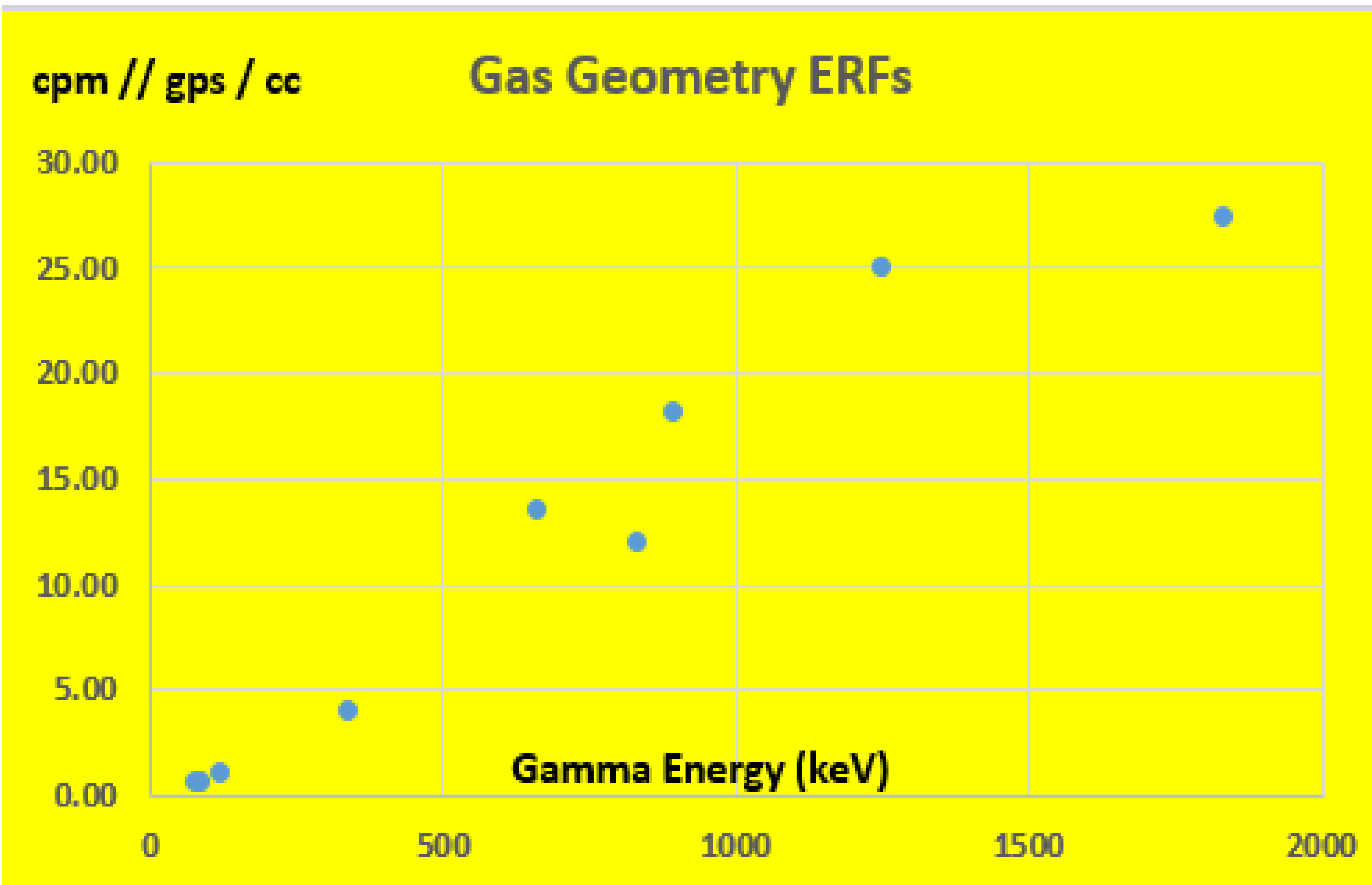
Convert Solid Source ERFs to Gas Geometry ERFs

- From the primary gas calibration, the ERF for Xe-133's 81 keV gamma in a gas geometry is 0.54 cpm // gps/cc
- The ratios of the solid source gamma energies to 81 keV are known.
- The ERFs for 9 gamma energies in a gas geometry (based on scaling to solid source ratios) are calculated
- In order to calculate the ERFs for the other 60 gamma energies,
  - Plot the 9 ERFs, do a curve fit and get equation
  - Calculate the 60 ERFs for the noble gas gammas

Convert ERFs from a Solid Geometry to Gas Geometry

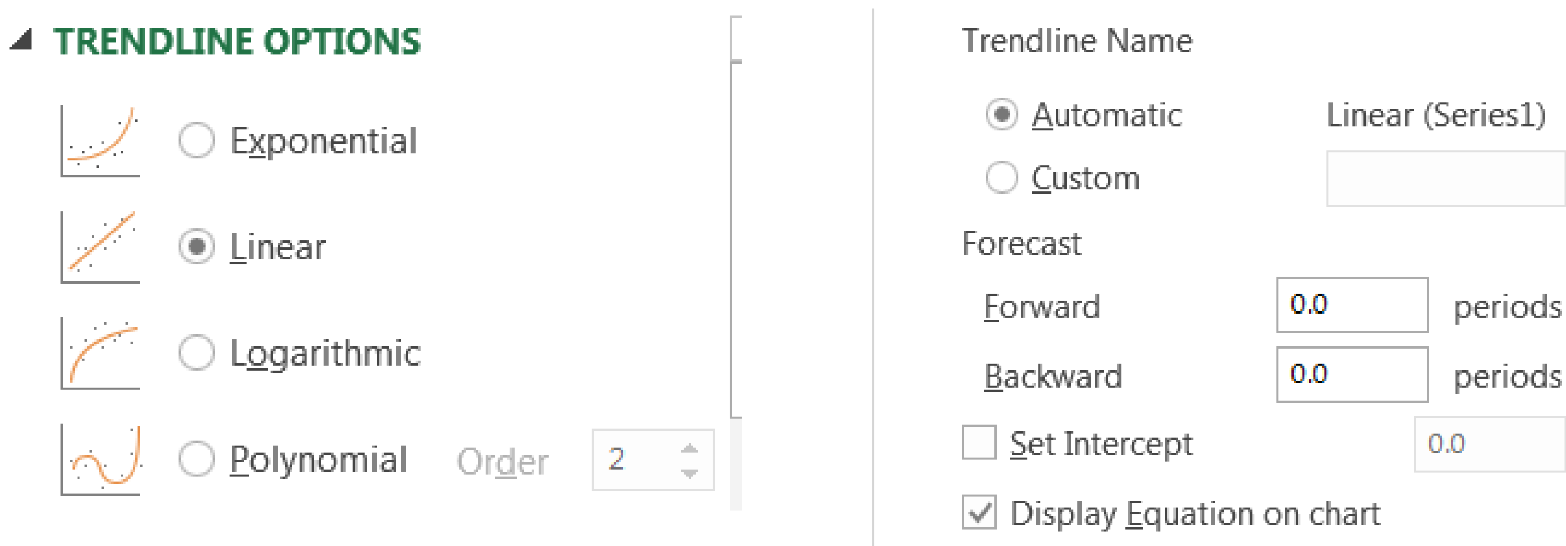
Radio-nuclide	Gamma Energy keV	Average Solid Source Geometry ERFs cpm // gps	Solid Geometry Ratio to 81 keV	Gas Geometry ERFs cpm // gps/cc
Ba-133	81	6.72E-05	1.0	0.54
Cd-109	88	7.77E-05	1.2	0.62
Co-57	124	1.31E-04	2.0	1.05
Ba-133	342	4.88E-04	7.3	3.92
Cs-137	662	1.68E-03	25.0	13.51
Mn-54	835	1.49E-03	22.1	11.94
Y-88	898	2.25E-03	33.5	18.08
Co-60	1253	3.11E-03	46.2	24.95
Y-88	1836	3.41E-03	50.7	27.37

Plot the ERFs in Gas Geometry



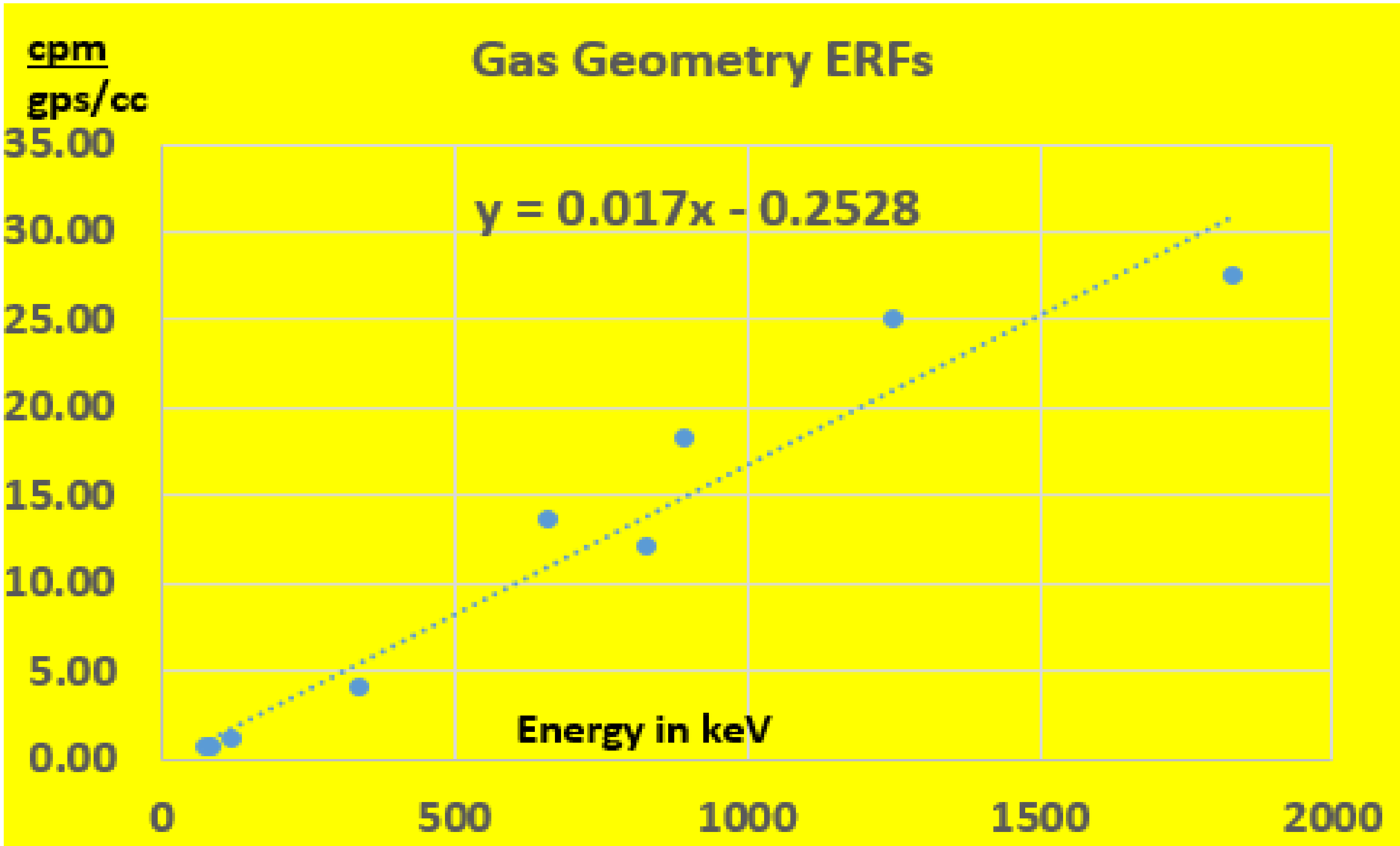
Excel Method

- Let Excel do the work
- Plot the 9 response factors, and do a Trendline



- Get an equation for energy response factors

Add Trendline & Curve Fit Equation



Next step:

- Calculate energy response factors for 60 gamma energies

- Use the Excel equation to calculate the 60 different gamma energy response factors

13 Noble Gases

6 Kryptons

- 1. Kr-83m
- 2. Kr-85m
- 3. Kr-85
- 4. Kr-87
- 5. Kr-88
- 6. Kr-89

7 Xenons

7. Xe-131m
8. Xe-133m
9. Xe-133
10. Xe-135m
11. Xe-135
12. Xe-137
13. Xe-138

Apply Excel equation to calculate 60 Gamma ERFs

ERF = 0.017* E – 0.2528

Nuclide	Half Life (hours)	gamma energy keV	ERF (in gas geometry) cpm / gps / cc
Kr-83m	1.9	9	-0.10
Kr-85m	4.5	150	2.30
	4.5	305	4.93
Kr-85	94,000	514	8.49
Kr-87	1.3	403	6.60
	1.3	674	11.21
	1.3	845	14.11
	1.3	1,175	19.72
	1.3	1,740	29.33
	1.3	2,010	33.92

Apply Excel equation to calculate 60 Gamma ERFs

ERF = 0.017* E – 0.2528

Nuclide	Half Life (hours)	gamma energy keV	ERF (in gas geometry) cpm / gps / cc
Kr-88	2.8	166	2.57
	2.8	196	3.08
	2.8	362	5.90
	2.8	835	13.94
	2.8	986	16.51
	2.8	1,000	16.75
	2.8	1,140	19.13
	2.8	1,180	19.81
	2.8	1,530	25.76

Apply Excel equation to calculate 60 Gamma ERFs

ERF = 0.017* E – 0.2528

Nuclide	Half Life (hours)	gamma energy keV	ERF (in gas geometry) cpm / gps / cc
Kr-89	0.053	197	3.10
	0.053	221	3.50
	0.053	345	5.61
	0.053	369	6.02
	0.053	411	6.73
	0.053	498	8.21
	0.053	586	9.71
	0.053	696	11.58
	0.053	738	12.29
	0.053	776	12.94

Nuclide	Half Life (hours)	gamma energy keV	ERF (in gas geometry) cpm / gps / cc
Kr-89	0.053	836	13.96
	0.053	867	14.49
	0.053	904	15.12
	0.053	1,108	18.58
	0.053	1,117	18.74
	0.053	1,274	21.41
	0.053	1,324	22.26
	0.053	1,473	24.79
	0.053	1,501	25.26
	0.053	1,532	25.79
	0.053	1,694	28.55
	0.053	1,903	32.10

Apply Excel equation to calculate 60 Gamma ERFs

ERF = 0.017* E – 0.2528

Nuclide	Half Life (hours)	gamma energy keV	ERF (in gas geometry) cpm / gps / cc
Xe-131m	288	164	2.54
Xe-133m	55	223	3.54
Xe-133	127	81	0.54
Xe-135m	0.25	527	8.71
Xe-135	9.2	250	4.00
	9.2	608	10.08
Xe-137	0.065	455	7.48
	0.065	1,491	25.09

Apply Excel equation to calculate 60 Gamma ERFs

ERF = 0.017* E – 0.2528

Nuclide	Half Life (hours)	gamma energy keV	ERF (in gas geometry) cpm / gps / cc
Xe-138	0.3	153	2.35
	0.3	242	3.86
	0.3	258	4.13
	0.3	396	6.48
	0.3	401	6.56
	0.3	434	7.13
	0.3	1,114	18.69
	0.3	1,768	29.80
	0.3	1,851	31.21
	0.3	2,005	33.83
	0.3	2,016	34.02

End of ERF Calculations

- It is now known how the detector will respond to various gamma energies in a gas geometry; i.e.,

- # of cpm // gps/cc for each of 60 gamma energies in a gas geometry

Step 4. Calibration Process

Instrument Response Factors

Dose Code Input
URI, MIDAS, RADDOSE-V, others

- Most dose assessment code input is based on a "total" (combined) radionuclide mix (**µCi/cc of a total mix**) or **Ci/sec of a time-dependent mix** of noble gases

Two Types of "Response Factors"

- Energy Response Factors (ERFs) (for each gamma energy)
  - **cpm or mR/hr // gps/cc**
  - different ERFs for each gamma energy

- Instrument Response Factors (IRFs) (for a mix of gases)
  - **cpm // µCi/cc of mix of noble gas nuclides**
  - **mR/hr // µCi/cc of a mix of noble gas nuclides**
  - **IRF values change as the time-dependent mix changes**

Gamma Flux

- Detectors respond to gamma flux
- Gamma flux:
  - Number of gammas per second (gps)
  - Energy of the gammas
- The gamma flux of a mix change as gases undergo radioactive decay
- So we need to know, as function of time:
- **Gamma flux (numbers of gammas and their energies)**

Gammas per second (gps)/cc

- Calculate the number of gps/cc in 1 µCi/cc of each isotope, at each energy
  - We start by taking 1 µCi/cc of each isotope
  - We identify each gamma energy
  - We identify the yield of each gamma energy
  - Then we calculate the # gps/cc in 1 µCi/cc of each gamma energy

Calculate # of gps/cc in 1 μCi/cc of each isotope

gps/cc // uCi/cc = 1 μCi x 3.7E4 gps//μCi x Yield

Nuclide	Half-life (hours)	ϒ energy (keV)	Yield gammas per disintegr	dps/cc // uCi/cc	gps/cc // uCi/cc uCi of each radionuclide	
Kr-83m	1.9	9	0.09	3.70E+04	**3,330**	gps/cc // uCi/cc
Kr-85m	4.5	150	0.75	3.70E+04	**27,750**	gps/cc // uCi/cc
	4.5	305	0.14	3.70E+04	**5,180**	gps/cc // uCi/cc
Kr-85	94,000	514	0.004	3.70E+04	**148**	gps/cc // uCi/cc
Kr-87	1.3	403	0.5	3.70E+04	**18,500**	gps/cc // uCi/cc
	1.3	674	0.02	3.70E+04	**740**	gps/cc // uCi/cc
	1.3	845	0.07	3.70E+04	**2,590**	gps/cc // uCi/cc
	1.3	1,175	0.01	3.70E+04	**370**	gps/cc // uCi/cc
	1.3	1,740	0.02	3.70E+04	**740**	gps/cc // uCi/cc
	1.3	2,010	0.03	3.70E+04	**1,110**	gps/cc // uCi/cc

Calculate # of gps/cc in 1 µCi/cc of each isotope

Nuclide	Half-life (hours)	ϒ energy (keV)	Yield gammas per disintegr	dps/cc // uCi/cc	gps/cc // uCi/cc uCi of each radionuclide	
Kr-88	2.8	166	0.03	3.70E+04	**1,110**	gps/cc // uCi/cc
	2.8	196	0.26	3.70E+04	**9,620**	gps/cc // uCi/cc
	2.8	362	0.02	3.70E+04	**740**	gps/cc // uCi/cc
	2.8	835	0.13	3.70E+04	**4,810**	gps/cc // uCi/cc
	2.8	986	0.01	3.70E+04	**370**	gps/cc // uCi/cc
	2.8	1,000	0.02	3.70E+04	**740**	gps/cc // uCi/cc
	2.8	1,140	0.01	3.70E+04	**370**	gps/cc // uCi/cc
	2.8	1,180	0.01	3.70E+04	**370**	gps/cc // uCi/cc
	2.8	1,530	0.11	3.70E+04	**4,070**	gps/cc // uCi/cc

Calculate # of gps/cc in 1 µCi/cc of each isotope

Nuclide	Half-life (hours)	ϒ energy (keV)	Yield gammas per disintegr	dps/cc // uCi/cc	gps/cc // uCi/cc uCi of each radionuclide	
Kr-89	0.053	197	0.02	3.70E+04	**740**	gps/cc // uCi/cc
	0.053	221	0.2	3.70E+04	**7,400**	gps/cc // uCi/cc
	0.053	345	0.01	3.70E+04	**370**	gps/cc // uCi/cc
	0.053	369	0.01	3.70E+04	**370**	gps/cc // uCi/cc
	0.053	411	0.03	3.70E+04	**1,110**	gps/cc // uCi/cc
	0.053	498	0.08	3.70E+04	**2,960**	gps/cc // uCi/cc
	0.053	586	0.17	3.70E+04	**6,290**	gps/cc // uCi/cc
	0.053	696	0.02	3.70E+04	**740**	gps/cc // uCi/cc
	0.053	738	0.04	3.70E+04	**1,480**	gps/cc // uCi/cc
	0.053	776	0.01	3.70E+04	**370**	gps/cc // uCi/cc
	0.053	836	0.01	3.70E+04	**370**	gps/cc // uCi/cc
	0.053	867	0.06	3.70E+04	**2,220**	gps/cc // uCi/cc
	0.053	904	0.07	3.70E+04	**2,590**	gps/cc // uCi/cc
	0.053	1,108	0.03	3.70E+04	**1,110**	gps/cc // uCi/cc
	0.053	1,117	0.02	3.70E+04	**740**	gps/cc // uCi/cc
	0.053	1,274	0.01	3.70E+04	**370**	gps/cc // uCi/cc
	0.053	1,324	0.03	3.70E+04	**1,110**	gps/cc // uCi/cc
	0.053	1,473	0.07	3.70E+04	**2,590**	gps/cc // uCi/cc
	0.053	1,501	0.01	3.70E+04	**370**	gps/cc // uCi/cc
	0.053	1,532	0.08	3.70E+04	**2,960**	gps/cc // uCi/cc
	0.053	1,694	0.04	3.70E+04	**1,480**	gps/cc // uCi/cc
	0.053	1,903	0.01	3.70E+04	**370**	gps/cc // uCi/cc

Calculate # of gps/cc in 1 µCi/cc of each isotope

Nuclide	Half-life (hours)	Υ energy (keV)	Yield gammas per disintegr	dps/cc // uCi/cc	gps/cc // uCi/cc uCi of each radionuclide	
Xe-131m	288	164	0.02	3.70E+04	**740**	gps/cc // uCi/cc
Xe-133m	55	223	0.1	3.70E+04	**3,700**	gps/cc // uCi/cc
Xe-133	127	81	0.36	3.70E+04	**13,320**	gps/cc // uCi/cc
Xe-135m	0.25	527	0.81	3.70E+04	**29,970**	gps/cc // uCi/cc
Xe-135	9.2	250	0.9	3.70E+04	**33,300**	gps/cc // uCi/cc
	9.2	608	0.03	3.70E+04	**1,110**	gps/cc // uCi/cc
Xe-137	0.065	455	0.31	3.70E+04	**11,470**	gps/cc // uCi/cc
	0.065	1,491	0.01	3.70E+04	**370**	gps/cc // uCi/cc
Xe-138	0.3	153	0.06	3.70E+04	**2,220**	gps/cc // uCi/cc
	0.3	242	0.04	3.70E+04	**1,480**	gps/cc // uCi/cc
	0.3	258	0.32	3.70E+04	**11,840**	gps/cc // uCi/cc
	0.3	396	0.06	3.70E+04	**2,220**	gps/cc // uCi/cc
	0.3	401	0.02	3.70E+04	**740**	gps/cc // uCi/cc
	0.3	434	0.2	3.70E+04	**7,400**	gps/cc // uCi/cc
	0.3	1,114	0.01	3.70E+04	**370**	gps/cc // uCi/cc
	0.3	1,768	0.17	3.70E+04	**6,290**	gps/cc // uCi/cc
	0.3	1,851	0.01	3.70E+04	**370**	gps/cc // uCi/cc
	0.3	2,005	0.05	3.70E+04	**1,850**	gps/cc // uCi/cc
	0.3	2,016	0.12	3.70E+04	**4,440**	gps/cc // uCi/cc

Calculate the isotopic <u>fractions</u>

- We just calculated the (# of gps_{ge}/cc) // (μCi_i /cc) **<u>of each isotope</u>** (i) at each of 60 energies (ge)
- Next step, we calculate the (# of gps_{ge} / cc) // (μCi/cc) **<u>of the mix</u>**
- **= isotope fraction of mix * # of gps_{ge}/cc // µCi/cc**

Isotopic Fractions

- The isotopic fractions change at each time step
- Time steps; e.g., T = 0 hr, T= 1 hr, T = 2 hr, T = 4 hr, T = 8 hr, T= 12 hr, T = 24 hr, T= 7 days, T = 30 days
- For each time step, calculate each isotope's fraction of the mix
- This takes several Excel calculations!

Calculating Isotopic Fractions
Core Melt

- We need to calculate noble gas isotopic fractions
- For example:
  - At T = 0 hrs, we have higher fractions of shorter-lived, with higher energy gamma isotopes
  - At T = 12 hours, we have higher fractions of longer-lived isotopes, with medium energy photons, and lower fractions of short-lived isotopes
  - At T = 30 days, we expect mostly Xe-133 and Kr-85

Example: Calculate Isotopic Fraction of Mix

Core Melt

		Activity (Curies)			Core Melt T= 0 hrs			Core Melt T= 1 hr
	Half-life (hours)	FSAR Table 15A-2	Activity Remaining	Isotope's Fraction of its original activity Remaining	Isotope's Fraction of the mix	Activity Remaining	Isotope's Fraction of its original activity Remaining	Isotope's Fraction of the mix
Kr-83m	1.9	9.24E+06	9.24E+06	1.00	0.020	6.42E+06	0.694	0.022
Kr-85m	4.5	1.93E+07	1.93E+07	1.00	0.041	1.65E+07	0.857	0.058
Kr-85	94000	**9.32E+05**	9.32E+05	1.00	**0.002**	9.32E+05	1.000	**0.003**
Kr-87	1.3	3.69E+07	3.69E+07	1.00	0.079	2.17E+07	0.587	0.075
Kr-88	2.8	5.18E+07	5.18E+07	1.00	0.111	4.04E+07	0.781	0.141
Xe-131m	288	8.59E+05	8.59E+05	1.00	0.002	8.57E+05	0.998	0.003
Xe-133m	55	4.68E+06	4.68E+06	1.00	0.010	4.62E+06	0.987	0.016
Xe-133	127	**1.51E+08**	1.51E+08	1.00	**0.324**	1.50E+08	0.995	**0.523**
Xe-135m	0.25	3.08E+07	3.08E+07	1.00	0.066	1.93E+06	0.063	0.007
Xe-135	9.2	3.31E+07	3.31E+07	1.00	0.071	3.07E+07	0.927	0.107
Xe-138	0.3	1.28E+08	1.28E+08	1.00	0.274	1.27E+07	0.099	0.044
Total		**4.67E+08**	**4.67E+08**		1.0	**2.87E+08**		1.0

Calculate Isotopic Fraction of Mix

Core Melt

	Core Melt			Core Melt			Core Melt		
		T= 2 hr			T= 4 hr			T= 8 hr	
	Activity Remaining	Isotope's Fraction of its original activity Remaining	Isotope's Fraction of the mix	Activity Remaining	Isotope's Fraction of its original activity Remaining	Isotope's Fraction of the mix	Activity Remaining	Isotope's Fraction of its original activity Remaining	Isotope's Fraction of the mix
Kr-83m	4.46E+06	0.482	0.018	2.15E+06	0.232	0.010	4.99E+05	0.054	0.003
Kr-85m	1.42E+07	0.735	0.057	1.04E+07	0.540	0.049	5.63E+06	0.292	0.031
Kr-85	9.32E+05	1.000	**0.004**	9.32E+05	1.000	**0.004**	9.32E+05	1.000	**0.005**
Kr-87	1.27E+07	0.344	0.051	4.37E+06	0.119	0.020	5.19E+05	0.014	0.003
Kr-88	3.16E+07	0.610	0.127	1.92E+07	0.372	0.090	7.15E+06	0.138	0.039
Xe-131m	8.55E+05	0.995	0.003	8.51E+05	0.990	0.004	8.43E+05	0.981	0.005
Xe-133m	4.56E+06	0.975	0.018	4.45E+06	0.951	0.021	4.23E+06	0.904	0.023
Xe-133	1.49E+08	0.989	**0.601**	1.48E+08	0.978	**0.688**	1.45E+08	0.957	**0.792**
Xe-135m	1.20E+05	0.004	0.000	4.71E+02	0.000	0.000	7.21E-03	0.000	0.000
Xe-135	2.85E+07	0.860	0.115	2.45E+07	0.740	0.114	1.81E+07	0.547	0.099
Xe-138	1.26E+06	0.010	0.005	1.24E+04	0.000	0.000	1.21E+00	0.000	0.000
Total	**2.48E+08**		1.0	**2.15E+08**		1.0	**1.82E+08**		1.000

Calculate Isotopic Fraction of Mix

Core Melt

	Core Melt T= 12 hr			Core Melt T= 24 hr			Core Melt T= 48 hr		
	Activity Remaining	Isotope's Fraction of its original activity Remaining	Isotope's Fraction of the mix	Activity Remaining	Isotope's Fraction of its original activity Remaining	Isotope's Fraction of the mix	Activity Remaining	Isotope's Fraction of its original activity Remaining	Isotope's Fraction of the mix
Kr-83m	1.16E+05	0.013	0.001	1.46E+03	0.000	0.000	2.30E-01	0.000	0.000
Kr-85m	3.04E+06	0.158	0.018	4.79E+05	0.025	0.003	1.19E+04	0.001	0.000
Kr-85	9.32E+05	1.000	**0.006**	9.32E+05	1.000	**0.006**	9.32E+05	1.000	**0.008**
Kr-87	6.15E+04	0.002	0.000	1.03E+02	0.000	0.000	2.85E-04	0.000	0.000
Kr-88	2.66E+06	0.051	0.016	1.36E+05	0.003	0.001	3.59E+02	0.000	0.000
Xe-131m	8.35E+05	0.972	0.005	8.11E+05	0.944	0.006	7.65E+05	0.891	0.006
Xe-133m	4.02E+06	0.860	0.024	3.46E+06	0.739	0.024	2.56E+06	0.546	0.021
Xe-133	1.41E+08	0.937	**0.849**	1.32E+08	0.877	**0.922**	1.16E+08	0.770	**0.958**
Xe-135m	1.10E-07	0.000	0.000	3.94E-22	0.000	0.000	5.05E-51	0.000	0.000
Xe-135	1.34E+07	0.405	0.081	5.43E+06	0.164	0.038	8.90E+05	0.027	0.007
Xe-138	1.17E-04	0.000	0.000	1.07E-16	0.000	0.000	8.97E-41	0.000	0.000
Total	**1.66E+08**		1.0	**1.44E+08**		1.0	1.21E+08		1.0

Calculate Isotopic Fraction of Mix

Core Melt

		Core Melt				Core Melt		
		T= 10 days (240 hrs)				T= 30 days (720 hrs)		
	Half-life (hours)	Activity Remaining	Isotope's Fraction of its original activity Remaining	Isotope's Fraction of the mix		Activity Remaining	Isotope's Fraction of its original activity Remaining	Isotope's Fraction of the mix
Kr-83m	1.9	8.89E-32	0.000	0.000		8.23E-108	0.000	0.000
Kr-85m	4.5	1.71E-09	0.000	0.000		1.35E-41	0.000	0.000
Kr-85	94000	9.30E+05	0.998	**0.022**		9.27E+05	0.995	**0.229**
Kr-87	1.3	1.01E-48	0.000	0.000		7.55E-160	0.000	0.000
Kr-88	2.8	8.26E-19	0.000	0.000		2.10E-70	0.000	0.000
Xe-131m	288	4.82E+05	0.561	0.011		1.52E+05	0.177	0.038
Xe-133m	55	2.27E+05	0.049	0.005		5.37E+02	0.000	0.000
Xe-133	127	4.08E+07	0.270	**0.961**		2.97E+06	0.020	**0.733**
Xe-135m	0.25	3.64E-282	0.000	0.000		0.00E+00	0.000	0.000
Xe-135	9.2	4.66E-01	0.000	0.000		9.25E-17	0.000	0.000
Xe-138	0.3	2.16E-233	0.000	0.000		0.00E+00	0	0.000
Total		**4.24E+07**		1.0		**4.05E+06**		1.0

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Mix Fractions (%)

(Core Melt)

	Half-Life	T = 0	T= 1	T=2	T=4	T=8	T=12	T=24	T=48	T=10 day	T = 30 days
Kr-83m	1.9	2%	2%	2%	1%	0%	0%	0%	0%	0%	0%
Kr-85m	4.5	4%	6%	6%	5%	3%	2%	0%	0%	0%	0%
Kr-85	94000	0%	0%	0%	0%	1%	1%	1%	1%	2%	23%
Kr-87	1.3	8%	8%	5%	2%	0%	0%	0%	0%	0%	0%
Kr-88	2.8	11%	14%	13%	9%	4%	2%	0%	0%	0%	0%
Xe-131m	288	0%	0%	0%	0%	0%	1%	1%	1%	1%	4%
Xe-133m	55	1%	2%	2%	2%	2%	2%	2%	2%	1%	0%
Xe-133	127	32%	52%	60%	69%	79%	85%	92%	96%	96%	73%
Xe-135m	0.25	7%	1%	0%	0%	0%	0%	0%	0%	0%	0%
Xe-135	9.2	7%	11%	11%	11%	10%	8%	4%	1%	0%	0%
Xe-138	0.3	27%	4%	1%	0%	0%	0%	0%	0%	0%	0%
Total		100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

	Half-life	T= 0 hr	T= 1 hr	T= 2 hr	T = 4 hr	T = 8 hr	T = 12 hr	T=24	T = 48	T = 7 days	= 30 days
Kr-85	94000	0.2%	0.3%	0.4%	0.4%	0.5%	0.6%	0.6%	0.8%	2.2%	22.9%
Xe-133	127	32.4%	52.3%	60.1%	68.8%	79.2%	84.9%	92.2%	95.8%	96.1%	73.3%
Xe-135	9.2	7.1%	10.7%	11.5%	11.4%	9.9%	8.1%	3.8%	0.7%	0.0%	0.0%

Calculating gps/cc //µCi/cc of mix for each energy for each isotope

(Core melt)

- We now know (for each time step):
  - ✓ Each isotope's fraction of a 1 µCi mix of isotopes
  - ✓ The number of gps_{ge}/cc in a 1 µCi/cc of each isotope
- For a 1 µCi/cc mix of isotopes, we can now calculate the number of gps/cc at each energy

= isotope's fraction * **# gps_{ge}/cc //1 µCi/cc of each isotope**

gps/cc //μCi/cc$_{mix}$ at T = 0
(Core melt)

	Half Life (hours)	Gamma energy (keV)	gammas per sec per cc per uCi/cc of each isotope	Core Melt T = 0 isotope's fraction of 1 uCi/cc total mix @ T = 0 hr	T = 0 gammas per sec per cc per uCi/cc of the mix T = 0 hr
Kr-83m	1.9	9	3330	0.020	**66**
Kr-85m	4.5	150	27750	0.041	**1,148**
	4.5	305	5180	0.041	**214**
Kr-85	**94,000**	**514**	**148**	**0.002**	**0**
Kr-87	1.3	403	18500	0.079	**1,463**
	1.3	674	740	0.079	**59**
	1.3	845	2590	0.079	**205**
	1.3	1,175	370	0.079	**29**
	1.3	1,740	740	0.079	**59**
	1.3	2,010	1110	0.079	**88**

gps/cc // µCi/cc at T = 0

(Core melt)

	Half Life (hours)	Gamma energy (keV)	gammas per sec per cc per uCi/cc of each isotope	Core Melt T = 0 isotope's fraction of 1 uCi/cc total mix @ T = 0 hr	T = 0 gammas per sec per cc per uCi/cc of the mix T = 0 hr
Kr-88	2.8	166	1110	0.111	**123**
	2.8	196	9620	0.111	**1,068**
	2.8	362	740	0.111	**82**
	2.8	835	4810	0.111	**534**
	2.8	986	370	0.111	**41**
	2.8	1,000	740	0.111	**82**
	2.8	1,140	370	0.111	**41**
	2.8	1,180	370	0.111	**41**
	2.8	1,530	4070	0.111	**452**

gps/cc // µCi/cc at T = 0

(Core melt)

	Half Life (hours)	Gamma energy (keV)	gps/cc / uCi/cc of each isotope	Core Melt T = 0 isotope's fraction of 1 uCi/cc total mix @ T = 0 hr	T = 0 gps/cc 1 uCi/cc of mix T = 0 hr
Kr-89	0.053	197	740	0.000	0.000
	0.053	221	7400	0.000	0.000
	0.053	345	370	0.000	0.000
	0.053	369	370	0.000	0.000
	0.053	411	1110	0.000	0.000
	0.053	498	2960	0.000	0.000
	0.053	586	6290	0.000	0.000
	0.053	696	740	0.000	0.000
	0.053	738	1480	0.000	0.000
	0.053	776	370	0.000	0.000
	0.053	836	370	0.000	0.000
	0.053	867	2220	0.000	0.000
	0.053	904	2590	0.000	0.000
	0.053	1,108	1110	0.000	0.000
	0.053	1,117	740	0.000	0.000
	0.053	1,274	370	0.000	0.000
	0.053	1,324	1110	0.000	0.000
	0.053	1,473	2590	0.000	0.000
	0.053	1,501	370	0.000	0.000
	0.053	1,532	2960	0.000	0.000
	0.053	1,694	1480	0.000	0.000
	0.053	1,903	370	0.000	0.000

gps/cc // µCi/cc at T = 0
(Core melt)

	Half Life (hours)	Gamma energy (keV)	gammas per sec per cc per uCi/cc of each isotope	Core Melt T = 0 isotope's fraction of 1 uCi/cc total mix @ T = 0 hr	T = 0 gammas per sec per cc per uCi/cc of the mix T = 0 hr
Xe-131m	288	164	740	0.002	1
Xe-133m	55	223	3,700	0.010	37
Xe-133	**127**	**81**	**13,320**	**0.324**	**4,310**
Xe-135m	0.25	527	29,970	0.066	1,978
Xe-135	9.2	250	33,300	0.071	2,362
	9.2	608	1,110	0.071	79
Xe-137	0.065	455	11,470	0.000	0
	0.065	1,491	370	0.000	0

gps/cc // µCi/cc at T = 0
(Core melt)

	Half Life (hours)	Gamma energy (keV)	gammas per sec per cc per uCi/cc of each isotope	Core Melt T = 0 isotope's fraction of 1 uCi/cc total mix @ T = 0 hr	T = 0 gammas per sec per cc per uCi/cc of the mix T = 0 hr
Xe-138	0.3	153	2,220	0.274	**609**
	0.3	242	1,480	0.274	**406**
	0.3	258	11,840	0.274	**3,248**
	0.3	396	2,220	0.274	**609**
	0.3	401	740	0.274	**203**
	0.3	434	7,400	0.274	**2,030**
	0.3	1,114	370	0.274	**101**
	0.3	1,768	6,290	0.274	**1,725**
	0.3	1,851	370	0.274	**101**
	0.3	2,005	1,850	0.274	**507**
	0.3	2,016	4,440	0.274	**1,218**
					25,322

Calculate Each Gamma Energy's Contribution to the IRFs

- ✓ We started with 1 µCi/cc of a total mix of nuclides
- ✓ At each of the 60 gamma energies, we calculated the # of gps/cc at each gamma energy in a 1 µCi/cc mix of isotopes
- For each gamma energy, we now we multiply the # gps/cc // µCi/cc mix by their ERFs (cpm //gps/cc)
- = (**# ~~gps/cc~~ // µCi/cc of a mix) X (# cpm // ~~gps/cc~~)**

= # of cpm // µCi/cc of a mix

IRF Contributions @ T = 0

Kr-83m, Kr-85m, Kr-85, Kr-87

Core Melt					
Nuclide	Half-Life	Gamma Energy	T = 0 hr gps/cc // uCi/cc of mix	Energy Response Factor (ERF)	Total gamma's contribution cpm // uCi/cc mix
Nuclide	(hours)	keV		cpm//gps/cc	
Kr-83m	1.9	9	66	0	-7
Kr-85m	4.5	150	1,148	2	2,637
	4.5	305	214	5	1,057
Kr-85	94,000	514	0	8	3
Kr-87	1.3	403	1,463	7	9,653
	1.3	674	59	11	656
	1.3	845	205	14	2,890
	1.3	1,175	29	20	577
	1.3	1,740	59	29	1,716
	1.3	2,010	88	34	2,977

IRF Contributions @ T = 0

Kr-88

Core Melt					
Nuclide	Half-Life	Gamma Energy	T = 0 hr gps/cc // uCi/cc of mix	Energy Response Factor (ERF)	Total gamma's contribution cpm // uCi/cc mix
Nuclide	(hours)	keV		cpm//gps/cc	
Kr-88	2.8	166	123	3	317
	2.8	196	1,068	3	3,288
	2.8	362	82	6	485
	2.8	835	534	14	7,445
	2.8	986	41	17	678
	2.8	1,000	82	17	1,376
	2.8	1,140	41	19	786
	2.8	1,180	41	20	814
	2.8	1,530	452	26	11,638

IRF Contributions @ T = 0

Xe-131m, Xe-133m, Xe-133, Xe-135m, Xe-135, Xe-137

Core Melt					
Nuclide	Half-Life	Gamma Energy	T = 0 hr gps/cc // uCi/cc of mix	Energy Response Factor (ERF)	Total gamma's contribution cpm // uCi/cc mix
Nuclide	(hours)	keV		cpm//gps/cc	
Xe-131m	288	164	1	3	3
Xe-133m	55	223	37	4	131
Xe-133	127	81	4,310	1	2,328
Xe-135m	0.25	527	1,978	9	17,223
Xe-135	9.2	250	2,362	4	9,442
	9.2	608	79	10	794
Xe-137	0.065	455	0	7	0
	0.065	1,491	0	25	0

IRF Contributions @ T = 0

Xe-138

Core Melt					
Nuclide	Half-Life	Gamma Energy	T = 0 hr gps/cc // uCi/cc of mix	Energy Response Factor (ERF)	Total gamma's contribution cpm // uCi/cc mix
Nuclide	(hours)	keV		cpm//gps/cc	
Xe-138	0.3	153	609	2	1,430
	0.3	242	406	4	1,568
	0.3	258	3,248	4	13,424
	0.3	396	609	6	3,946
	0.3	401	203	7	1,333
	0.3	434	2,030	7	14,464
	0.3	1,114	101	19	1,897
	0.3	1,768	1,725	30	51,424
	0.3	1,851	101	31	3,168
	0.3	2,005	507	34	17,169
	0.3	2,016	1,218	34	41,434
		Total	25,322		230,163 cpm// uCi/cc mix T = 0

IRF @ T = 1 hr

Nuclide Nuclide	Half-Life (hours)	Gamma Energy keV	Core Melt T = 1 hr gps/cc // uCi/cc of mix	Energy Response Factor (ERF) cpm//gps/cc	Each gamma's contribution cpm // uCi/cc mix
Xe-138	0.3	153	98	2	231
	0.3	242	66	4	253
	0.3	258	524	4	2,167
	0.3	396	98	6	637
	0.3	401	33	7	215
	0.3	434	328	7	2,334
	0.3	1,114	16	19	306
	0.3	1,768	278	30	8,300
	0.3	1,851	16	31	511
	0.3	2,005	82	34	2,771
	0.3	2,016	197	34	6,687
		Total	**19,567**		**102,401 cpm// uCi/cc mix T = 1 hr**

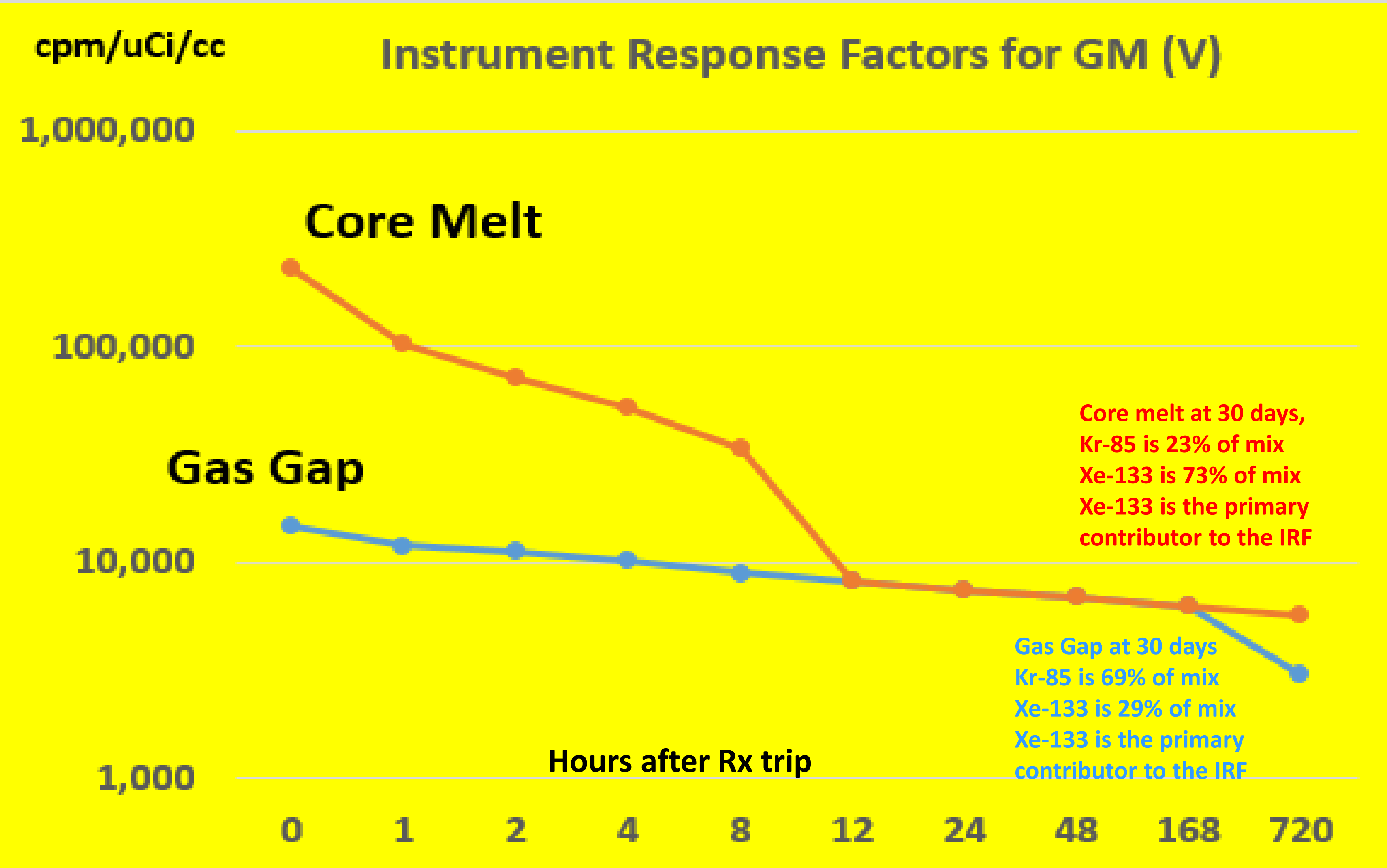
IRF @ T = 2 hrs and 4 hours

Nuclide	Half-Life	Gamma Energy	Core Melt T = 2 hr gps/cc // uCi/cc of mix	Energy Response Factor (ERF) gps/cc // uCi/cc of mix	Each gamma's contribution cpm // uCi/cc mix	Core Melt T = 4 hr gps/cc // uCi/cc of mix	Energy Response Factor (ERF) gps/cc // uCi/cc of mix	Each gamma's contribution cpm // uCi/cc mix
Nuclide	(hours)	keV						
	0.3	242	8	4	29	0	4	0
	0.3	258	60	4	248	1	4	3
	0.3	396	11	6	73	0	6	1
	0.3	401	4	7	25	0	7	0
	0.3	434	38	7	268	0	7	3
	0.3	1,114	2	19	35	0	19	0
	0.3	1,768	32	30	951	0	30	11
	0.3	1,851	2	31	59	0	31	1
	0.3	2,005	9	34	318	0	34	4
	0.3	2,016	23	34	767	0	34	9
		Total	18,224		71,773 cpm// uCi/cc mix T = 2 hr	17,248		52,346 cpm// uCi/cc mix T = 4 hr

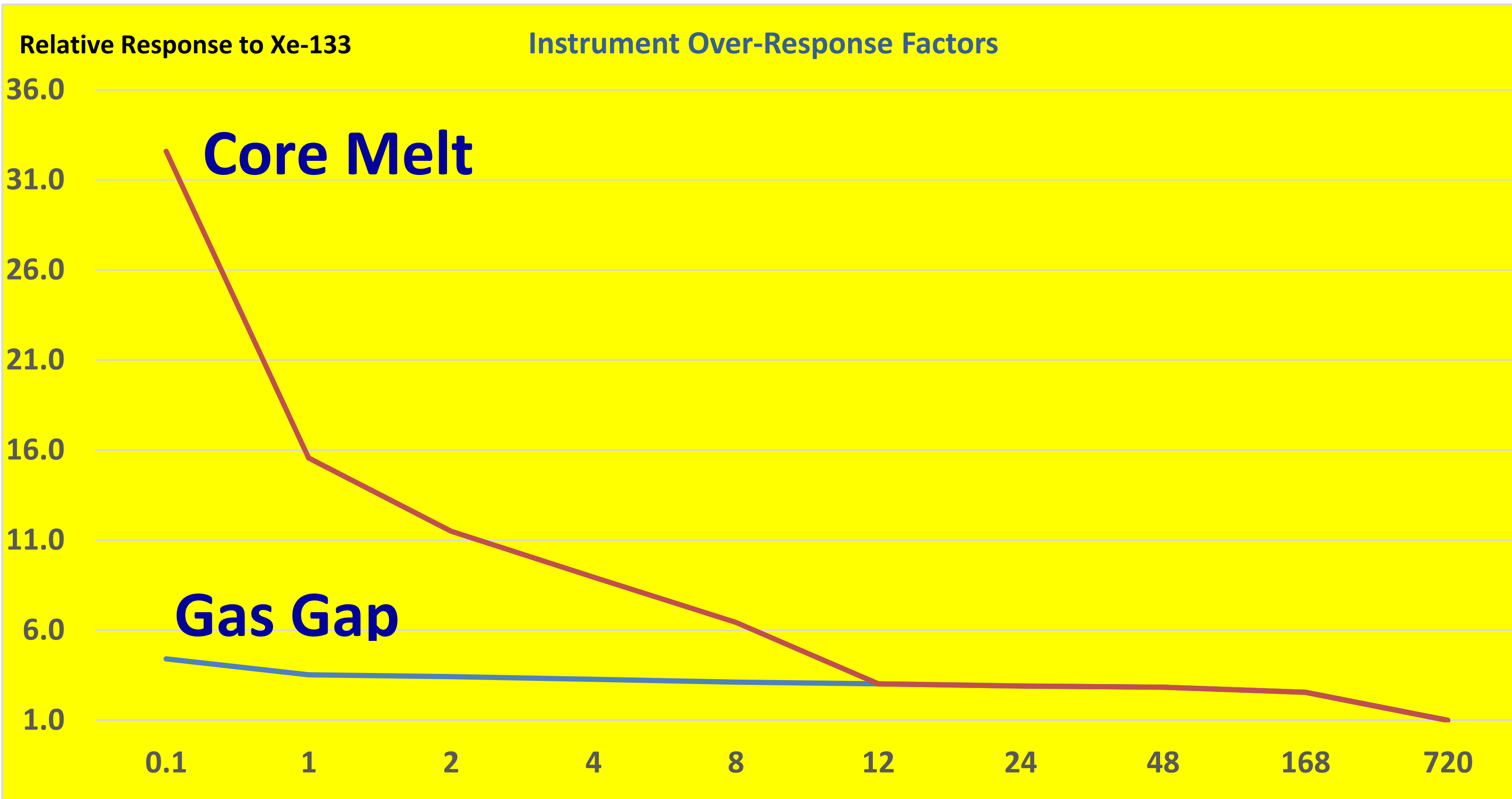
IFRs GM (V)

	Xe-133	Gas Gap	Core Melt	Gas Gap	Core Melt
Time (hours)	cpm// uCi/cc Xe-133	cpm// uCi/cc mix	cpm// uCi/cc mix	Relative Response to Xe-133	Relative Response to Xe-133
0	7193	14,632	230,163	2.0	32.0
1	7193	11,910	102,401	1.7	14.2
2	7193	11,131	71,773	1.5	10.0
4	7193	10,066	52,346	1.4	7.3
8	7193	8,877	33,233	1.2	4.6
12	7193	8,238	8,238	1.1	1.1
24	7193	7,399	7,399	1.0	1.0
48	7193	6,937	6,937	1.0	1.0
168	7193	6,252	6,252	0.9	0.9
720	7193	2,986	5,631	0.4	0.8

Core Melt IRFs



GM Instrument Relative Response Factors compared to calibration based on Xe-133



Assumptions & Limitations

- Assumed ideal conditions
  - There is no impact from loss of AC power, degraded voltage, high temp & humidity, monitor saturation
  - There is no iodine spiking
  - No background interference from adjacent sample lines or filter banks

Note: for a PWR Reactor Building with 100% NG and 25% iodine release into containment, at T=0 , the shine through containment 3' walls is ≈ 30 R/h

Assumptions & Limitations

- There is:
  - no contamination of sample lines or chambers
    - Important contaminants are
      - Kr-88 decays to daughter Rb-88 particulate (18 min half life)
      - Xe-138 decay to Cs-138 particulate (32 min half life)
  - no dose rate from HEPA/Charcoal filter banks
  - no impact from changes in temperature, humidity,
  - A/C power is available or stable voltage

Conclusions

- Detector response (in cpm or mR/hr) is highly dependent on incoming photon energy
- The incoming photon energy spectrum decreases rapidly after an accident
- Time-dependent instrument response factors are needed to convert detector response from cpm to uCi/cc of the mix

Questions