INTERNAL DOSIMETRY
AT NUCLEAR POWER PLANTS

Fission and Activation Products

Actinides

Case Studies

Learning Objectives

- Identify radionuclides of concern at nuclear power plants
- Identify appropriate bioassay methods
- Analyze two case studies

Exposure Conditions

- Usually external dose is more of issue than internal dose
- Activation products such as Co-60 exist in corrosion around pipe seals and similar locations
- Tritium always around, especially at BWRs
- Fission products mostly contained in fuel rods, except for cases of fuel failure and “tramp” U
- Failed fuel releases volatile nuclides such as Cs-137 and I-131
- “Control β-γ and you control α”…usually

Fission and Activation Products

- Beta-gamma emitters: Cs-137, Co-60, etc.

  In general, in-vivo bioassay is excellent
  typical MDA is <0.1% ALI

- Iodines:

  External thyroid counting fairly easy for gamma-emitters; because of high thyroid doses, air monitoring important

- Tritium:

  Sensitive bioassay (MDA$\rightarrow$ CEDE <1 mrem) air sampling difficult; low dose/unit intake

Co-60

Strong gamma-emitter (1.17, 1.33 MeV, each 100%), 5.7 yr half-life

Easy to detect, MDA for WBC = 0.1 kBq

DCF W inh = 9×10^{-9} Sv/Bq (33 mrem/µCi)

Y inh = 6×10^{-8} Sv/Bq (0.2 rem/µCi)

W ing = 3×10^{-9} Sv/Bq (11 mrem/µCi)

Y ing = 7×10^{-9} Sv/Bq (26 mrem/µCi)

ALI W inh = 6×10^{6} Bq (200 µCi)

Y inh = 1×10^{6} Bq (30 µCi)

W ing = 2×10^{7} Bq (500 µCi)

Y ing = 7×10^{6} Bq (200 µCi)

Co-60 con’t

- Can exist as either Class W or Class Y material
- If process knowledge is inadequate, can distinguish by sequential whole-body counting over a few weeks.
- Because so easy to detect via WBC, frequently serves as a marker for other, harder to detect radionuclides, such as actinides
- Radionuclide ratios determined from analysis of air filters or smears

Tritium

- A ubiquitous contaminant; HTO or T_2O is dosimetrically more significant than T_2 gas because of rapid uptake and exchange with body water; tritiated organic compounds are frequently used in biological research.
- Reference man body water = 43 L, daily water intake is 3.0 L, so biological time constant = 3/43 = 0.0698; Biological half-life T(b) = 0.693/0.0698 = 10 d
- HTO absorbed directly through skin; dose coefficient for inhalation includes this pathway (0.33 intake by skin)

Tritium Dosimetry

- All soft tissue (65 kg) is considered to be uniformly irradiated.
- DCF is 2×10^{-11} Sv/Bq (0.006 mrem/µCi)
- MDA for BLS urinalysis = 2000 dpm/L
- Rule of thumb: 1 µCi/L in urine= 100 mrem for samples soon after acute intake
- Treatment is by forcing fluids (water works, but beer is preferred, because alcohol inhibits pituitary secretion of anti-diuretic hormone, which inhibits kidney re-absorption of water)

DOSE IMPLICATIONS OF TRITIUM IN URINE

(1000 dpm/L at 1 day after end of Chronic Exposure of t days duration,
or at t days after an Acute Exposure)

Days since Acute Exposure or Days of Chronic Exposure (t)	ACUTE INHALATION Intake (dpm)	ACUTE INHALATION CEDE (mrem)	CHRONIC INHALATION Intake (dpm)	CHRONIC INHALATION CEDE (mrem)
1	44 500	0.00126	46 100	0.00130
2	47 700	0.00135	47 600	0.00135
3	51 100	0.00145	49 300	0.00140
4	54 800	0.00155	50 900	0.00144
5	58 700	0.00166	52 700	0.00149
6	63 000	0.00178	54 400	0.00154
7	67 200	0.00191	56 200	0.00159
8	72 600	0.00205	58 000	0.00164
9	77 400	0.00220	59 800	0.00170
10	83 400	0.00236	61 800	0.00175
14	110 000	0.00311	69 600	0.00197
21	179 000	0.00506	84 600	0.00240
28	290 000	0.00823	101 000	0.00286
35	472 000	0.0134	119 000	0.00336
42	768 000	0.0218	137 000	0.00389
49	1 250 000	0.0354	157 000	0.00444
56	2 030 000	0.0575	176 000	0.00501
60	2 680 000	0.0760	188 000	0.00534
365	-	-	1 130 000	0.0320

Cs- 137

- Important because of long physical half-life and biological accumulation.
- Uptake is 100%; two retention components:

  10% with 2-d biological half-life and

  90% with 110 d.
- DCF = 8.6×10^{-9} Sv/Bq (0.03 rem/µCi) inhal.

  = 1.4×10^{-8} Sv/Bq (0.05 rem/µCi) ingest.
- ALI = 6 MBq inhalation, 4 MBq ingestion
- MDA for 30 min WBC = 40 Bq (~ 1 nCi)

Cs-137 (con't)

- Cs is a potassium analogue, so is uniformly distributed throughout body (mostly muscle).
- Body burden from global fallout is about 0.3 Bq Cs-137 per g K, or 40 Bq average.
- Excretion of Cs can be enhanced by giving "prussian blue" (ferric ferricyanate), 1-3 g three times a day up to three weeks; inhibits reuptake from GI tract, so reduces biological half-life to 35 d and is well tolerated.

Iodines

- All ALI's (except I-120m, I-128, I-134) are based on non-stochastic limit of 500 mSv CODE to thyroid (w_T = 0.03)
- Volatile, so easily dispersed; treatment is usually blocking with stable KI (325 mg); unblocked thyroid deposition = 25%; KI administered within 1-2 minutes lowers to 2%, after 6 hr lowers to 10%, no effect more than 12 hr after intake; however, daily dose prevents re-uptake of circulating iodide
- MDA in thyroid for photon-emitting isotopes is less than 0.4 Bq

Actinide Dosimetry

- In general, actinides have long physical half-lives and also long biological half-lives; consequently, the CDE is actually delivered over a protracted time
- Most are alpha emitters with little gamma, so low external hazard, high internal; low f_1's.
- With the exception of uranium, actinides deposit in bone and liver; usually ALI is determined by non-stochastic limit for bone surface following inhalation.

Assessing Intake Mode from Sequential Whole-Body Counts

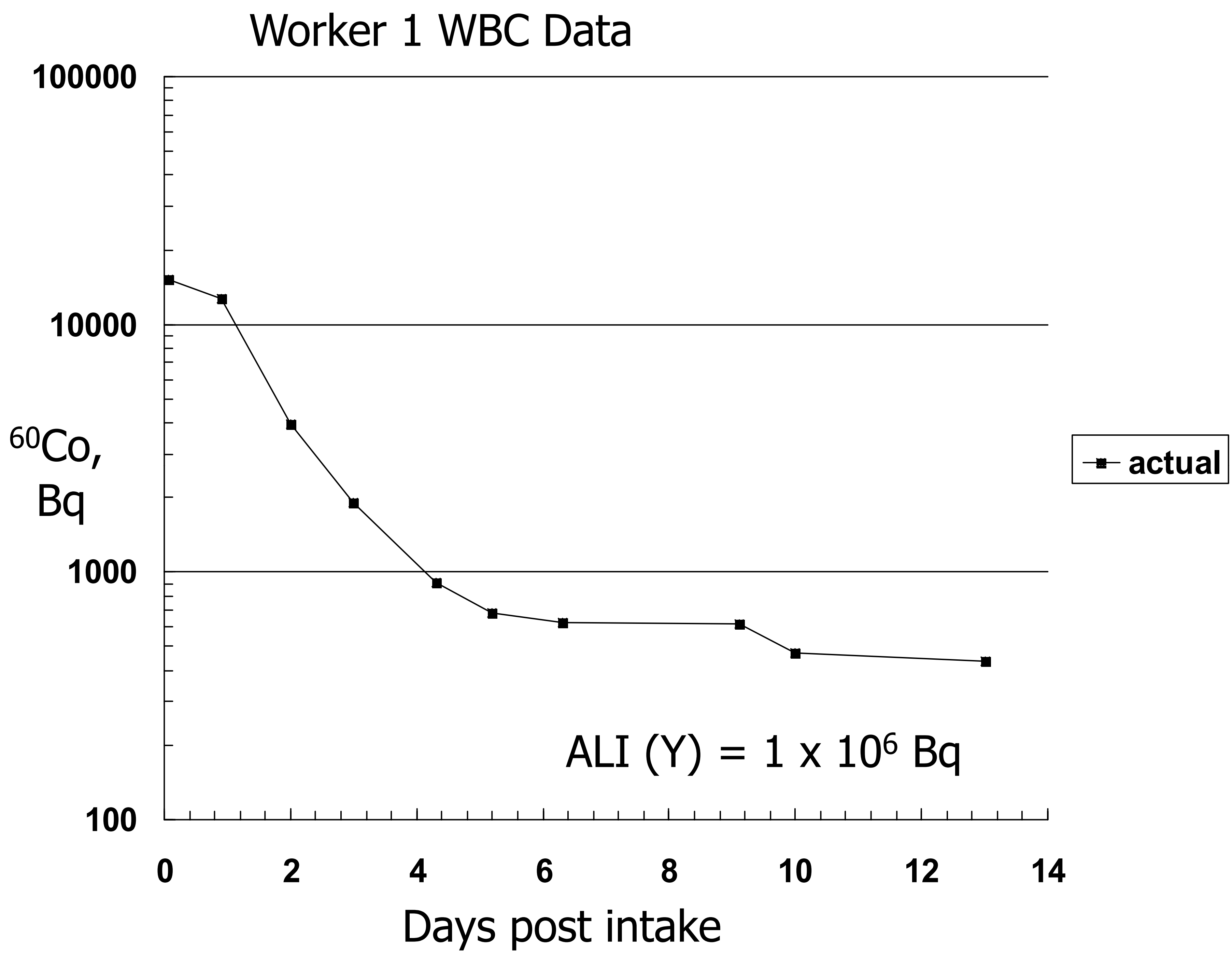
R. E. Toohey, ORISE, Oak Ridge, TN

R. L. Nimitz, USNRC, King of Prussia, PA

R. Pedersen, USNRC, Rockville, MD

Exposure Circumstances

- Two workers removing debris from a fuel transfer canal during a refueling outage
- No respiratory protection or air sampling provided
- Workers found to have facial contamination on exit, and referred for whole-body counts
- Incident is described in NRC information notice number 97-36

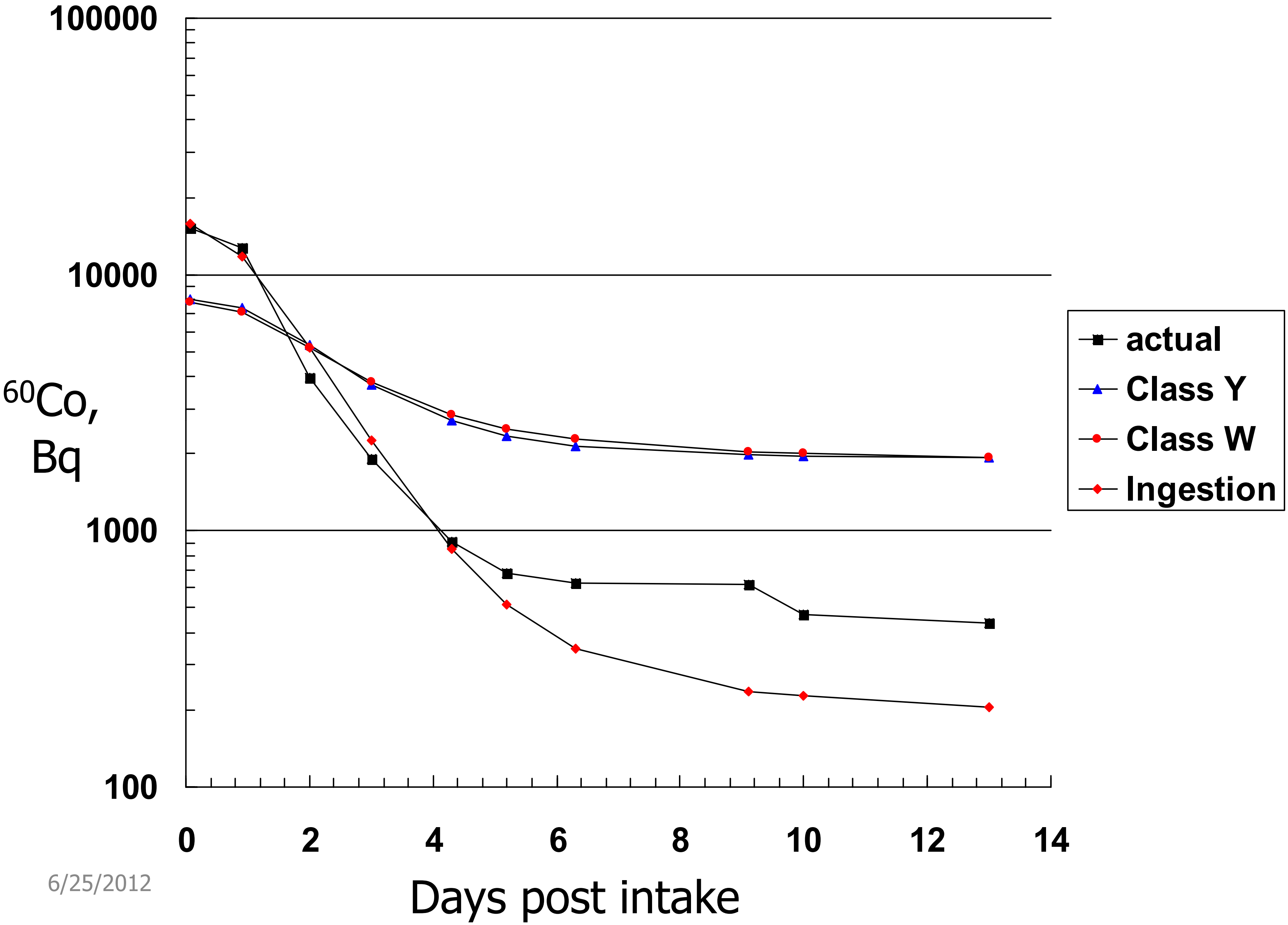


Worker 1 WBC Data
100000
10000
1000
100
^{60}Co, Bq
actual
ALI (Y) = 1 x 10^{6} Bq
0
2
4
6
8
10
12
14
Days post intake

Need for Careful Assessment

- Plant had a history of fuel failure
- Analysis of debris samples showed high α/β activity ratios and various TRU, including ^{238}Pu, $^{239,240}Pu$, ^{241}Am, and ^{244}Cm
- Initial calculation of CDE to bone surfaces exceeded 1 Sv
- Results from fecal samples for TRU were highly variable

Worker 1: Fits to WBC Data



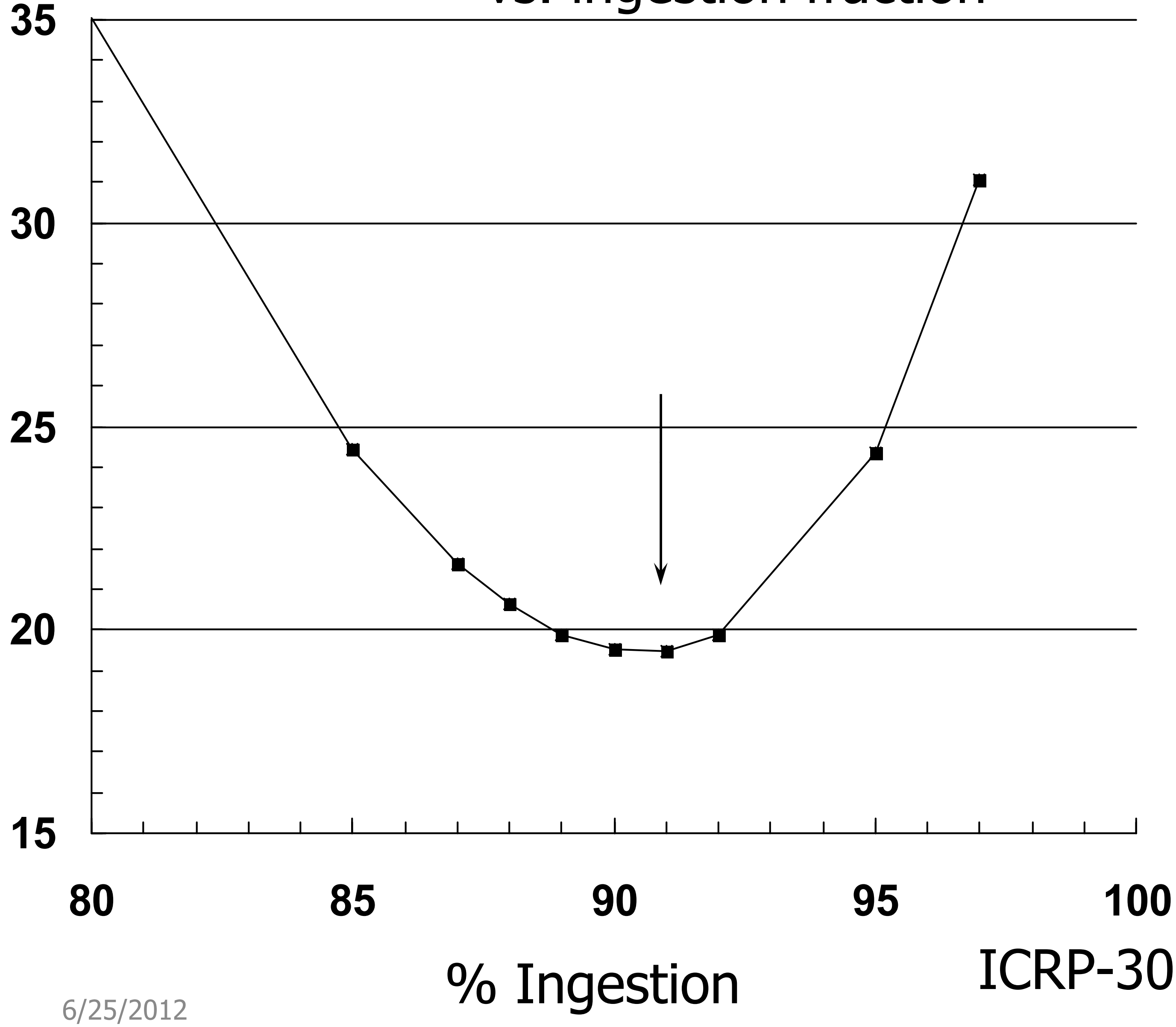
Determining “Best Fit” to data

- Typically in bioassay data analysis, we assume an intake model, and use least squares to determine the best estimate of the intake
- We can also compare intake models, by comparing the sum of squared deviations between predicted and observed values of the bioassay data

Ingestion vs. Inhalation

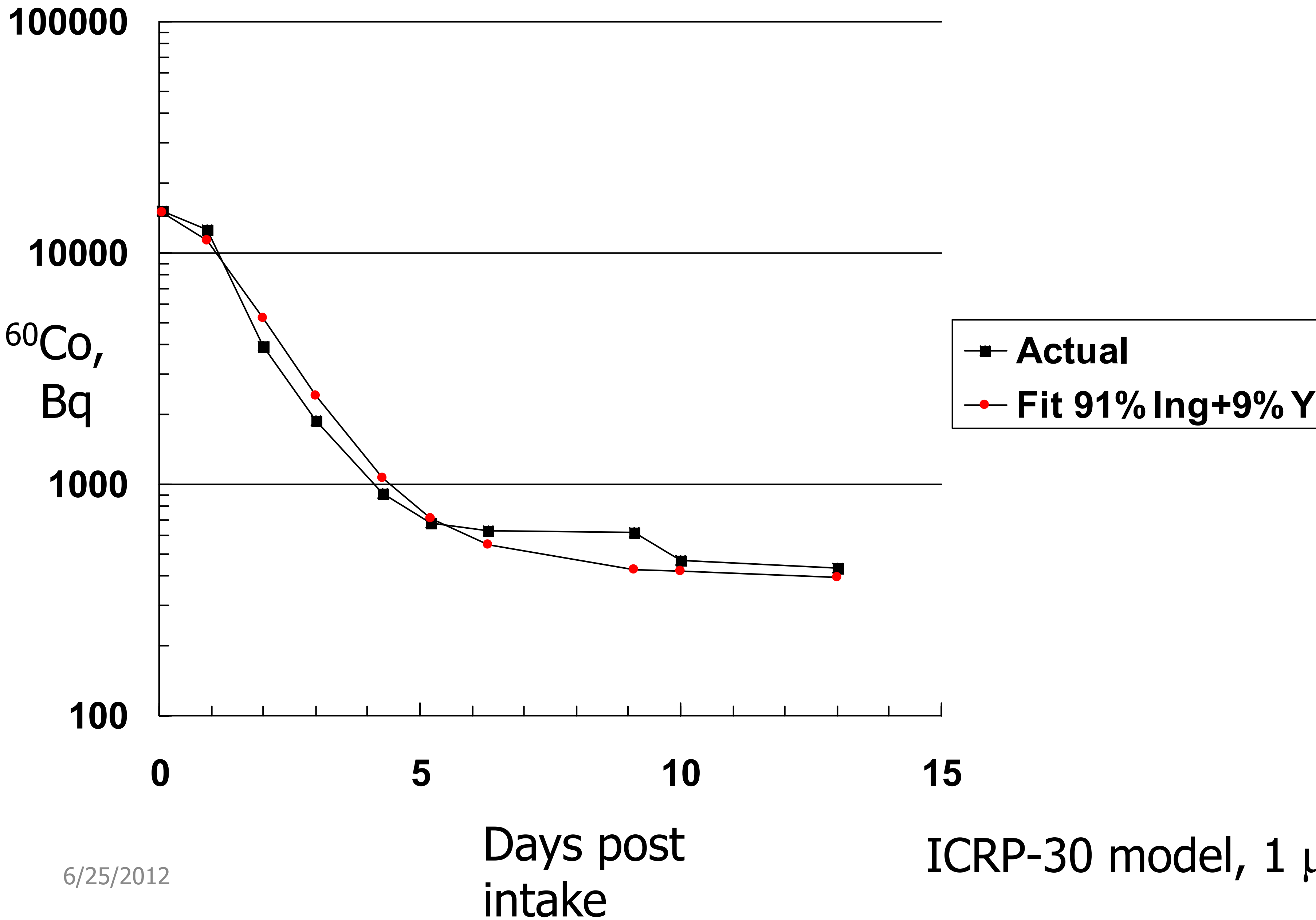
- The first comparison of models involved assuming different fractions of inhalation vs. ingestion, e.g.:
  - 100% inhalation
  - 90% inhalation, 10% ingestion
  - 80% inhalation, 20% ingestion
  - etc., etc., etc.
- Using ICRP 30 models, 1 μ AMAD

Worker 1: Summed square deviations vs. ingestion fraction



ICRP-30 model, 1 μ

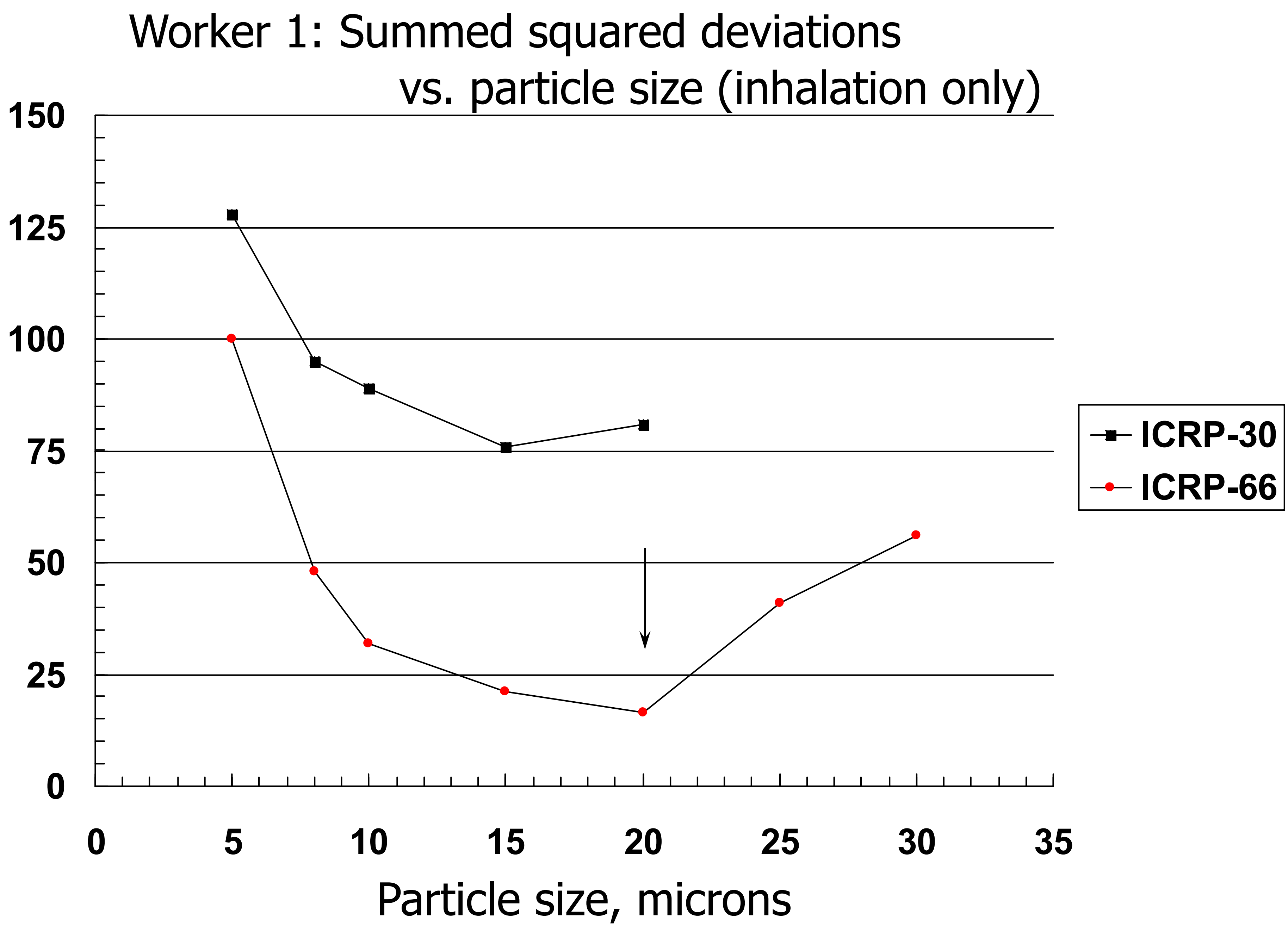
Worker 1: Best fit to WBC Data



ICRP-30 model, 1 μ

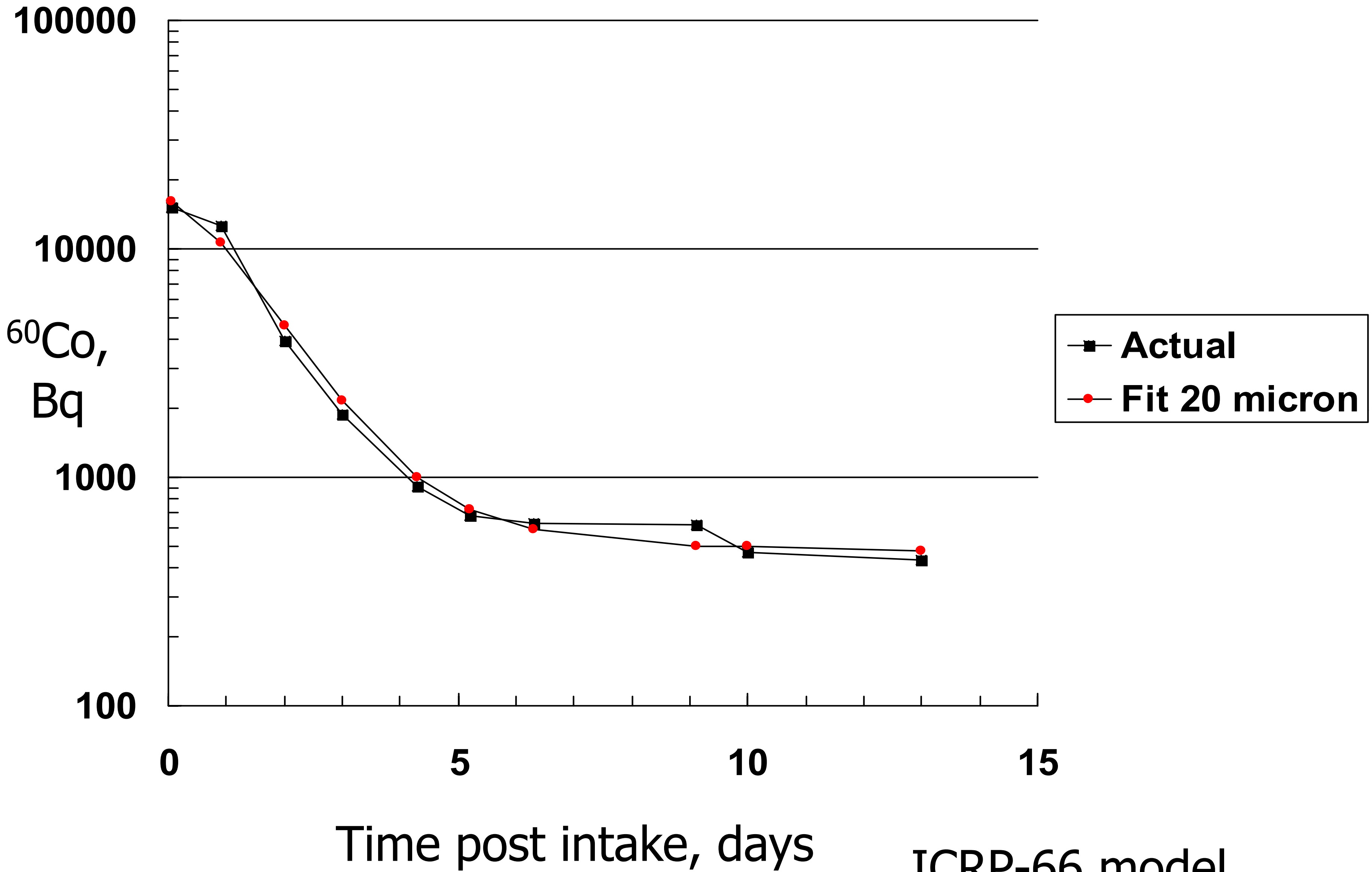
What About Particle Size?

- The combination of inhalation and ingestion could reflect a larger particle size, resulting in greater deposition in the upper respiratory tract, leading to mucociliary clearance and swallowing of inhaled material
- Repeat least squares analysis for 100% inhalation vs. particle size



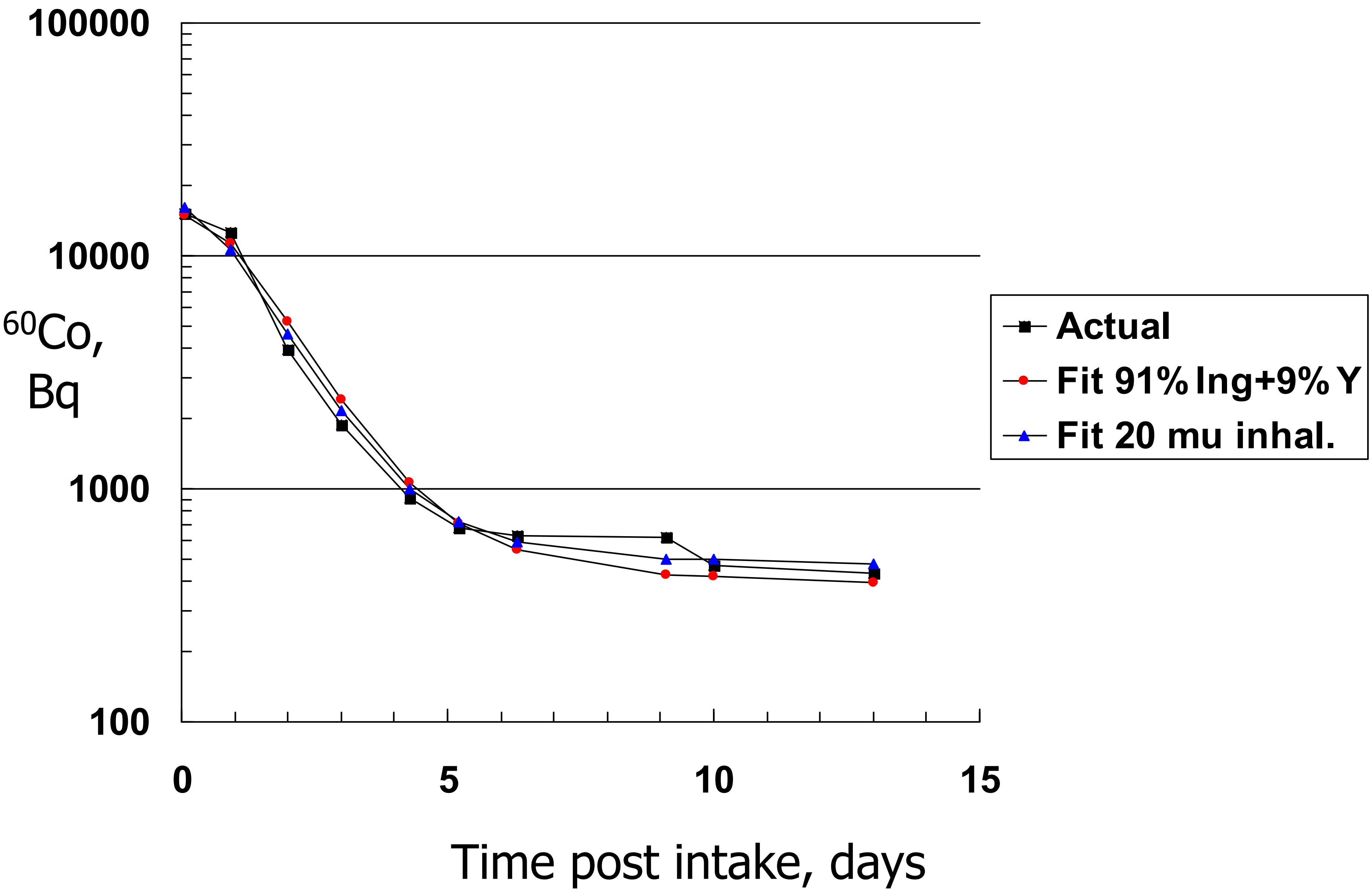
Worker 1: Summed squared deviations
vs. particle size (inhalation only)
150
125
100
75
50
25
0
0
5
10
15
20
25
30
35
ICRP-30
ICRP-66
Particle size, microns

Worker 1: Best fit to WBC data, inhalation only



ICRP-66 model

Worker 1: comparison of intake models



Dose Assessment

- If 1 μ particles, inhalation plus ingestion:

  ^{60}Co intake = 1.4 kBq inh. + 14 kBq ing.

  CEDE = 4.4 mSv; CDE (BS) = 77 mSv

- If 20 μ particles, inhalation only:

  ^{60}Co intake = 400 kBq

  CEDE = 3.4 mSv; CDE (BS) = 59 mSv

- Dose is almost entirely from TRU

Conclusions

- Accurate intake assessment is needed when TRU nuclides are involved
- More complete fecal sampling (especially at early times) would have helped
- Ease of detection of ^{60}Co by WBC makes it useful as a marker radionuclide
- Only definitive way to characterize intake would be by particle size analysis

Alpha Emitter Intakes at NPPs

- Two reactors have been under major refurbishment for five years
- Lay-up of the reactors was in place for many years before this (approximately ten years total)
- Significant decontamination efforts had been conducted prior to refurbishment to improve conditions for working
  - H-3 source term had been reduced
  - Beta gamma contamination levels were low
  - Much work was conducted without respiratory protection
- As contamination ages, ratios decrease and the alpha proportion becomes more significant dosimetrically
- Unaware that Beta to Alpha ratios were now in the range of 7:1, vs. 10,000:1 during operation

Refurbishment Work

- U2 feeder work completed successfully in fall 2009
  - No detection of any beta airborne activity
  - Low beta contamination levels
- Unit 1 commenced at the end of November 2009
  - Same controls used in Unit 2 were used in Unit 1
  - Airborne beta activity detected early
  - Additional controls were placed on work
  - Work tented to enclose activity
  - Further monitoring added
  - Detected alpha contamination

Dose Assessments

- Difficult to assess dose based on limited information
- Prioritized assessment process developed
- Dose estimates based on:
  - Vault access logs that documents all entries for all personnel
  - Air sample results (beta and alpha)
  - Conservative models to determine the hazard levels during work evolution
- All workers in vault assessed for possible exposures:
  - Before building tents for feeder work
  - After tents until the end of feeder work

Significant Challenges

- Lack of familiarity with alpha - not an issue in operating plants so individual knowledge limited
- Large number of people to reach out to
- Large-volume Alpha bioassay analysis available but limited and results not quickly available
- Alpha bioassay analysis process is complicated, therefore dose results not quickly available
- New suppliers required for fecal analysis
- Alpha related work restrictions necessary to ensure sample purity
- Complicated issue to explain and lack of trust
- Several stakeholders

Interim actions

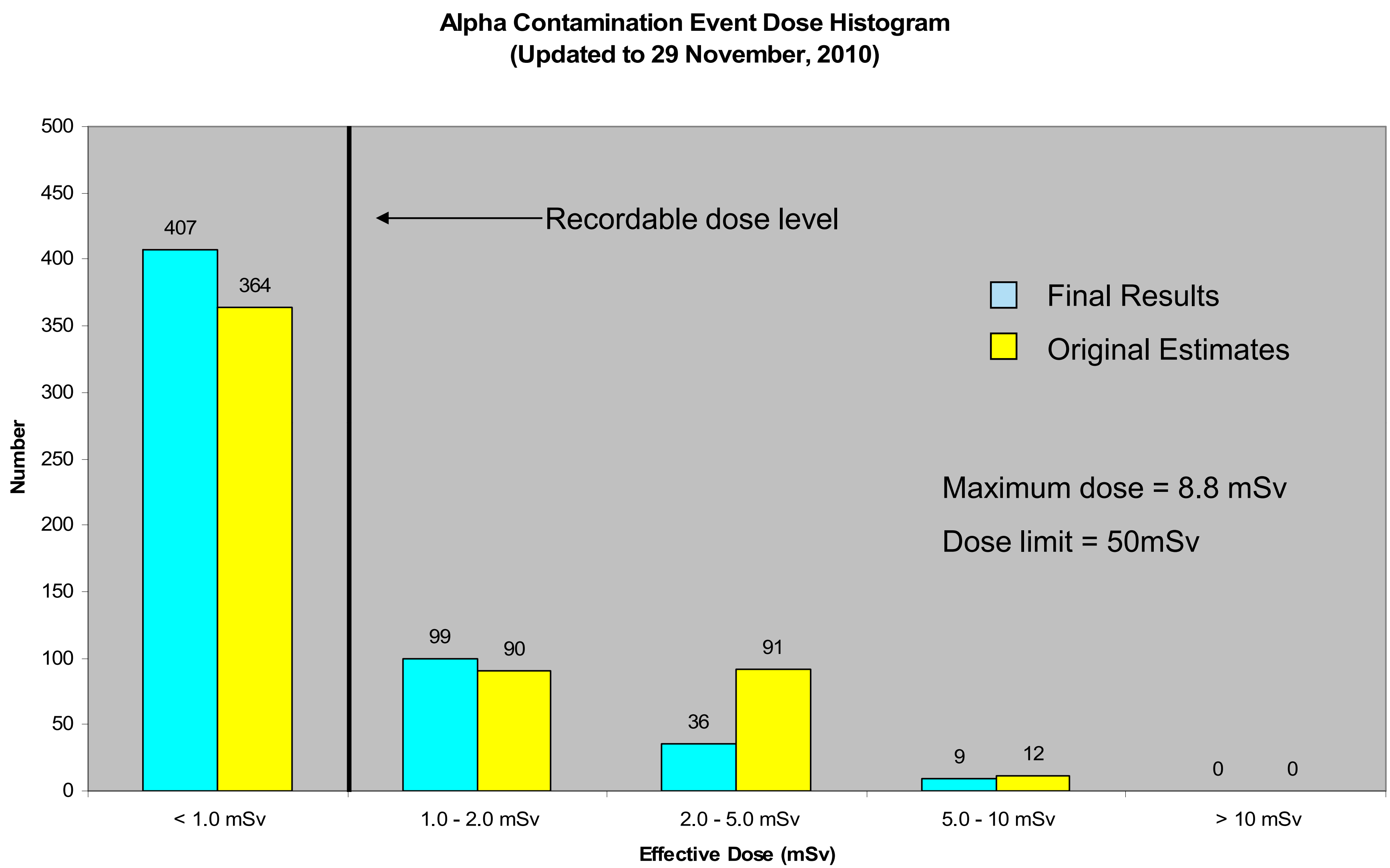
- Alpha monitoring controls were added to U1 and U2 vault for general access:
  - Personal alpha contamination monitors
  - Routine air sample counting for alpha
- Back to Work
  - Staged return to work process developed (all work was suspended for 2 months)
  - Return to work criteria and plan for work in both vaults were established – additional alpha contamination and airborne monitoring and controls included
  - Comprehensive alpha characterisation of systems and areas
- Protocols/procedures developed
  - Work planning criteria and work controls for alpha
  - Alpha monitoring and air sampling protocols
  - Alpha free release standards and protocols
  - Verification waste streams to consider alpha
  - Incident response for alpha, including dosimetry requirements

Summary of Improvements Made

- Improvements initially focused on restart, but now extended to all operating units and fuel handling:
  - New standards for alpha control
  - New RPPE
  - New procedures
  - New training
  - New alpha instrumentation
  - Enhanced air sampling program
  - New alpha dosimetry processes
  - Permits revised for alpha controls
  - Engaged external experts

Bioassay sampling statistics

- 556 people were in the vault during the work period in question
  - Initial estimates indicated up to 193 could require further bioassay testing
- 552 personnel were tested - at least one sample
  - 33 individuals provided multiple samples (average 4 each)
  - 9 individuals remain on ongoing sampling
  - Process of dosimetry has taken 12 months to complete
- Final results confirm initial estimates



Alpha Contamination Event Dose Histogram
(Updated to 29 November, 2010)
Number
500
450
400
350
300
250
200
150
100
50
0
407
364
Recordable dose level
Final Results
Original Estimates
Maximum dose = 8.8 mSv
Dose limit = 50mSv
99
90
36
91
9
12
0
0
< 1.0 mSv
1.0 - 2.0 mSv
2.0 - 5.0 mSv
5.0 - 10 mSv
> 10 mSv
Effective Dose (mSv)

Future Activities

- Extent of condition work expanded to identify any historical doses
  - Workers in restart from previous work
  - Workers in fuel handling
  - Workers from other facilities
- 1008 individuals will be sampled
  - To date 700 samples complete
- Work is ongoing to assess doses to all personnel
  - Approximately ten percent of those sampled indicated potential intakes
  - Challenge is sensitivity of fecal historically, lack of lower threshold urinalysis capability and volume of personnel
  - Working with industry to create new bioassay laboratory
  - Ongoing, routine dosimetry practices to be defined

Summary

- Significant radiological event with large number of workers exposed to alpha and large consequences for company
- Ongoing work to assess historical impact of alpha and continue to identify any other issues
- Major contributors were lack of understanding of characterization implications and reliance on old assumptions
- Extremely vital to have accurate technical basis, believe instruments when indicating an abnormal condition and challenge assumptions