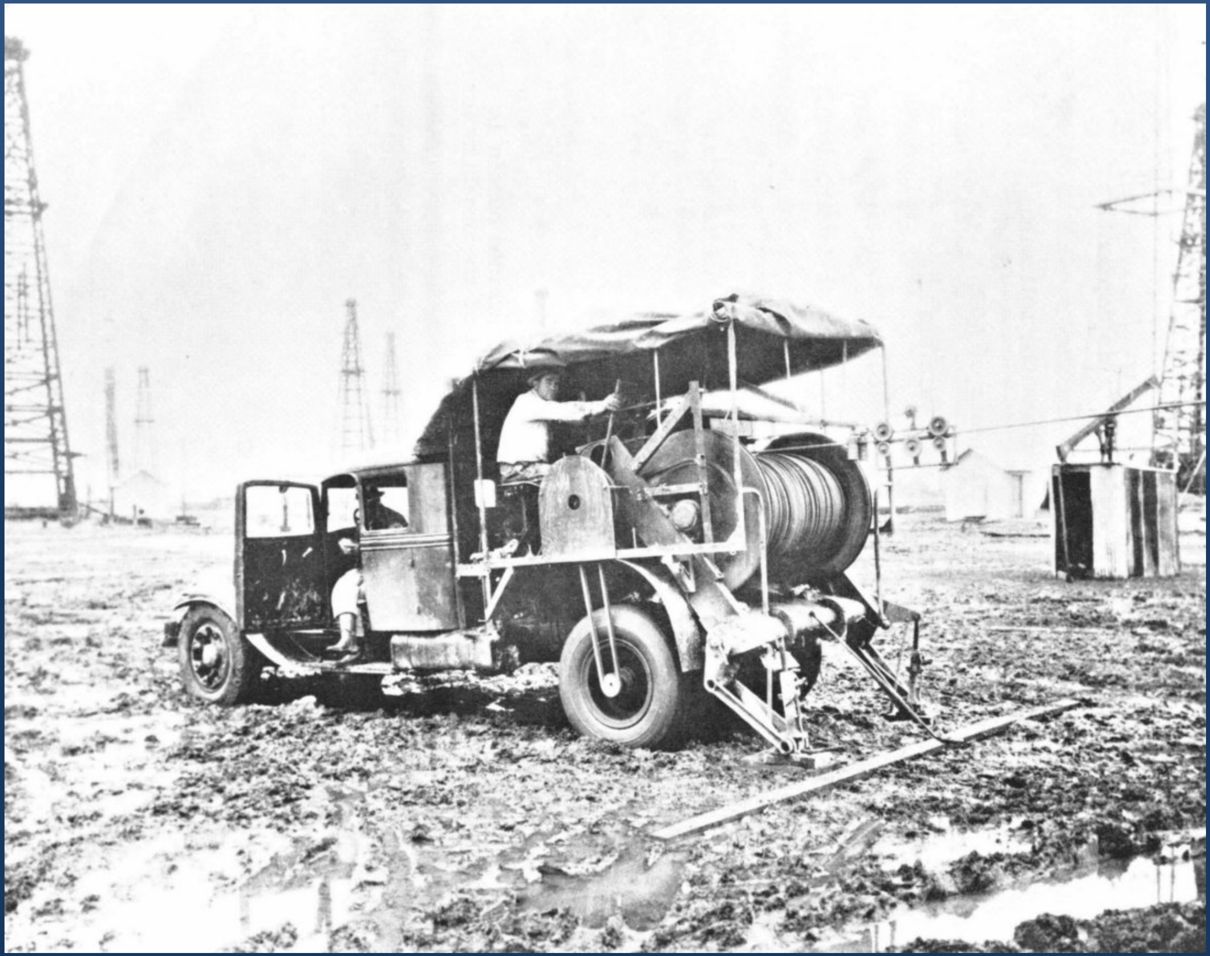
Borehole Wire-line Logging for Uranium



Colin Skidmore - SMEDG Symposium 11 September 2009

Why use borehole logging?

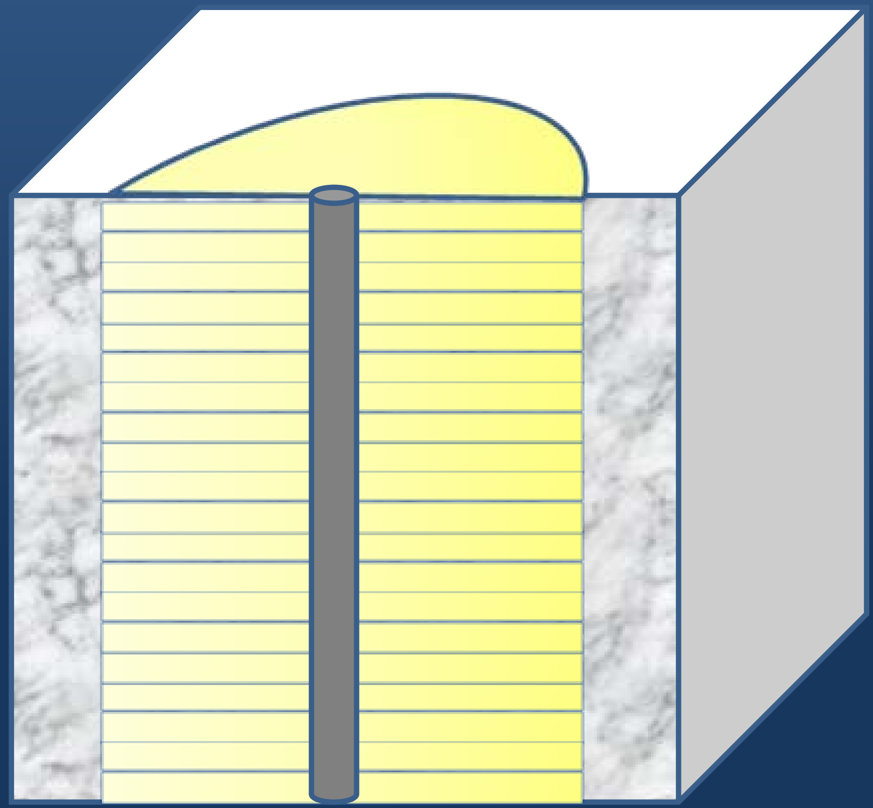
- Cost effective
- Instantaneous results
- Very accurate depth control
- Excellent resolution of narrow intervals (typically 1cm compared to ~1m with physical sampling)
- Measures larger sample volume compared to collection of physical sample
- Measures a wide range of petro-physical properties

Different material sampled

Physical Sampling

1x Small Sample

Borehole Logging



100x Large Samples

Note: Uranium mineralisation is highly heterogeneous and nuggetty in many deposits

Wire-line Tools – Uranium Grade

- Total Gamma
  - Indirect measurement of uranium (^{214}Bi & ^{214}Pb)
  - Cheap and reliable equipment
  - Measures all radio-nucleotides (Sum of K+Th+U+…)
- Spectral Gamma
  - Measures the energy spectrum of gamma radiation and to a degree can discern between different radio-nucleotides
  - Only cryogenic high-purity germanium systems can potentially discern peaks directly associated with uranium (e.g. 1.001MeV of Protactinium ^{234m}Pa)
- PFN *(Prompt Fission Neutron)*
  - Direct measure of ^{235}U
  - Provides spontaneous measure of disequilibrium
  - Expensive, complex, high maintenance system
  - Requires specialist radiation licensing
  - Limited availability
  - Very slow logging speed (~0.5m/min)
  - Restricted access to appropriate calibration facilities

Wire-line Tools - Geology

- SP & Resistivity
  - Commonly used in historic logs with variable success discerning permeable strata
  - Poor results with modern digital systems due to drift and with modern saline drilling mud which results in insufficient resistivity contrast
- Neutron Porosity
  - Generally excellent at determining variations in porosity
  - Uses sealed neutron source (AmBe) requiring licensed operators and radioactive substance management
- Induction (single or dual)
  - Good results in dry holes and saline conditions
  - Be careful of sulphides as give very high conductivities
- Focused Resistivity (Guard/ Laterolog)
  - Very useful at picking lithological boundaries
  - Only useable below the watertable
  - Safety considerations as requires long bridle and can expose operator to potential electrocution
- Magnetic Susceptibility

Note: If gamma is collected with every tool suite run it can be used to depth match between separate suite runs

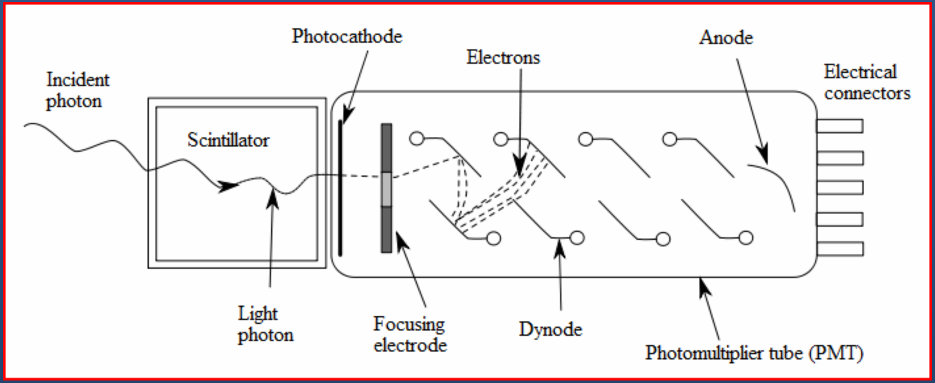
Wire-line Tools – Others

- Caliper
  - Borehole diameter (critical factor for grade determination)
- Deviation
  - Borehole orientation
- Optical
  - Expensive additional cost (typically ~$5 per meter)
  - Geology, structure, well casing integrity etc.

Note: If gamma is collected with every tool suite run it can be used to depth match between separate suite runs

Gamma Technology

Gamma - Overview



- Gamma radiation causes flashes of light in a scintillometer (typically NaI crystals)
- Photomultiplier tube converts light energy into electrical pulses which are statistically counted (CPS – counts per second)
- Larger the crystal the more sensitive but reaches saturation quicker
- Borehole logging commonly uses slimline crystals of 1 to 4 cubic inches
- Indirect method as no readily detectable gamma emitted from uranium (derived from ^{214}Bi and ^{214}Pb)
- Gamma can be logged through casing. Logging speeds optimal ~6m/min

Gamma - Calibration

- Several calibration factors and assumptions need to be estimated to convert CPS to eU_3O_8 including:
  - Dead-time
  - K-Factor
  - Moisture / Density Factors
  - Hole size
  - Radon Degassing
  - Casing Factors etc.

- Certified calibration facility at Glenside, South Australia (Amdel Test Pits) installed in 1981 which simulate an infinite slab of known constant grade ~1 metre thick.

AM1 (0.219% eU_3O_8)	108mm
AM2 (0.92% eU_3O_8)	108mm
AM3 (0.054% eU_3O_8)	108mm
AM7 (0.17% eU_3O_8)	108mm, BQ, NQ, HQ & PQ
AM6 (4.52% K, 37ppm U_3O_8, 70.3ppm ThO_2)	

Determining Gamma Calibration Factors

Dead Time Calculation (ms):

$$Dead\ Time = \frac{(\text{High Grade} \times \text{Low Counts}) - (\text{Low Grade} \times \text{High Counts})}{(\text{High Grade} \times \text{High Counts} \times \text{Low Counts}) - (\text{Low Counts} \times \text{Low Counts} \times \text{High Counts})}$$

Calculation of Dead Time Corrected Counts (CPS):

$$Dead\ Time\ Corrected\ Counts = \frac{\text{Observed Counts}}{(1 - \text{Observed Counts x Dead Time})}$$

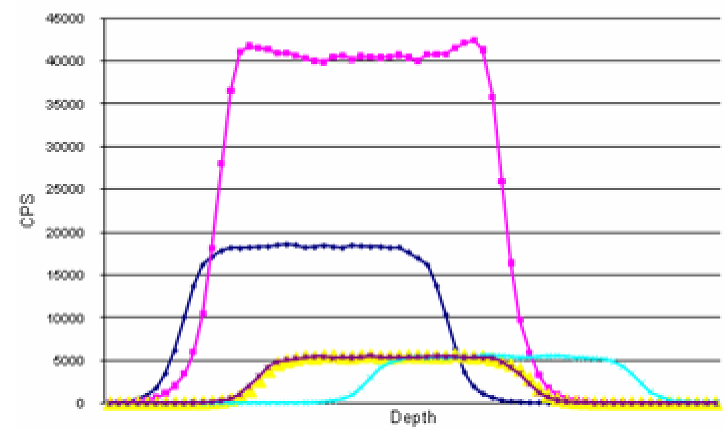
K Factor Calculation (m % eU_3O_8 per CPS):

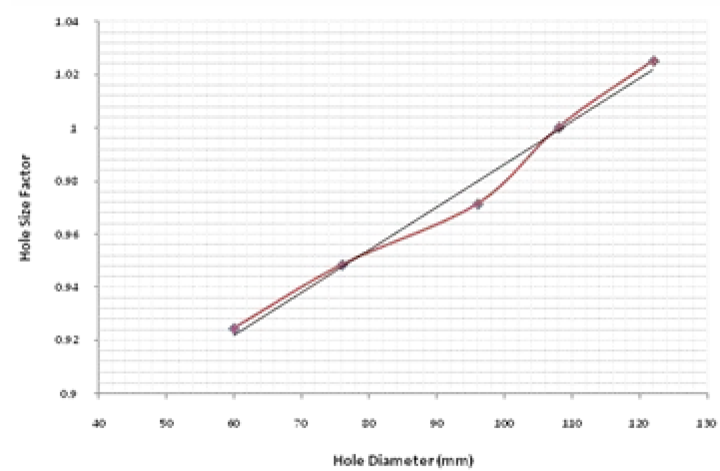
$$\text{K Factor} = \frac{\text{Dead Time Corrected Counts}}{\text{Grade of Calibration Pit}} \text{ x Sampling Interval}$$

Calculation of eU_3O_8:

$$eU3O8 = \frac{(\text{Gamma} \times \text{K Factor} \times \text{Sampling Rate} \times \text{BHCF} \times \text{Hole Size Factor})}{1 - (\text{Dead Time} \times \text{Gamma})}$$

BHCF = Moisture & Density Correction Factors



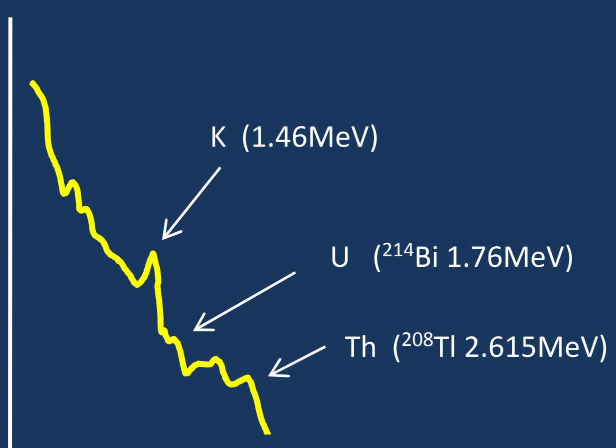


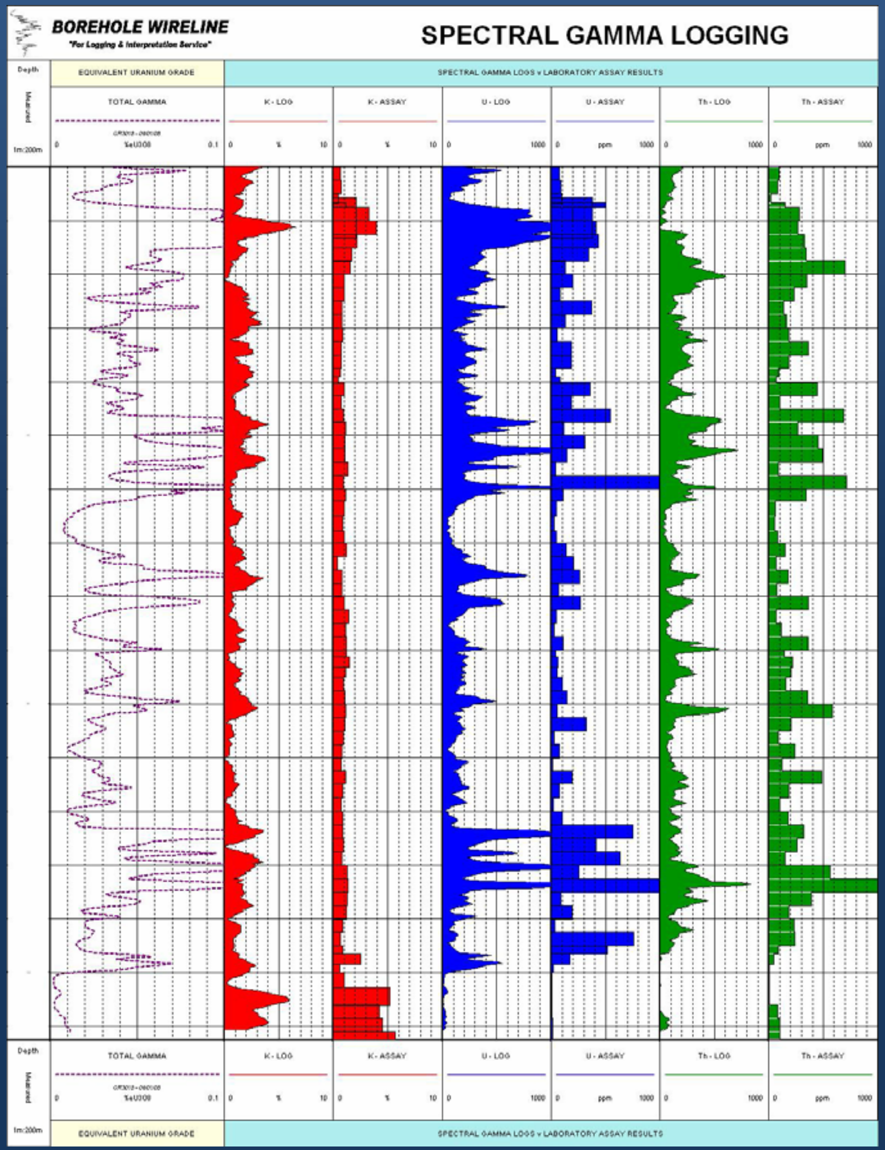
Calibration & QA/QC

- Gamma logging systems are sensitive to mechanical damage, temperature, electrical fluctuations and must be calibrated regularly.
- Contractors should provide full calibration datasets before and after each logging job; whenever the equipment is in Adelaide or is repaired.
- Probes should be tested in a jig using a known gamma source before each run
- Calibration factors should be recorded on each log and linked in a database
- Radon degassing should be considered particularly if using air drilling methods
- Log runs should be routinely repeated and ideally be undertaken both down and up hole and then compared for accuracy and precision
- Depth measuring devices should also be regularly calibrated
- Disequilibrium adjustment of eU_3O_8 to U_3O_8 can be estimated statistically by analysing numerous samples across a deposit using chemical and closed can gamma methods.

Spectral Gamma

- Spectral gamma systems sort the energy spectra of gamma into three windows plus total count
- Uranium channel is least discernable and relies on indirect measure of Bi^{214}
- Best application in deposits where K and Th are abundant



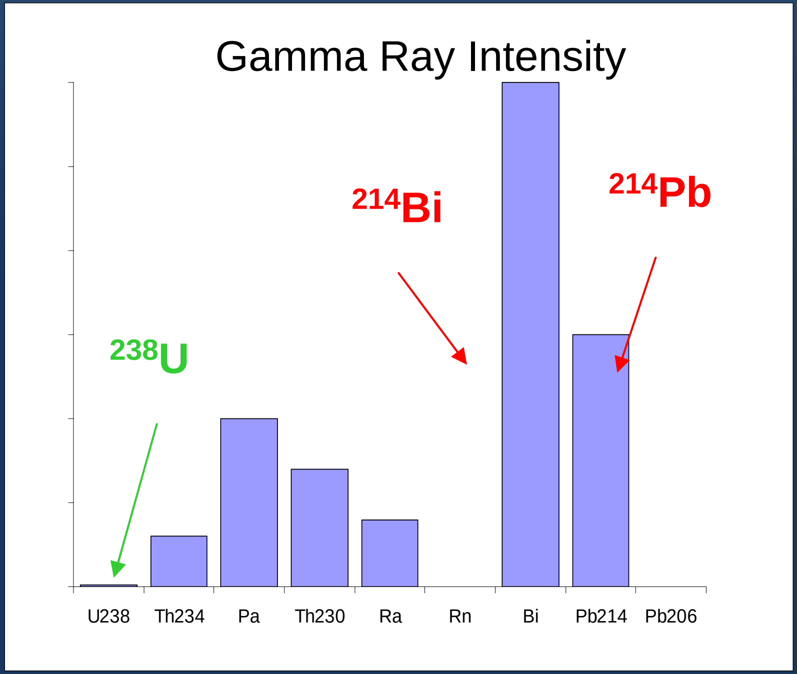


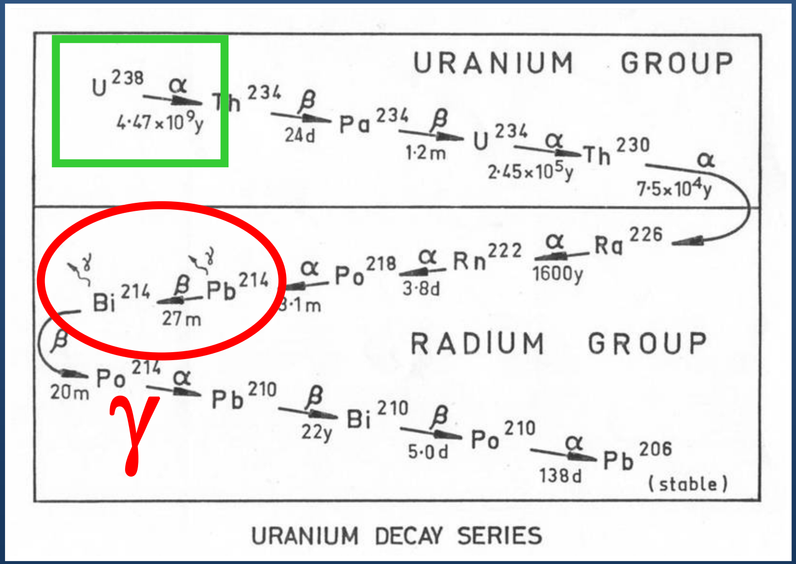
PFN Technology

"Prompt Fission Neutron"

The Disequilibrium Problem

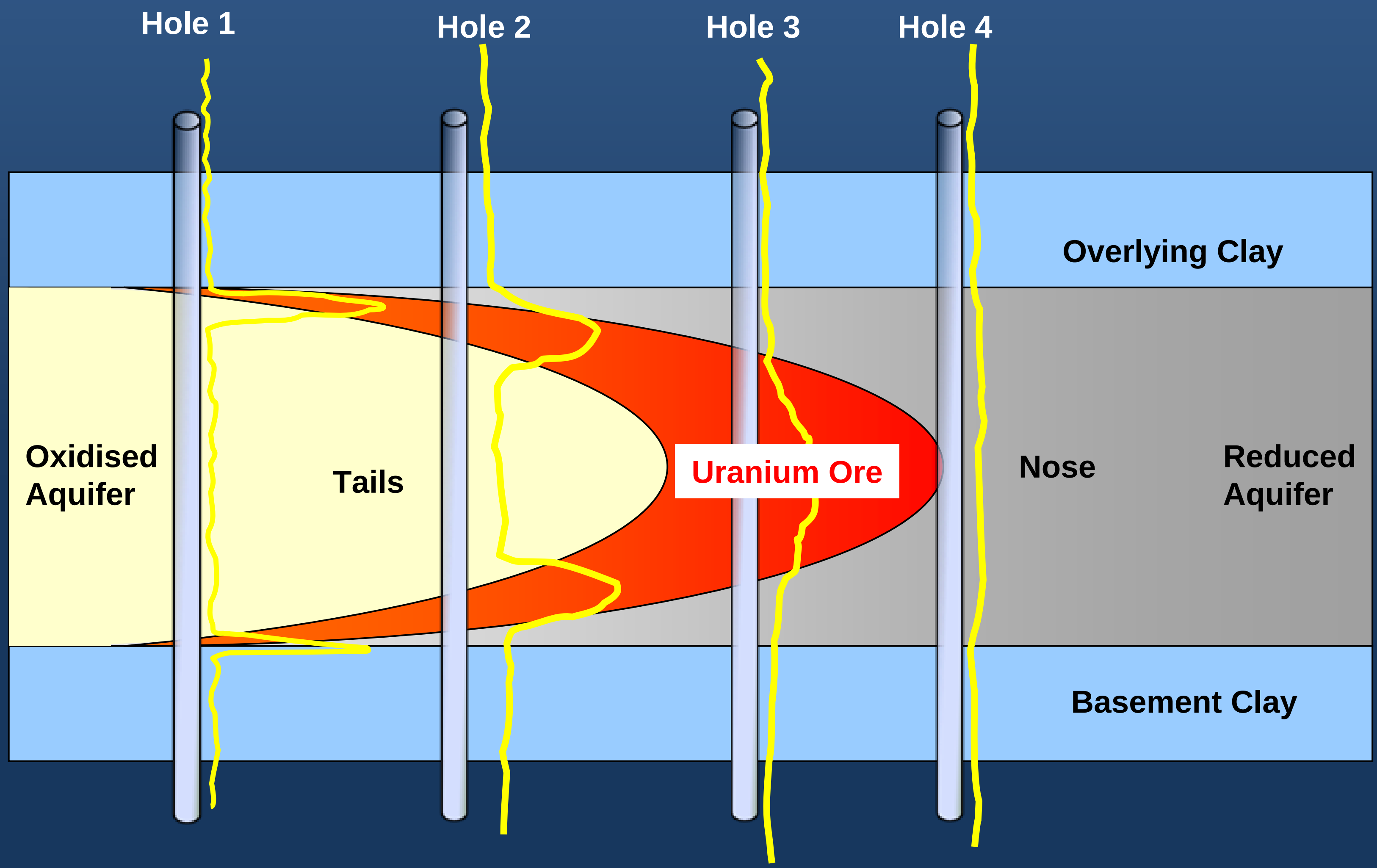
Gamma is the traditional tool used to measure eU_3O_8 grade and evaluate resources...



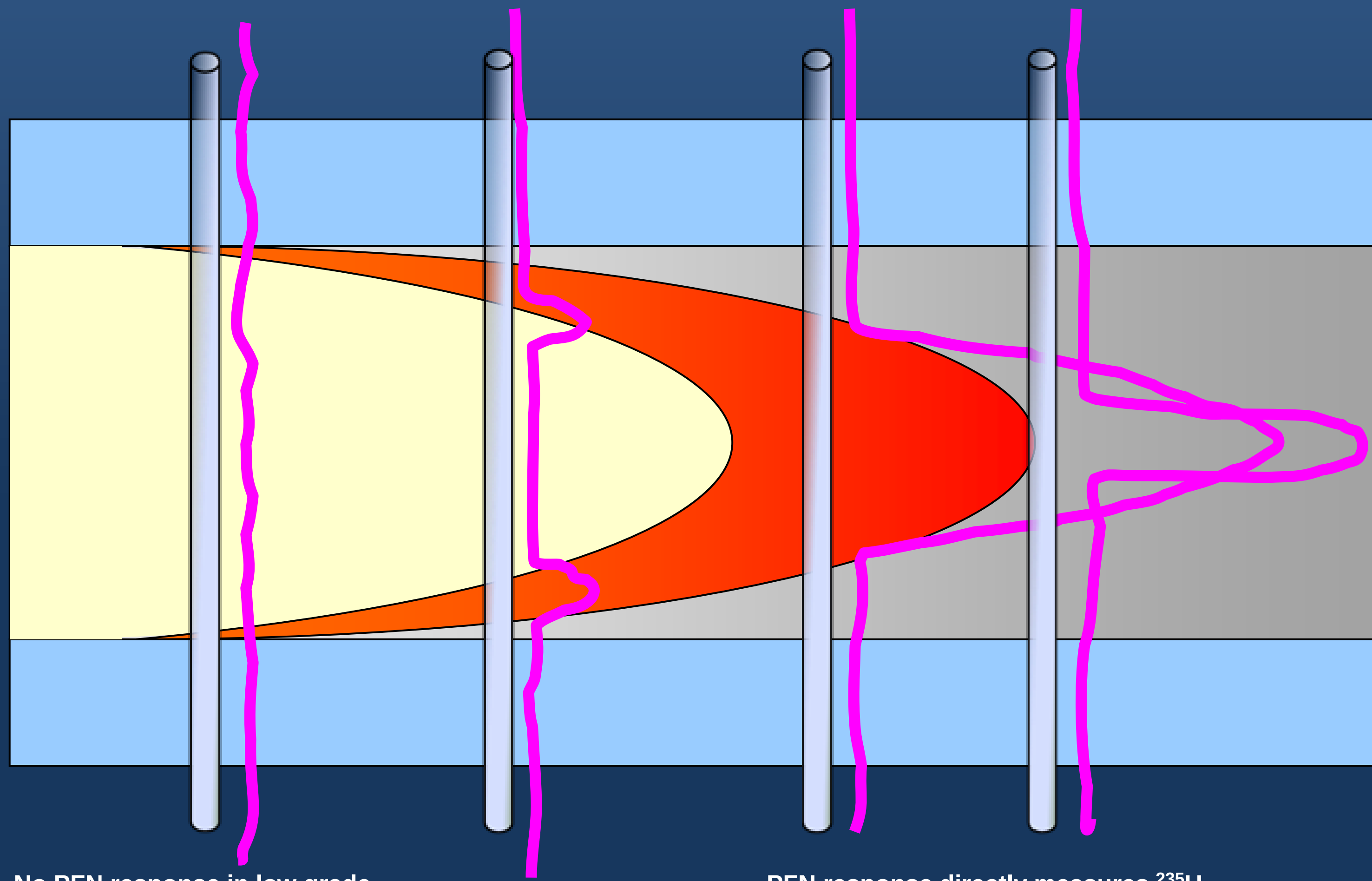


...but in some sandstone-hosted deposits uranium is not in equilibrium with its daughters as they are too young and uranium is still actively mobile.

Schematic Gamma Response



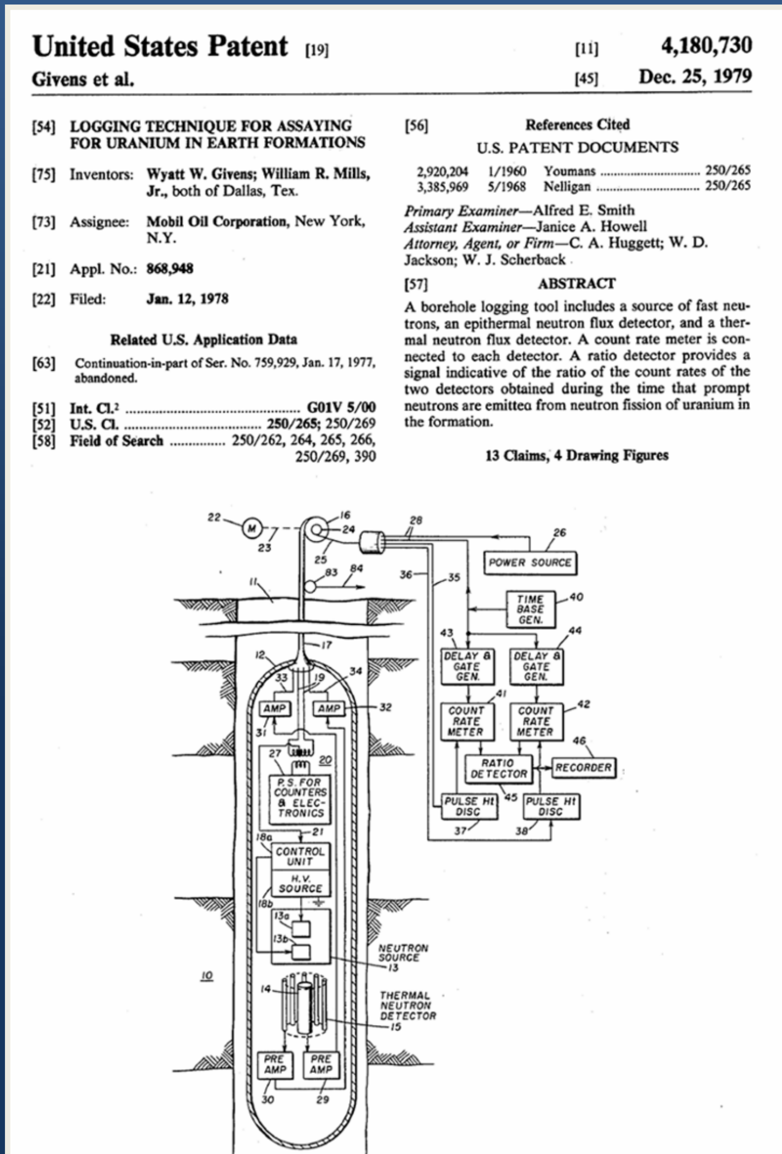
Schematic PFN Response



No PFN response in low grade tails as daughters only

PFN response directly measures ^{235}U concentrated in high grade nose

History of PFN



United States Patent [19] [11] 4,180,730

Givens et al. [45] Dec. 25, 1979

[54] LOGGING TECHNIQUE FOR ASSAYING FOR URANIUM IN EARTH FORMATIONS

[75] Inventors: Wyatt W. Givens; William R. Mills, Jr., both of Dallas, Tex.

[73] Assignee: Mobil Oil Corporation, New York, N.Y.

[21] Appl. No.: 868,948

[22] Filed: Jan. 12, 1978

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 759,929, Jan. 17, 1977, abandoned.

[51] Int. Cl.[2] G01V 5/00

[52] U.S. Cl. 250/265; 250/269

[58] Field of Search 250/262, 264, 265, 266, 250/269, 390

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2,920,204	1/1960	Youmans	250/265
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Primary Examiner—Alfred E. Smith
Assistant Examiner—Janice A. Howell
Attorney, Agent, or Firm—C. A. Huggett; W. D. Jackson; W. J. Scherback

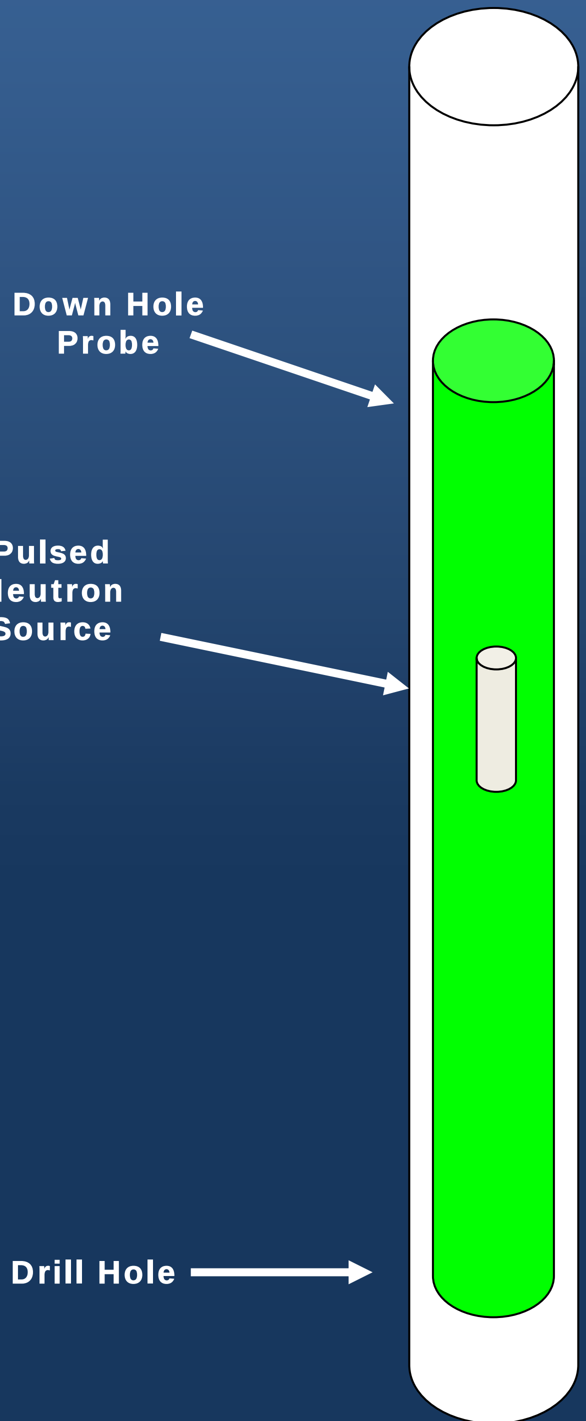
[57] ABSTRACT

A borehole logging tool includes a source of fast neutrons, an epithermal neutron flux detector, and a thermal neutron flux detector. A count rate meter is connected to each detector. A ratio detector provides a signal indicative of the ratio of the count rates of the two detectors obtained during the time that prompt neutrons are emitted from neutron fission of uranium in the formation.

13 Claims, 4 Drawing Figures

- PFN was invented by Sandia Laboratories & Mobil R&D in Texas during the 1970's to directly measure in-situ ore-grade uranium.
- Mothballed for 20 years after the Three Mile Island Reactor Incident in 1979.
- US Patents for PFN expired in 1999.
- Russians developed their own hybrid KND system in 1980's - used extensively in ISR mines throughout Kazakhstan

How does PFN work?



- Probe 3.2 metres long, 76mm diameter
- Winched into a typically 120mm open drill hole connected by 4 conductor cable
- Pulsed neutron generation (1000Hz) at 75KV

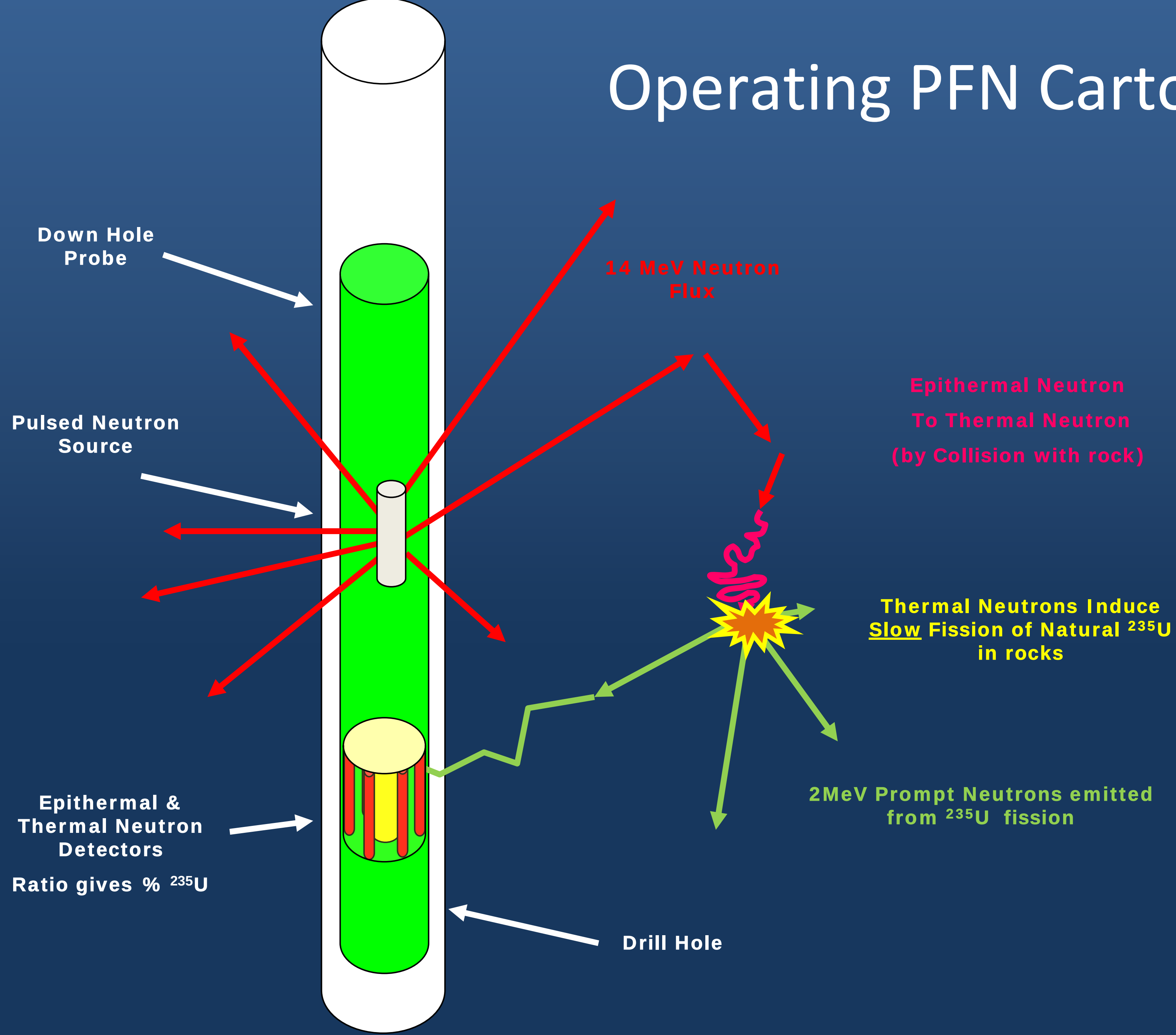
PFN Neutron Generator

- High voltage accelerates deuterium (^{2}H) ions into a tritium (^{3}H) target

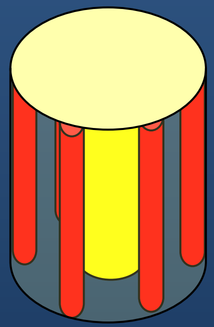
$$^{2}H + {}^{3}H \rightarrow n + {}^{4}He \qquad (E_n = 14.2\,\mathrm{MeV})$$

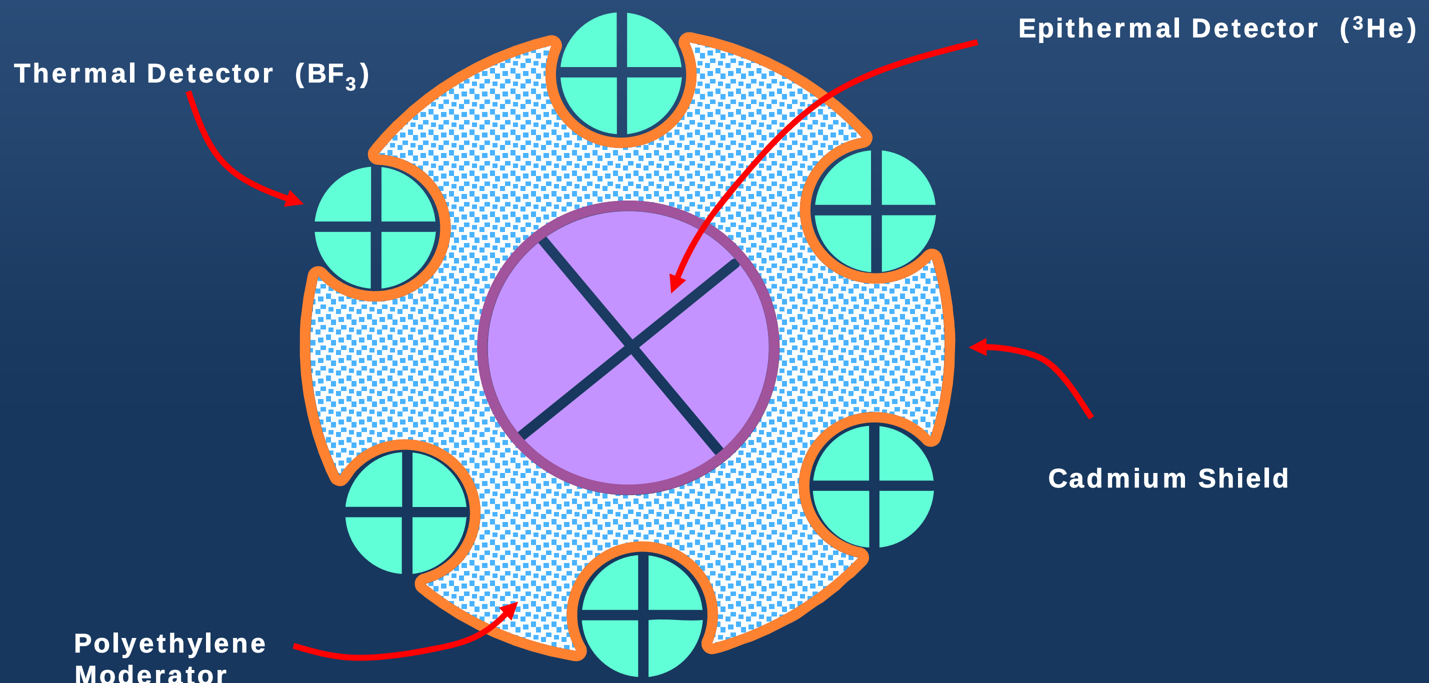
- Pulses at 1000 cycles per second & emits ~10^{8} neutrons per second
- Manufactured in USA by Halliburton, Thermo Electron and AOL

Operating PFN Cartoon

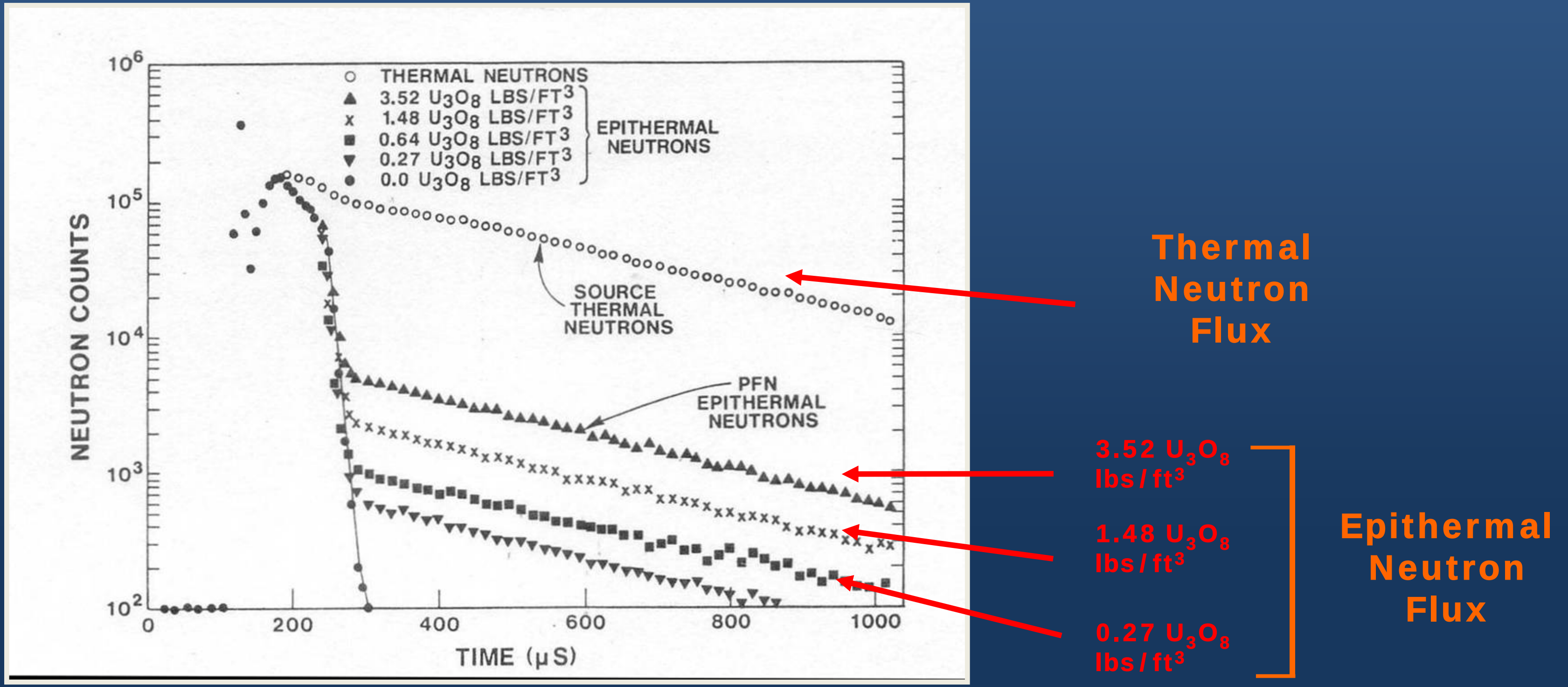


PFN Neutron Detector Geometry





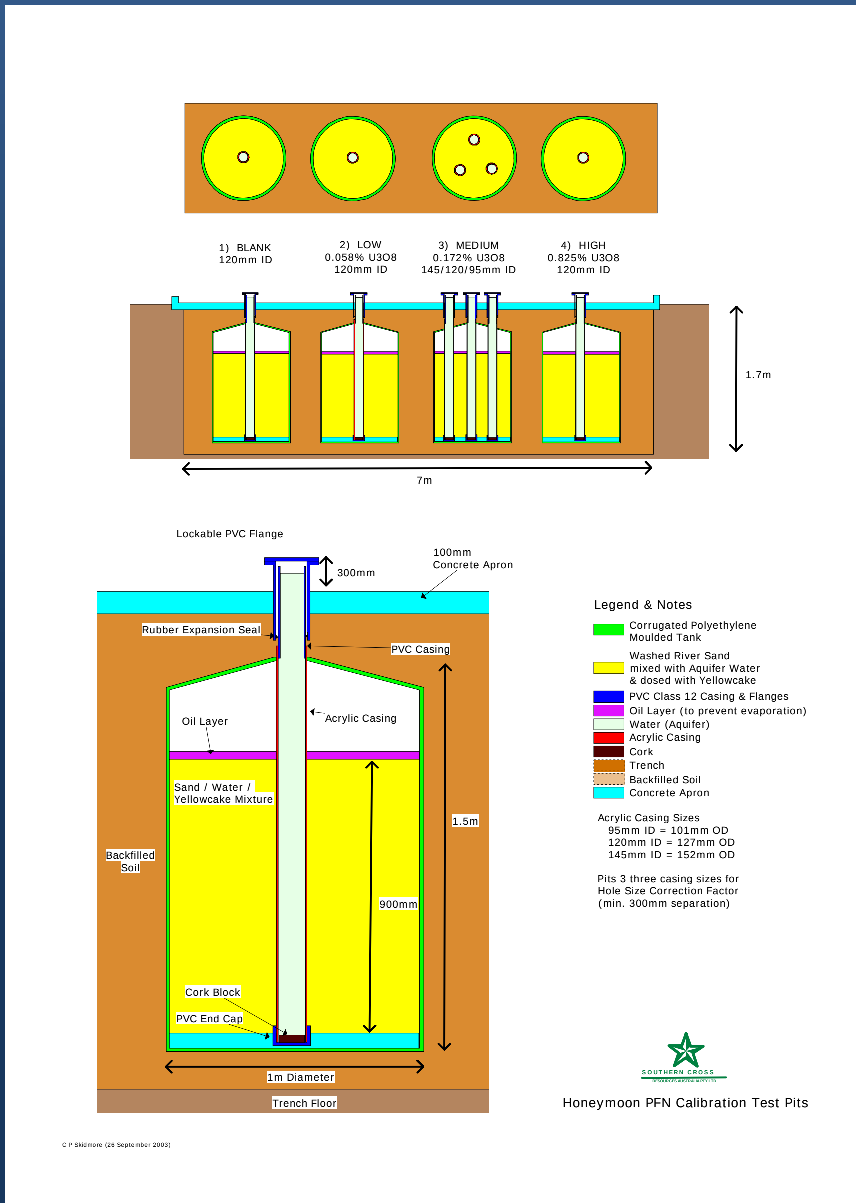
PFN Results



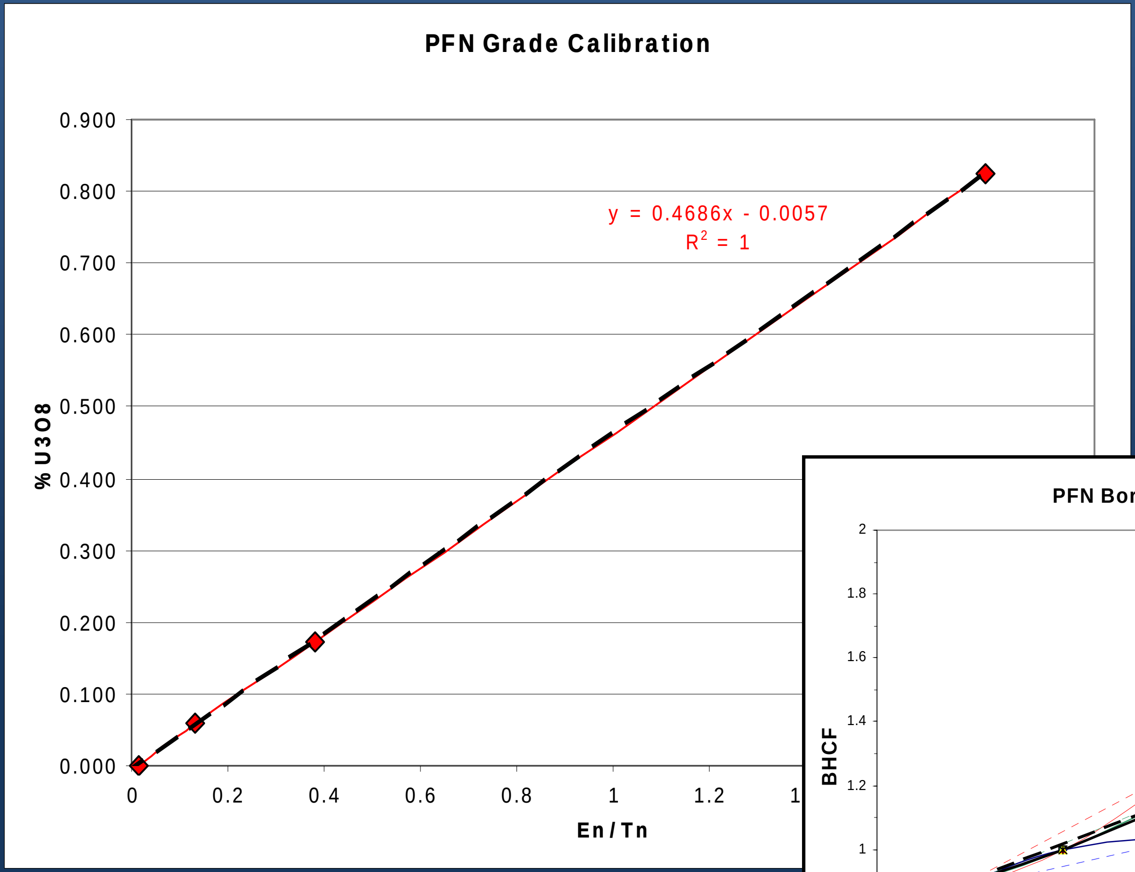
- Ratio of Epithermal to Thermal Neutrons is Directly Proportional to ^{235}U
- Only ^{235}U is Fissionable in the Natural Environment
- Deposits considered in Isotopic Equilibrium 0.72% ^{235}U 99.27% ^{238}U

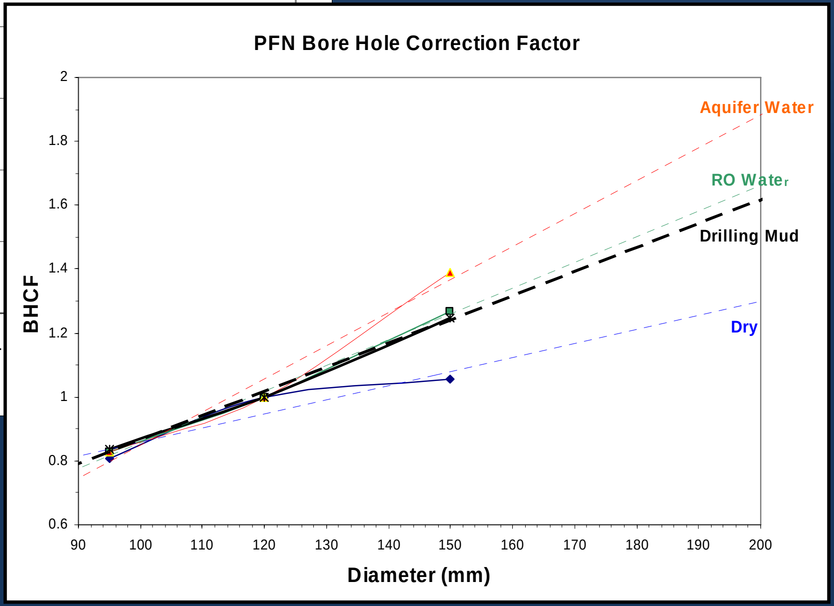
PFN Logging Platform

PFN Calibration



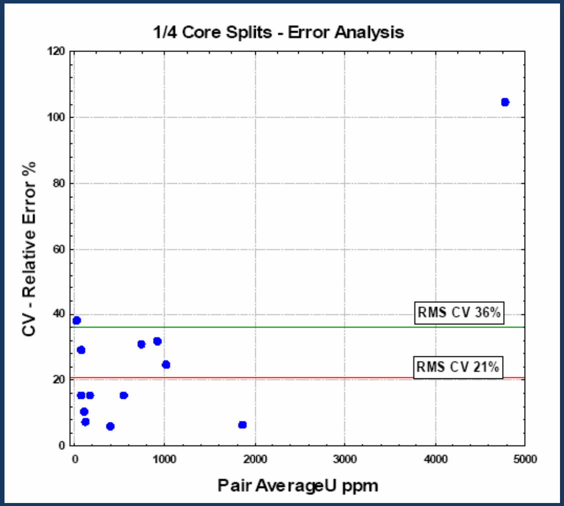
PFN Calibration Curves

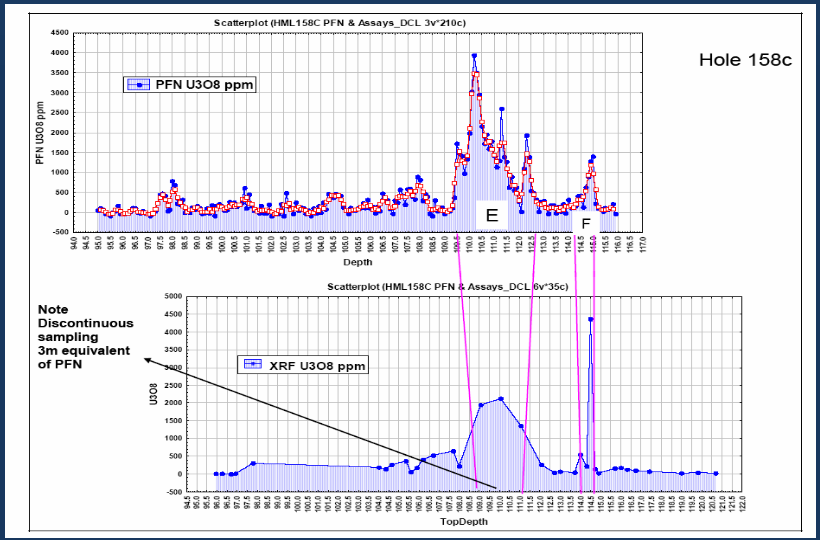




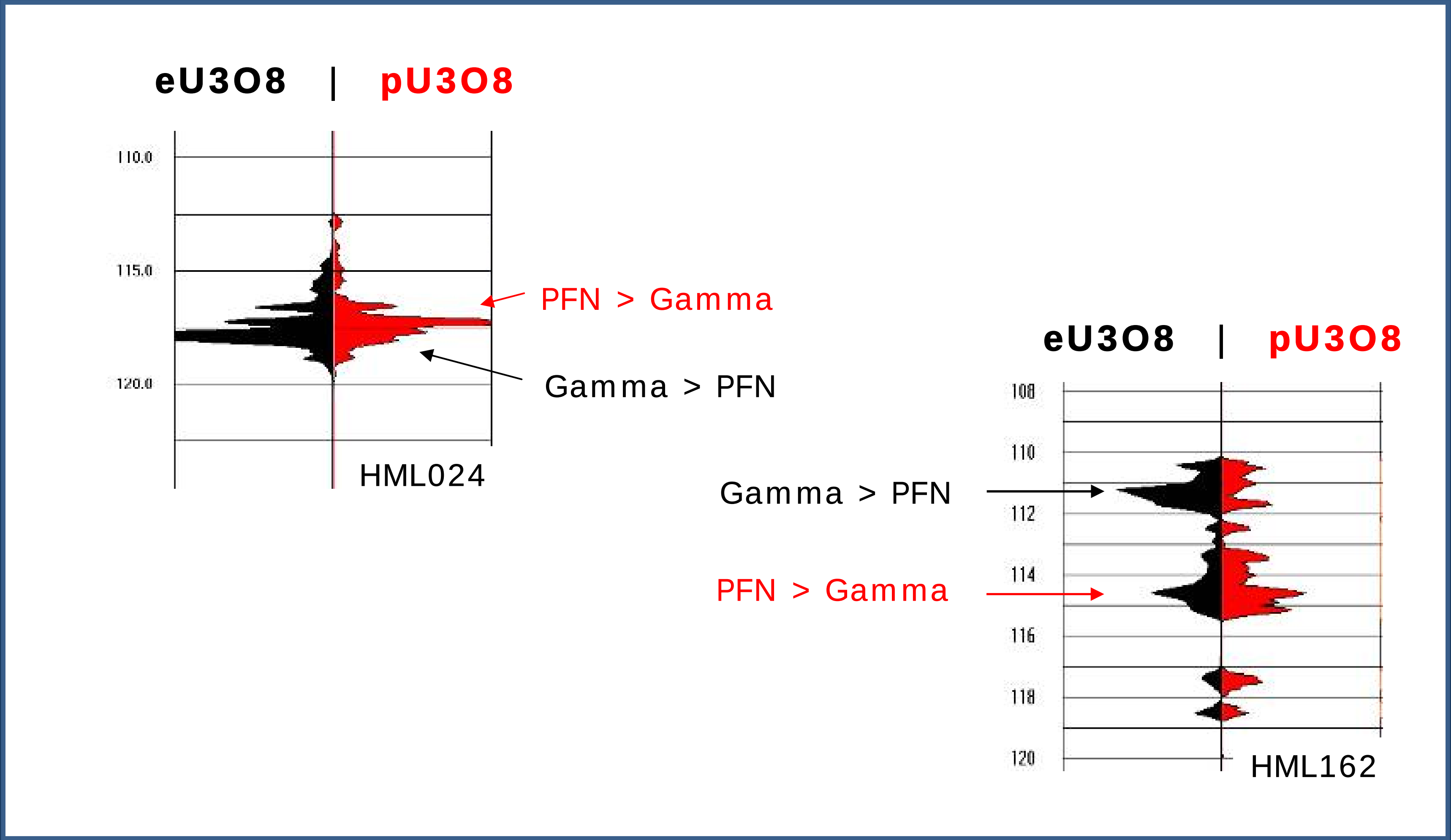
PFN - QA/QC

- Regular calibration runs in pits
- Reconciliation of PFN grades against core assays
- Duplicate runs of PFN tool in holes
- Detection Limit of PFN tool is 0.025% U_3O_8
- PFN Sampling Error is ~20% whereas ¼ Core Sampling Error is ~36%
- Analytical Errors of PFN and XRF are comparable





Examples of Disequilibrium



Advantages of PFN

- Crucial for most Tertiary Uranium deposits as they are young and can suffer extreme disequilibrium
- Uses a safe neutron generator rather than a radioactive source
- Produces an accurate direct measurement of *insitu* uranium over narrow intervals
- Results are instantaneous
- Measures a large sample volume (~500mm sphere – 600x larger than quarter core)
- QA/QC analysis demonstrates PFN is preferable to physically sampling core
- Obviates the need to drill costly core for grade estimation
- Can be used during ISL mining to quantify recovery
- Exploration tool – disequilibrium vector towards mineralisation
- Necessary requirement to measure indicated resources in ISR type deposits

Data Management & Processing

Data Management & Processing

- General output from logging software is a LAS file, a space delimited ASCI file with header information.
- Voluminous data generated (eg: At 1cm sampling 10,000 records are generated every100m logged for each run and for each individual tool)
- Original files should be archived to maintain integrity. Work on copies!
- WellCad™ is recommended software (www.alt.lu/software) which reads raw data files
- Sensor off-set adjustment, depth matching, formula processing, lithological and stratigraphic interpretation undertaken in WellCad™
- Processed data can be setup to automatically be uploaded into a database (Access or SQL). Recommend storage as integers to minimise database size and efficiency.
- Collar details, Drill chip and core logging data including photographs can be directly imported into WellCad™ from the database using ODBC links to assist interpretation and to make final well-log images

Wire-line Log Output

Drill Chip Photo

Natural Gamma

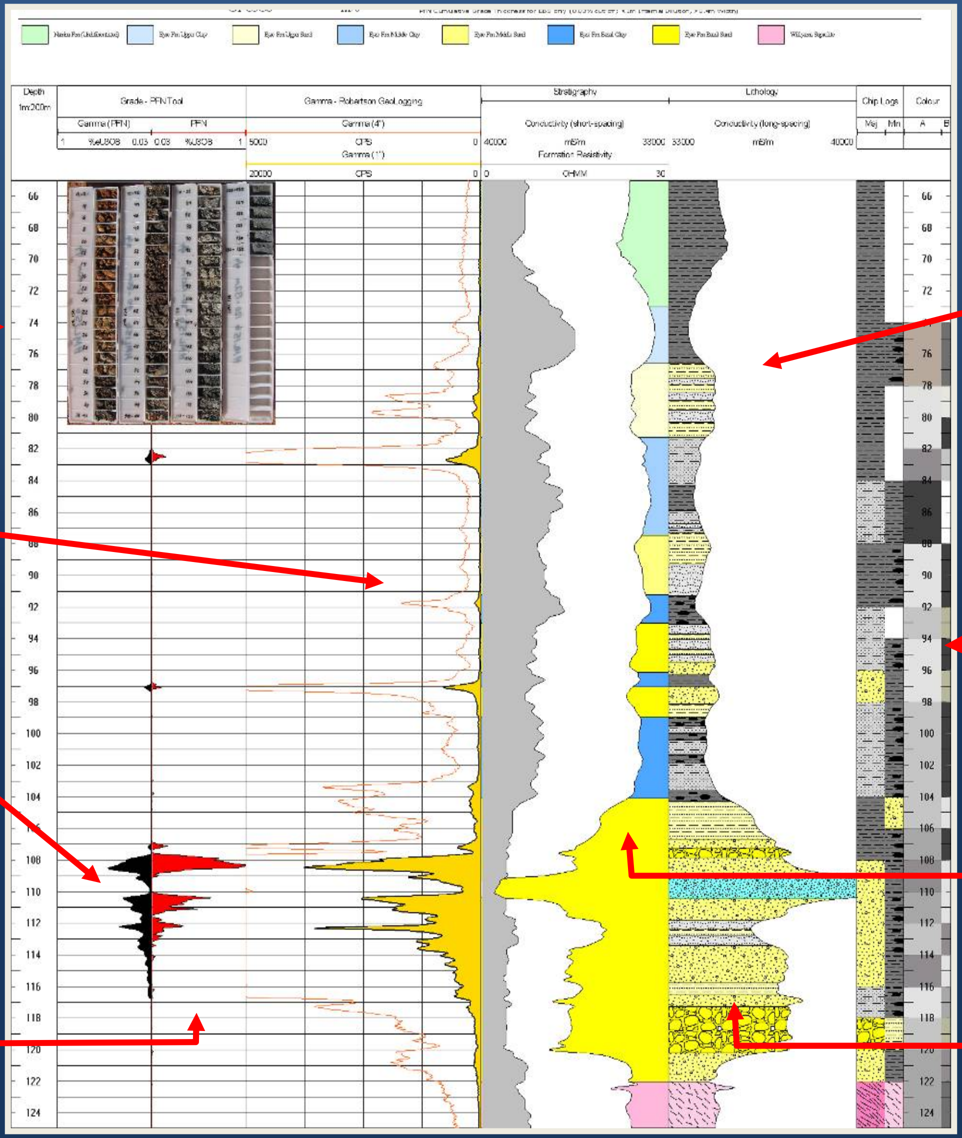
- Total count natural gamma radiation measured by up to three scintillometers with varying NaI crystals sizes

eU_3O_8 (Black)

- Calculated from calibrated natural gamma using a number of factors)

pU_3O_8 (Red)

- Direct measure of U^{235} insitu using ration of epithermal to thermal neutrons – PFN



Dual Induction & Guard

- Define lithology by measuring porosity using EM and Electrical methods. Similar to SP / Resistivity but better suited to highly saline conditions

Chip Lithology & Colours

- Logged lithology and Munsell Colours. Assist interpretation and identifies oxidation state

Stratigraphic Interp

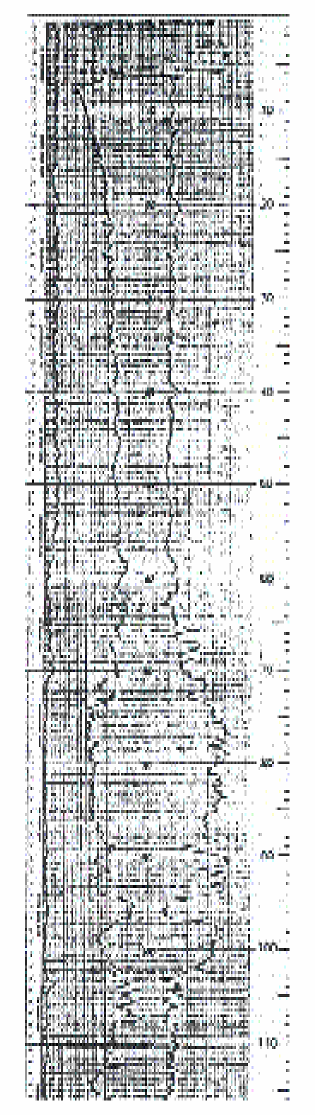
- Broad classification of stratigraphic subunits

Lithological Interp

- Detailed interpretation of all datasets to identify facies and to reflect leachability

Using Historical Borehole Logs

- Commonly only gamma, SP and Resistivity
- Analogue systems printed directly onto paper with varying quality of preservation
- Paper rewound and overprinted at different scales in anomalous zones
- Poor or absent calibration data (certified test pits built 1981 in Australia)
- Digital ticker tape printouts use time base a scaling factor
- Early packages which computed eU3O8 onto paper logs apply moving point averages and other statistical methods as well as often prefixed and spurious calibration criteria



Code-compliant Resource Reporting

- Gamma is generally acceptable for the reporting of Inferred Resources
- For higher code-compliant categories gamma alone is not considered as it is an indirect measure, is derived from poorly defined calibration factors and does not factor disequilibrium
- Spectral gamma methods are also questionable as the uranium channel is poorly resolved; still reliant on ^{214}Bi; and available calibration facilities are inadequate
- Gamma can be acceptable in conjunction with adequate physical sampling and analysis to reconcile disequilibrium and calibration “fudge” factors. (e.g. Kazakhstan where 70% of the mineralised horizons are cored)
- PFN as a direct measuring technique is acceptable provided regular appropriate calibration and a high level of QA/QC can be demonstrated
- Borehole logging does not negate the need for sound geological understanding of mineralisation, host lithology, sedimentalogical facies etc. which are only obtained from core

Thank You

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