Mitigating Risks of Sealed Radionuclide Sources used in E & P Industry:

Regulations to Protocols to Technology*

Ahmed Badruzzaman+ PhD, ANS Fellow
Pacific Consultants & Engineers, Hayward, CA
SME Consultant to US Dept. of Energy NNSA

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+Contact: abadruzzman@Pacific-CE.com; Ahmed.Badruzzaman@gmail.com

Opinions are of speaker alone, not necessarily of others

Premise of the Talk

- Radioactive sources: Omnipresent and essential in E&P industry, both in upstream and downstream
- Security/safety risks: Significant, despite current protections: *A Multiple-discipline Challenge-HSSE & SR,D&C,RD&D*
- Mitigation: Regulations to Guides to Technology
  - ➢ *What's on the table & their impacts: Good and bad?*
  - ➢ *Industry: "Fight or Flight" i.e. Mitigate or Abandon?*
- A Path Forward?

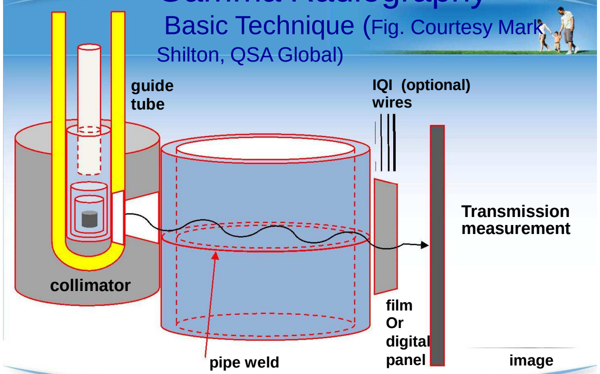
Application of Sealed Radioactive Sources

- Non-destructive Testing/Radiography: Integrity/ failure prevention: components, connections; Structures, such as pipelines, etc.
- Well Logging- Accurate reserves estimates, well placement, completion, monitoring; safety;
- How and Impact?

NDT: Gamma Radiography

Gamma Radiography

Basic Technique (Fig. Courtesy Mark Shilton, QSA Global)



Prevents Serious Consequences

Pipeline
Weld failure

Blast Zone

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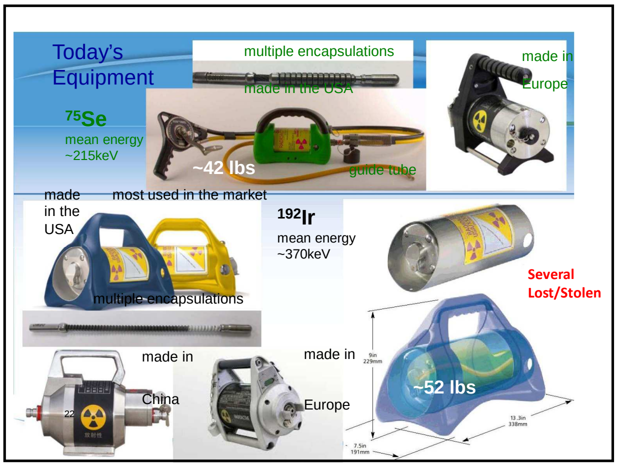
Serious Pipeline Incidents in US
(Data courtesy Mark Shilton, QSA Global)

- Gas Distribution (1994-2013): 745 incidents, 278 fatalities, 1069 injuries, over $110 million property damage
- Gas Transmission (1994-2013): 41 fatalities, 195 injuries, over $448 Million property damage
- 1400 pipeline spills and accidents: 2010-2013 (Wall street journal)
- Radiography critically important

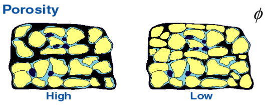


Well Logging

Reservoir Characterization:
Definitions/parameters

Key Petrophysical Parameters

Porosity

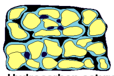


High Low

Porosity = Pore volume/formation volume

$$\phi = \frac{V_{Pore}}{V_{Total}}$$

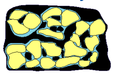
Saturation



$$S_{HC} = \frac{V_{HC}}{V_P}$$

Hydrocarbon saturation = Hydrocarbon volume/pore volume

Permeability



Ꝁ: Property of rock matrix that determines flow behavior

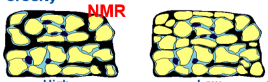
Oil Water

- **Rock:**
  - *Lithology* (Gross rock-type): affects all three parameters
  - *Mineralogy:* Assessing shale resources
  - *Condition:* Safety
- **Fluid Type:** gas/liquid; oils
- **Rock mechanics:** drilling safety well design

Reservoir Characterization:
Measurements

Key Petrophysical Parameters

Porosity Radionuclides, acoustic, NMR



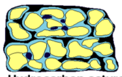
High Low

Porosity = Pore volume/formation volume

$$\phi = \frac{V_{Pore}}{V_{Total}}$$

Desired accuracy: 1 porosity unit (pu)

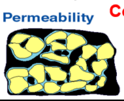
Saturation Electrical



$$S_{HC} = \frac{V_{HC}}{V_P}$$

Hydrocarbon saturation = Hydrocarbon volume/pore volume

Permeability Core samples: Lab



Ꝁ: Property of rock matrix that determines flow behavior

Oil Water

- **Rock**
  - *Lithology:* Nuclear (GR, Neutron)
  - *Mineralogy:* (n-ɣ) spectroscopy
  - *Condition:* Nuclear, Acoustic
- **Fluid Type:** Nuclear, NMR
- **Rock mechanics:** Acoustic

Reserves Uncertainty in Barrels with 1 Porosity Unit (pu) Error

Porosity (pu)	Reserve = 100 million barrels	Reserve = 1 billion barrels	Reserve = 10 Billion barrels	Reserve = 50 billion barrels
5	20 million	200 million	2 billion	10 Billion
15	6.7 million	67 million	670 million	3.33 billion
30	3.33 million	33 million	333 million	1.67 billion

Note: Many major fields have reserves ~10 Billion barrels and porosities in the range 5-15 pu. ±1pu accuracy critical. Only radioactive source tools achieve this

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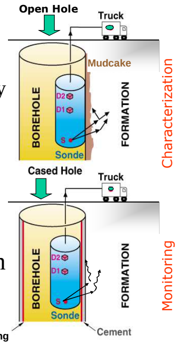
Nuclear/Atomic Logging Measurements

- Detect natural gamma ray → lithology
- Open-hole: Porosity, density, rock type
  - –Am-Be source: neutron porosity, mineralogy
  - –Cs–137 source: Density to porosity
- Neutron porosity and density are:
  - Backscatter measurements
- Mineralogy: Detect secondary radiation
- Cased-hole: Remaining hydrocarbon
  - Neutron generators; some rad sources



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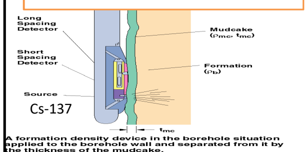
Radioactive Source-use in Petroleum Industry: *Examples*

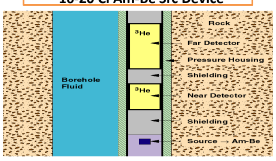
Application	Isotope	Half-life (yr.)	IAEA Safety Category	Health Effect
Neutron porosity/ Mineralogy	Am-241 (Mostly)	433	2-3	Death/permanent injury
Density	Cs-137	30	3	Permanent injury
Frack-pack monitoring	Am-241	433	High 3 to 4 (vendor?)	Permanent injury to temporary injury
Vessel or pipe-line gauges	Co-60	5	3 to 4	Permanent injury to temporary injury
Inter-well tracer	Kr-85	10.76	3	Permanent injury

Radionuclide-based Characterization Tools

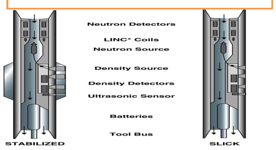
Wireline Density to porosity, P E to lithology
~ 2 Ci Cs-137 Device



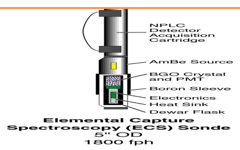
Wireline Neutron Porosity
~16-20 Ci Am-Be Src Device



A Logging-While-Drilling Device: Am-Be & Cs-137 Src.



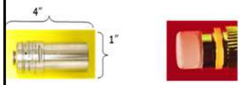
An n-gamma capture mineralogy device Am-Be Src.(~16 Ci)



Logging Source Capsules and Shielded Containers

Source material doubly-encapsulated in steel, for 25+ Kpsi. Cs-137 src material in glass matrix.

A Cs-137 Source Capsule (left) and actual source size equal to an eraser (right)
(Adopted from Badruzzaman et al, SPE Paper 123593, 2009)



An Am-Be Source Capsule
(Adopted from Hearn, WINS Workshop, Paris, 2014)

A Neutron Source Container

A Density Source Container

Figure: Courtesy of Halliburton (Ref: SPE 123593, 2009)

Containers transported in compliance with DOT and NRC Protocols
Sources are secure in storage and during transport

Why the concern?

Logging Source Risks Profile
Also applicable to Radiography Sources

Loss of control: Security vs. Safety
(Schematic Adapted from René Schlee, IAEA)

SAFETY

Inadvertent loss/ Damage

SECURITY
(heightened concern post-9//11)

Intentional

Damage
- **Sabotage**

Acquisition
- **Theft**
- **Illegal purchase**

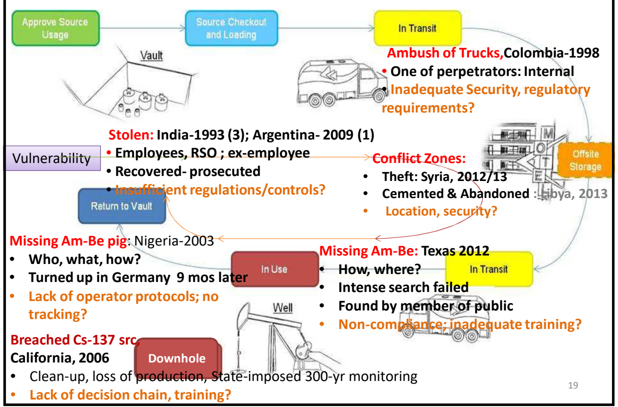
Malicious motive
- **Cause harm**

Financial motive

Let's look at a few examples of incidents & think through:

- Where they fit?
- What could have been done differently?
- Could a safety incident cross over into a security incident?

Logging Source Incidents & Vulnerabilities
(Cartoon adapted from Butler et al., Proc. 2015 INMM Conference, PNNL-SA-110866)



Well Logging Source Risk Factors: Summary

- Small, mobile, hard to detect; thousands in field
- Transported widely
- In politically unstable regions
- Illicit source trade, in general
- No clear insurance mechanism to cover damage:
  US: Insurance coverage with special dispensation from federal government under provisions of a special law, US Public Law 107-297-Terrorism Risk Insurance Act of 2002 (TRIA).
- **Malfeasance; Inadequate awareness, regulations, protocols, and training; non-compliance?**

Mitigation is critically important

Risk Mitigation Approaches

- Several: In parallel, not always coordinated
  - Regulations: Governments
  - New Source Handling Guides: Various players
  - Electronic Tracking- Tag technology R&D: National lab design under industry field test
  - Alternative logging technologies:
    - Industry:30+ yrs. R&D
    - National labs: Off & on
- Studies and Discussions: Governments, industry
- How well do these fit industry landscape?

Industry Landscape: *Well Logging*

- Diverse, Complex: Generally, evolved into distinct groups of service providers and users ('operators')
- Logging Service Providers:
  - Big-4 integrated international companies
  - National/regional logging companies
  - Smaller players- Some "Mom & Pop"
    - 60-70% of US logging units
      - Use off-the-shelf technology, third party tool vendors-
      - Compete effectively using current logging sources;
      - Will be Hard-pressed to switch technology, or adapt new regulations or protocols: Need help

Industry Landscape: *Well Logging* (contd.)

- Oil companies (Users/Operators):
  - Five/six major International Oil Companies (IOC's): US-and Europe-based
  - National Oil Companies- Some bigger than IOC's
  - Smaller oil companies
  - Not logging source licensees, but sources are used on their premises: Exposure to liability
- Business State:
  - Stressed due to downturn, but still generally robust

Regulations

Regulations Upgrade

- Many countries- e.g.,
  - Nigeria: Permit to utilize nuclear sources, radionuclide or generator, on each and every well
  - US- Examples
    - Background check of source handlers- Major Int'l logging cos adopting as a 'Best Practice' in all operations
    - Monitor Cat 3 sources if "aggregate" becomes Cat 2: On truck, Cat 3 individually- Cat 2 in aggregate?
      - Example: One 15.9 Ci Am-Be Neutron source + One 2 Ci Cs-137 Density source: Procedure- during Q&A
  - Emerging IAEA Security Guidelines vs. Safety

Protocols: Handling Guides

New Source Handling Guides

- IAEA: Intl. Atomic Energy Agency
  - Safety: Draft handling guide (2012)): Under review
  - Security categorization of sources based on condition of use (new). Logging sources are Cat 3 for safety, & normally Cat C for security but could be upped to Cat B: size, mobility, locale
- Joint USDOE-Industry initiative (2010): ⇒ Physical security protocols. *Ex: No single-person entry into vault*
- In-house protocols by a major operator to complement logging cos (2010)
- WINS: World Institute of Nuclear Security, Vienna: Best Practice Guide 5.2, Revision 3.1, 2016

Recommended Operator Protocols

(Ref. Badruzzaman et al., SPE 123593, 2009)

- Complement logging co. protocols
- Based on authors' learnings with incidents
- Elements
  - Track inventory on property: Entry to return
  - Clearly define onsite procedures
  - Clear decision chain w/ coordination & oversight
  - Training (of Operator personnel)
  - Incident handling, including reporting
- Hope other operators consider these

WINS Best Practice Guide on Logging Source Security

- Basis of a satisfactory security regime
  - Start at top: Leadership buy-in and drive
  - Understand evolving regulatory requirements?
  - Communication & record-keeping
  - Integrate safety and security: Safety and security may sometimes be in conflict
- Supplies a checklist for organizational success

Electronic Tracking

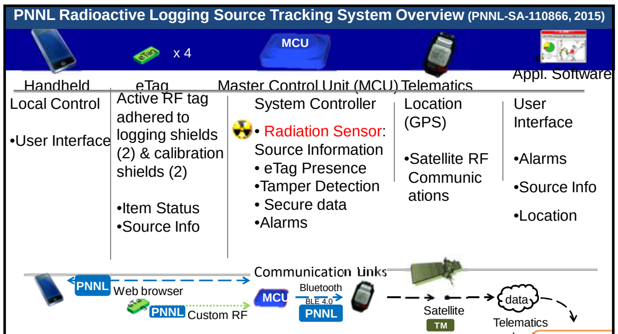
(e-tags)

Source Tracking Technology Issues

A survey of likely oil industry requirements (Speaker)

- Key: Cover entire movement chain; provide position alerts; temper-proof; monitor interference; inexpensive
- e-tagging of source capsules: Challenges
  - ➢Very high radiation environment
  - ➢"Seeing" inside complex metallic containers?
  - ➢ 20kpsi and 400 deg.F tolerance
- e-tag for shielded containers: A system designed by USDOE Pacific Northwest National Lab (PNNL) is under field-test by a major service co.

PNNL Radioactive Logging Source Tracking System Overview (PNNL-SA-110866, 2015)



Tracking System For well-logging source containers

- Transmit operational status during transportation, storage & use
- Would benefit logging companies of all sizes, especially small cos.

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A container fitted with a PNNL eTag

e-tag

- Detect Position, interference
- Indicates absence of radiation source in container
- Developed for both well logging and radiography source containers
- Being field tested
- Cost: Expected <$1K?

Ref: C. Swedberg, RFID Tracks Radioactive Materials Used by Oil Services Providers to Explore New Well Sites, RFID Journal, May 18, 2015

http://www.rfidjournal.com/articles/view?13049#back-from-modal

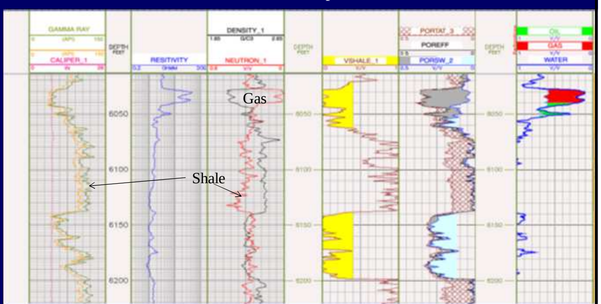
Long-Term Solution: Replacing Radionuclide Source Logging Tools

Desired Attributes of Replacements

- Current radionuclide tools: Fit-for-Purpose
- Alternative technologies:
  - ❑ As accurate and reliable?
  - ❑ Cost-effective to develop and deploy?
  - ❑ Compatibility with 50-60 yr. legacy data?
  - ❑ Sideline smaller logging companies, a major segment of the industry?

Reservoir characterization: Shale identification, porosity, and saturation

Ref: Badruzzaman, Proc. Am. Nucl. Soc. Topical Conf. Santa Fe, NM, 2002



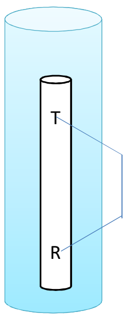
- GR and Neutron: Shale/Lithology: Neutron porosity tool: ~16 Ci Am-Be*
  Neutron and Density: Gas; Density tool: 2-3 Ci Cs-137*
- Electrical resistivity: Hydrocarbon (oil or natural gas) ** Replace?*

Requirements to be Replacement

(Ref: Badruzzaman et al, LLNL-TR-679101, Oct 30, 2015)

- Accuracy: Density: ±.015 g/cc or ±1 pu in porosity: Why?
  Saw: 1-pu error in a 15-pu reservoir with a nominal reserve of 1 billion barrels would result in 67 million barrel uncertainty.
- Must provide accurate lithology for well construction/ completion: some wells cost over $100 million
- Harsh environments: Over 400 degF, 30000 psi+, 1000g vibration in LWD
- Reliability: close to 100%. Tool failures can cost millions
- Acceptable data quality @ 1800ft/hr acquisition in wireline
- Both nonnuclear and nuclear-based alternatives tested

Non-Nuclear: Acoustic Technique



•Acoustic travel time ⇨ total porosity; rock anisotropy

→ Average Transit time (Δt)→ porosity:

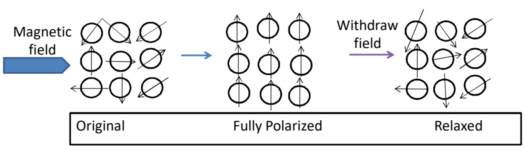
$$\Delta t = (1-\phi)\Delta t_{matrix} + \phi \Delta t_{fluid}$$

Vs. Average density:

$$\rho_B = (1-\phi)\rho_{matrix} + \phi \rho_{fluid}$$

Accuracy: 2-4 pu vs. 1pu from Cs-137 density

Non-Nuclear: "Nuclear" Magnetic Resonance (MRI)



$$M_{Polarization} = M_o\,(1-e^{-t/T_1})$$

$$M_{Relaxation} = M_o\,e^{-t/T_2}$$

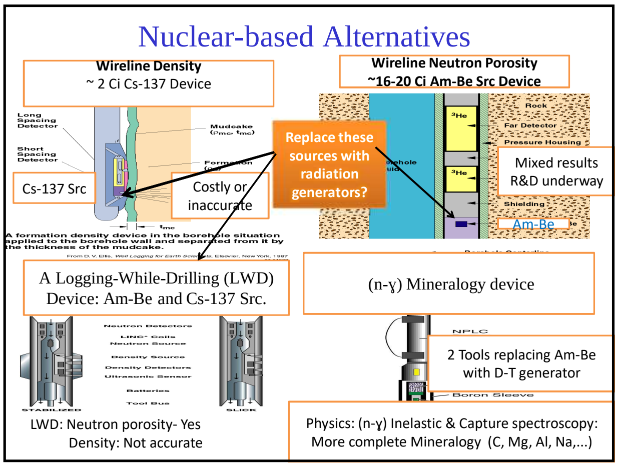
- **Apply magnetic field to align (polarize) H2 nuclei of liquids for interval t_w**
- **Turn magnet off: Nuclei return (relax) to original state.**

T_1: Polarization constant of a given liquid: 3 sec for water
T_2: Relaxation constant for a fluid

⇨ **T_1 and T_2 related to Porosity, and <u>additional</u> info: Fluid type, Permeability, etc. Porosity accuracy 2 pu; 1/10 logging speed in wireline**

Tested/ Proposed Nuclear Alternatives

- Industry ~ 30+ yrs. of R&D:
  - Tested: Cs-137 & Am-Be replacement-ways to go
  - Ongoing
- US National Academy of Sciences (2008)
  - Recommended replacing Am-Be neutron logging sources with D-T generators or Cf-252
  - Left Cs-137 density source alone
- National Labs: Recently studied novel ideas, but….



State of Alternatives: Summary

- Nonnuclear methods: Not sufficient as replacement; add info, however
- Tested radiation generator tools:
  - Density: Cannot replace Cs-137
  - Neutron Porosity: Mixed results
  - Mineralogy: Better than replacement quality
- Novel radiation generators
  - Density: None suitable
  - Neutron porosity: Some promising - R&D Underway
- **No magic bullet yet for porosity**

Studies and Ongoing Discussions

Studies & Ongoing Discussion

- Governments:
  - ➢ USDOE: Scoping Study on Alternatives (2015)
  - ➢ ISTC/STCU/USDOE: Targeted Initiative on Security and Alternatives focused on Central Asia & Caucasus (2016-2017)
  - ➢ UK Government: Workshop on Alternatives (2018)
- Professional Societies
  - ➢ SPWLA: Ongoing discussion and technical papers on Alternatives on Alternatives (since ~2001)
  - ➢ AESC: Presentations on risk and mitigation (2013-2015)
  - ➢ SPE: Technical papers
- Are these adequate? If not, what needs to change?

SUMMARY

- Radioactive logging sources: Critically important; Risky
- A multiple-discipline challenge
- *A Quiz: Mitigate risk or abandon source use?*
- Risk mitigation- Multiple fronts: Regulations to Technology: Complex, but must be done, alternative can be an “ultimate mitigation” but with a long time horizon
- Industry & Governments: Co-own challenge & partner?

A Path Forward?

- Professional Society Role:
  - Awareness: Risks, mitigation options, industry landscape
  - Platform: For industry players to consider the elements of risk mitigation
  - Industry-Government dialog
- SPE: Being multi-disciplinary, can be take lead; partner with SPWLA, AESC
- A recommendation: Form a Multiple-discipline Working Group to take on the above, systematically

Thanks & Disclaimer

- Thanks to
  - SPE HSSE & SR for the invite; Trey Shaffer, Angelo Pinheiro and Shasta Foy & you all
  - US Department of Energy
  - Industry colleagues
  - My former employers
- Disclaimer: Opinions expressed are of the speaker alone and not intended to reflect those of others

Thank you

Extra Slides for Q&A

A Typical Workflow in Conventionals Utilizing Log Data

(Courtesy Brett Wendt, Prez, SPWLA)

Clay Volume ←
- Natural Gamma-ray
- Cs-137 Density –Am-Be Neutron (Den-Neu)

↓

Primary Lithology ←
- Photoelectric (PEF) and Den data from Cs-137
- Den-Neu
- Sometimes Sonic

↓

Porosity ←
- Directly from Den: most accurate porosity
- Den-Neu X-Plots; Sonic to correct for light HC
- Sometimes NMR (big players)

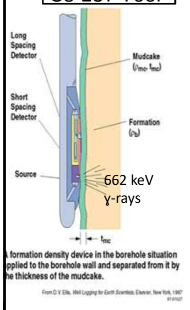
↓

Water Saturation ←
- Resistivity
- Combine with porosity, clay volume, lithology.

Alternatives to Cs-137 for Density

Cs-137 Alternatives: *Switchable*

Cs-137 Tool



- Direct (Tested): *X-rays from 3.5 MeV electron accelerator (LINAC): King et al, 1987*
  - *Logging speed 3-fold higher*
  - *Lower density sensitivity: Greater depth of investigation (D.O.I)*
  - *PE issues.*
  - *Not commercialized*
- Indirect (Tested): *γ-rays from inelastic scattering of 14-MeV neutrons from D-T generator- Initially Cased hole in 1990's: (Wilson, Badruzzaman, Odom) LWD:(Evans-2000; Reichel-2012)*
- Direct (Potential):~ A 700 keV line γ-ray generator tested by a national lab: Chen 2013- *Hardware not yet feasible for logging*

(n-gamma) Density Accuracy (Reichel et al , 2012)

Neutron Generator

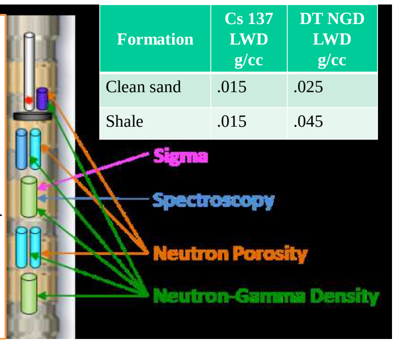
Near Neutron Detectors: Epithermal and Thermal

SS Gamma Detector

Far Neutron Det.

LS Gamma Det.

Formation	Cs 137 LWD g/cc	DT NGD LWD g/cc
Clean sand	.015	.025
Shale	.015	.045



$$I_{LS} \sim Sn^* f_1 f_2..\exp(-g\mu_c x) \quad \text{Vs.} \quad I \sim I_0 \exp(-\mu_c x)$$

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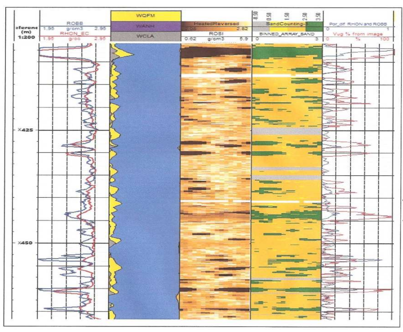
n-gamma vs. Cs-137 density: A Fractured Dolomite

Ref: del Angel et al., 2014 SPWLA Symposium Paper J



Left-most track:

RHOBB: Cs-137 density
RHON: n-gamma inelastic density

Δρ ~0.2 g/cc !!

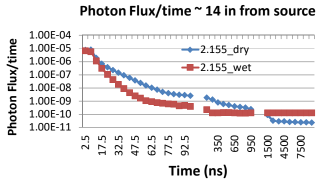
Poor vertical resolution

Vuggy formation filled with liquid?

High hydrogen index?

Why the errors? Starting point is Neutrons: Impact of H2?

Photon flux vs. time: Source on only at t=0
Wet vs. Dry Formation- same density
(Badruzzaman, Petrophysics, **55**, 5, 413-434, 2014)



Comments: 1. Wet formations : Hydrogen "softens" neutron spectrum, fewer inelastic photons produced, and thus lower counts.
Not an issue w/ Cs-137 (γ-rays) or Linac (X-ray): photon physics only

2. Complex corrections to extract inelastic gamma-ray info for density

Determined by Neutron Physics: *Not a pure density measurement*
Unlikely to be Cs-137 replacement. Special case use?

Alternatives to Am-Be source for Neutron Porosity Tools:

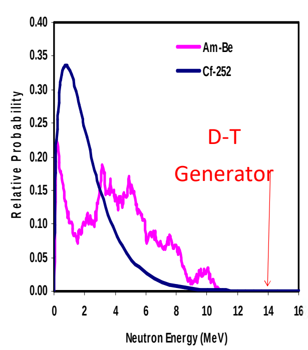
- Neutron generators (Switchable)
- Cf-252: A less "hot" source

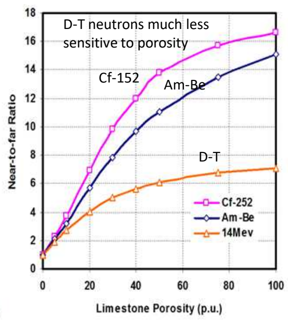
Neutron porosity: Am-Be Replacement: *Industry Effort*

- D-T generator (switchable):
  - Already used in cased-hole logging
  - Two open-hole tools in market- Wireline (1990) and LWD tool (2000, 2012)
- Cf-252 for LWD (2006): Still a chemical source; Short half-life: Recalibration, frequent replacement & disposal issues
  - Vendor was acquired by the D-T tool vendor. Future?

Physics to Porosity Response: Am-Be, Cf-252, and 14 MeV neutrons

(Xu, et al., *Petrophysics*, June, 2010)

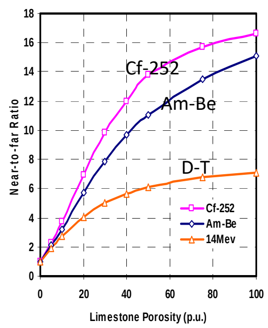




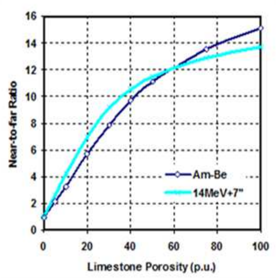
- Source Energy affects response
- Design change can help

Interpretation: Porosity w/ design change

Near-to-far ratio of a dual-detector device with source variation in a 6 -¾" tool (Xu, et al, *Petrophysics*, June, 2010)



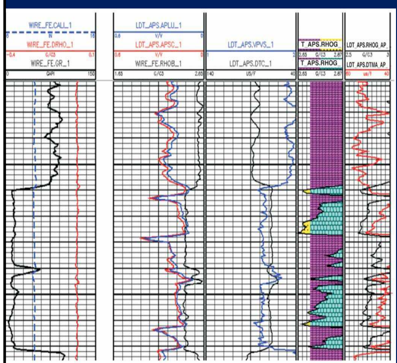
Add 7 inches to Far detector



Much closer to Am-Be

Longer tool- Desirable? Other issues?

Porosity from wireline D-T source neutron tool in wet sandstone. (Fig. Badruzzaman, Petrophysics, Vol. 46, No 3, 2005)



Why the spikes? Are we seeing carbonates?

Interpretation, Operations, or Design?

All three

High-pressure reservoir; challenging operation; tool-wall contact (standoff) varies?

Could not be corrected for by standard procedure.

Redo tool design?

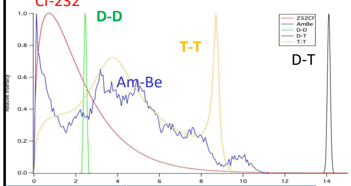
Vendor: A complex software fix- issues remain

Other Neutron Generators:

Several proposed by National Labs

Neutron Source Spectra and Neutron Yields

Data Courtesy of Dr. Jim Rutledge, Los Alamos, presented at a Teleconference with oil industry, May 2011

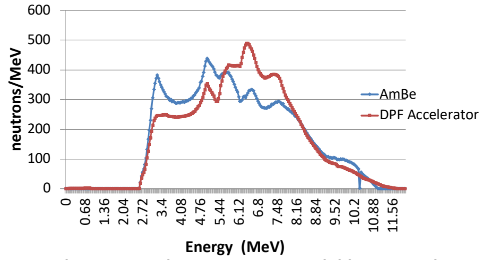


Neutron Source	Nominal Neutron Yield (n/sec)
Am-Be	1.87 x10^7
Cf-252	6.7 x 10^7
D-T	1.0x10^8
D-D	1.0x10^6
T-T	1.0x10^6

- **Comments:**
  - D-D & T-T Neutron yield too low: Too slow logging
  - T-T spectra similar to Am-Be: similar porosity sensitivity, but........
  - D-D lower energy – will show greater porosity sensitivity (a later slide), but..
- Is this all the choice?

Am-Be vs. Dense Plasma Focus Accelerator (DPF) Neutron Spectra from Theory

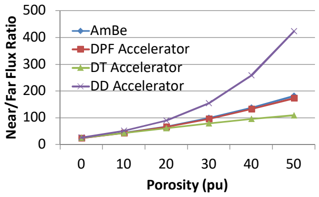
(Figure: Courtesy of Andrea Schmidt, Lawrence Livermore NL)



- **DPF Accelerator: Produce neutrons much like Am-Be but electronically**
- **Neutron yield** - DPF Acc. (model): 1.0 e+07 vs. Am-Be: 1.7E+07, DT: 1.0E+08
- ***Will DPF Accelerator function in a logging environment***?

Porosity Sensitivity in Spherical Geometry Model. Source at center. Near location is 10 inch and Far location is 22 inch

(Badruzzaman et al, Proc. 2017 SPWLA Symposium)



- Similarity between Am-Be and DPF response is expected
- D-D more sensitive to porosity, but ……
- Would the somewhat greater sensitivity of D-D response in low porosity be useful?
- A practical question: Should we bother with 'exotic' neutron sources or should D-T be the Am-Be Alternative, despite its lower porosity sensitivity?

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Why: D-T gives a richer mineralogy, in addition, plus other parameters