Alternatives to Radionuclide-based Well Logging Techniques-*Why and How?**

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[+]Opinions expressed are of the speaker alone; not intended to reflect those of others

Premise of the Presentation

- Radioactive sources: *Critically important in upstream (well logging) & downstream (monitoring), but can be risky*
- Focus on well logging sources
- *Committee's Queries (Broad Categories)*
  - Risk-Safety & Security: (Q-1 and Q-6, Q-7)
  - Alt-Tech, Now and Future: (Q-2, Q-3, Q-4, Q-5)
- Industry Landscape

Industry Landscape

- Logging Service Providers: Source licensees
  - Big-4 integrated cos; not equal on Alt-Tech state
  - Small/medium independents: Many “Mom & Pop”
    - 60-70% of US logging units
      - Use off-the-shelf technology, third party tool vendors- *compete effectively using current sources*
      - Limited technological/financial capabilities: Mandating change would likely bankrupt them
  - National logging companies

Industry Landscape (Contd.)

- Petroleum companies (Users/"operators"
  - ~Six major International Oil Companies (IOC's) -three US-origin;
    - Often complex/offshore formations; across continents
  - Smaller oil companies: Often simpler formations
  - National oil companies- Some bigger than IOC's
  - Business drivers and tech needs vary across users

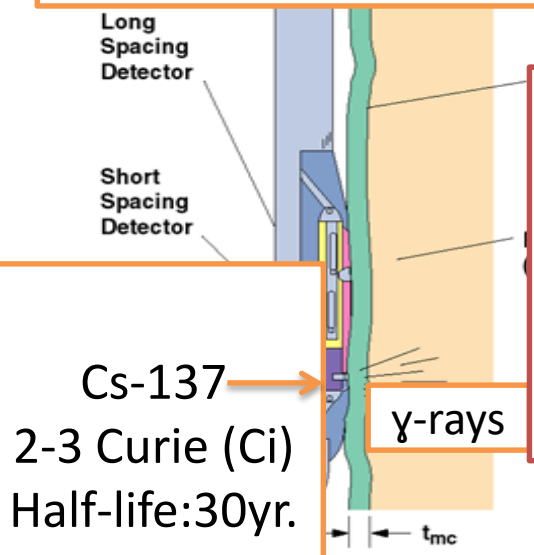
- Industry in distress

- Landscape: Diverse & complex ⇒ Complicated transition ⇒ One-size-fits-all solution is unlikely to do

Logging Source Risks Profile

Radionuclide-based Tools & Intl. Atomic Energy Agency (IAEA) Risk Category

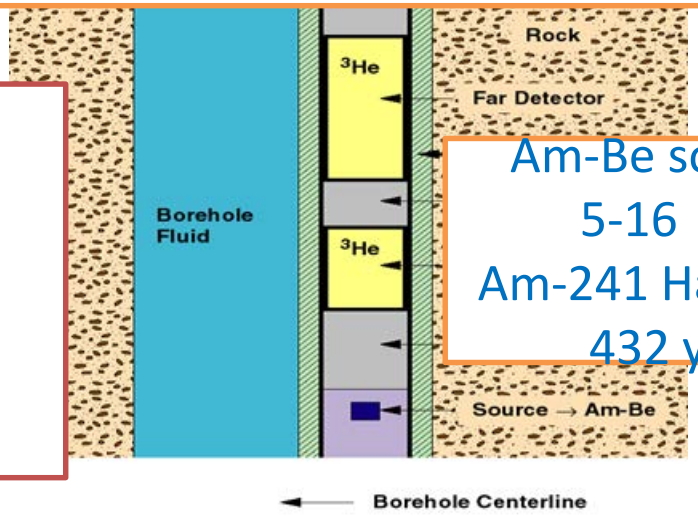
Wireline Density/PE Tool



Cs -137: Cat 3
Am-Be: Now Cat 3, but

Cat 2: Death
Cat 3: Permanent Injury

Wireline Neutron Porosity Tool



Am-Be source
5-16 Ci
Am-241 Half-life: 432 yr.

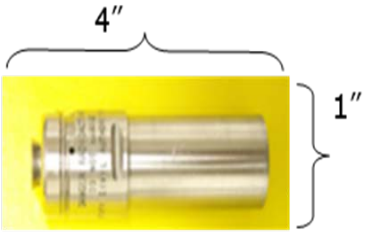
LWD tools look different- *but*, use same sources

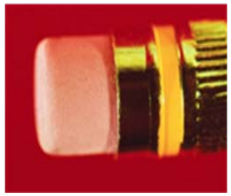
New US regulations: multiple sources on a truck can aggregate to a higher risk category

Logging Sources Storage, Transport & Concerns

Source material: *Doubly-encapsulated in steel @ 25+ Kpsi. Cs-137 src material in glass matrix.*

A Cs-137 Source Capsule (left): actual source (right) (Ref: Badruzzaman et al, SPE 123593, 2009)





An Am-Be Source Capsule (Ref: Hearn, WINS Workshop, Paris, 2014)

Main Storage: Secure Vaults (Company/Govt.)

Transport: In shielded containers: follow government or International Atomic Energy Agency (IAEA) protocols

A Neutron Source Container

A Density Source Container

Figure: Ref: SPE 123593, 2009

Site/rig storage: Often container storage

Why Security Concerns: *Small, mobile, remote use ⇒ Diversion ⇒* ***RDD****: Radiological Dispersal Device?*

Logging Source Incidents: *Examples*

- Stolen: Argentina (2009); India (1993)-several
- Lost/missing: Several
- Conflict zones/Direct attack: Libya (2013); Syria (2012/2013)/Colombia (1998)

⇒Source transportation shows the largest vulnerability

- Breached downhole: California (2006)

No RDD with logging source; all industry players recognize potential & operate accordingly, but….

Outcome of a Couple of Incidents

Ref: Badruzzaman, et al. SPE123593, 2009

- Lost/missing: Nigeria (2003): 18 Ci Am-Be pig⇒ Tiff between logging co, and oil co; pig turned up in Germany several months later!!!!!!!!! ?
  - Root cause: Lack of real-time tracking

- Breached downhole: California (2006): 2 Ci Cs-137 source breached downhole during retrieval of stuck tool

⇒ Oil Co: Radioactive mud clean-up; loss of well/production: $$$$$$$ immediately; State-imposed 300-yr monitoring- Cost?

  - Root cause: Reliance on logging co, lack of in-house decision chain

  - *Risks: Safety; environment; Security (RDD); Financial loss*

⇒ Oil co. deployed in-house source guide as complement (2010)

RDD Risk Impact of Logging Sources?

- Cs-137 density source: No suitable study: Sandia study: 3,000 Ci CsCl; logging source is 2-3 Ci vitrified Cs-137

- Am-Be neutron source: Only study I found; Henry Kelly's report to US Senate (2002) (Ref: SPE123593, 2009)
  - Medical supervision: Several city blocks
  - Five-block area: Radiation doses above annual worker max
  - Evacuation of larger area before the radiation cloud passes.
  - Impact not uniformly distributed:

  $\Rightarrow$A complex event to prepare for or mitigate

  - Was the study complete?

A Couple of Observations

- Need application-based realistic risk analysis, include physical and psycho-social impacts

- Clarify security vs. safety: Often used synonymously – In some languages, same word

- From 2017 NNSA Workshop in Kazakhstan, my SPE Distinguished Lecturer visits last year, and IAEA and NRC presentations last two days
  - ➢ Point to a ‘language barrier.’

⇒ Greater regulator-user dialog

Risk Mitigation

- Tighter Regulations: Governments: e.g., NRC requirement of background check adopted by all major logging companies as a best practice worldwide

- Tighter Protocols/New Source Handling Guides: Various players
  - One oil company deployed in-house guide as complement
  - Discussion underway (SPE): Explore source safety/security training module development

- Electronic tracking by licensee- e-tagging of container. Technology developed by PNNL; field-tested by one large logging company- likely to deploy

- Alternative Technologies: Industry, national labs

Alt-Tech

- Ultimate Mitigation
- Industry R&D Alt-Tech: 37+ yr.– mixed results, but new ideas
- Alt-Tech: Non-nuclear and accelerator-based

Reservoir Characterization

- Parameters
  - *Porosity*: Volume fraction of rock that is porous
  - *Saturation* (of desired fluid): Fraction of pore fluid that is the desired fluid (water, oil or gas)
  - *Permeability*: Composite of properties of solid matrix that allow or hinder flow
  - *Lithology (rock type*), *mineralogy*: Affects all of the above

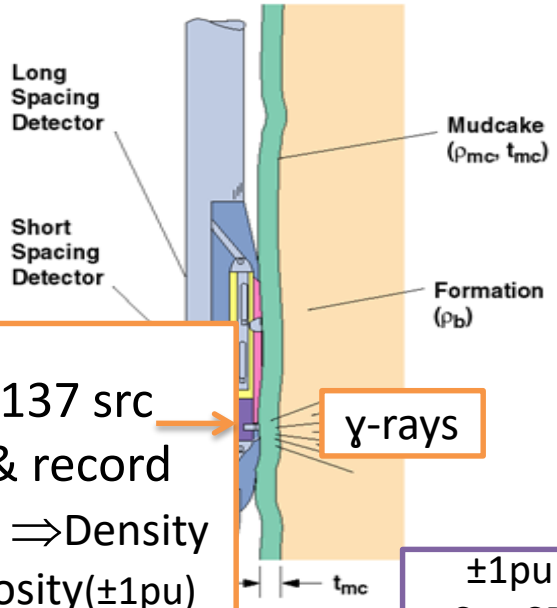
Measuring Subsurface Parameters for Reservoir Characterization

- Core sampling: Extracting rock samples for laboratory measurement

- Well Logging: Continuous downhole measurement
  - Wireline logging: Insert instrument string, post-drilling
  - Logging-While-Drilling (LWD)
  - Devices:
    - Radioactive source-based: Mainly
    - Acoustic, NMR (MRI): Special purpose

Radionuclide-based Tools & Measurements

Wireline Density/PE Tool

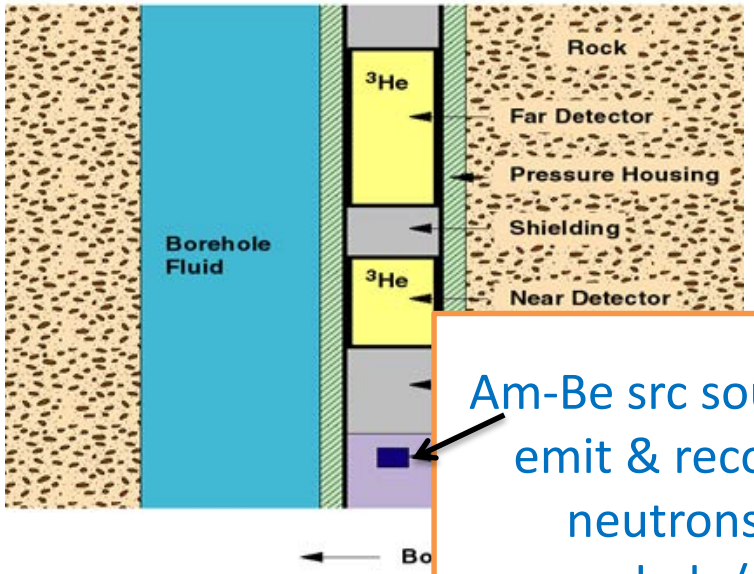


Cs-137 src emit & record ɣ-rays ⇒Density ⇒ porosity(±1pu) ⇒reserves
PE ⇒ Image,

ɣ-rays

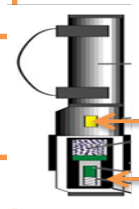
±1pu uncertainty: See SPE 123593 for estimate of economic impact

Wireline Neutron Porosity Tool



Am-Be src source: emit & record neutrons ⇒ gas, shale/sand

Mineralogy Tool



emit neutrons → capture ɣ's

Am-Be src

detector: ɣ counts vs. energy → mineralogy

D-T generator → inelastic + capture ɣ's ⇒ better mineralogy

Am-Be will be replaced:
Not discussed further

Alt-Tech as Replacement

(US DOE Scoping Study LLNL TR-679101,2015)

- Accuracy (±1 pu in porosity) & equivalence
- Reliability: *How to ensure this?*
- Operational compatibility (e.g.: logging speed)
- Survivability (> 175^0 C; > 25 kpsia; 1000G in LWD, etc.)
- Cost: Develop, deploy, & use
- *Will new technology fit all players, large & small?*

Non-nuclear Logging Techniques

Parameter	Acoustic	NMR
Physics: Porosity from	Δt of sonic wave	Magnetic polarization/ relaxation constant
Porosity accuracy[+]	±2-4 pu	±2 pu: can it improve?
Lithology++	Limited	No
Mineralogy++	No	No
Inapplicable in	Unconsolidated sands: Major fields	Very low porosity; micro-pores & paramagnetics: Major fields
Logging speed?	1800 ft./hr. plus	Wireline: ~ 240 ft./hr.
Cost	Moderate	High*
Additional value	Anisotropy	Fluid type; Permeability indicator

[+] Cs-137 density porosity accuracy: ± 1 pu; ++ Am-Be provides these

* Complex technology: Unaffordable/unusable by small players.

Nuclear-based Alternatives

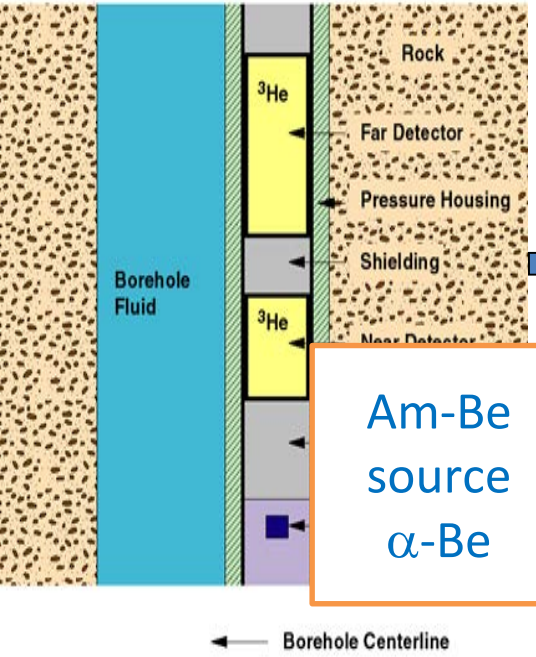
Tested Alternatives to Cs-137 for Density

Parameter	Cs-137: Ref	INGD	X-ray density
Density from	Compton scattering of emitted ɣ-rays	Scattering of y-rays from inelastic scatter of 14 MeV D-T neutrons	Scattering of X-rays from 350 keV end-point X-ray source
Physics:	Photon only	Coupled n-photon	Photon only
Nominal Δρ	±0.015 g/cc Clean & shale	±0.025: Clean ±0.045 shale much worse in field	Similar to Cs-137 with large photoelectric correction
Δ(Porosity) sand/shale	< ± 0.6pu	±1.5 pu (sand) ± 2.7 pu (shale)	±1 pu: if PE correction correct
Z-effect++	**Correctable**	No?	strong
Inapplicable in	**N/A**	N/A	High Z rocks?
Logging speed?	1800 ft/hr	1800 ft./hr. plus	Similar
Cost		Moderate to high*	High*

*Will be unaffordable by small players

Am-Be Alternatives: *n-Generators*

Wireline Neutron Porosity Tool



Am-Be source
α-Be

Generators

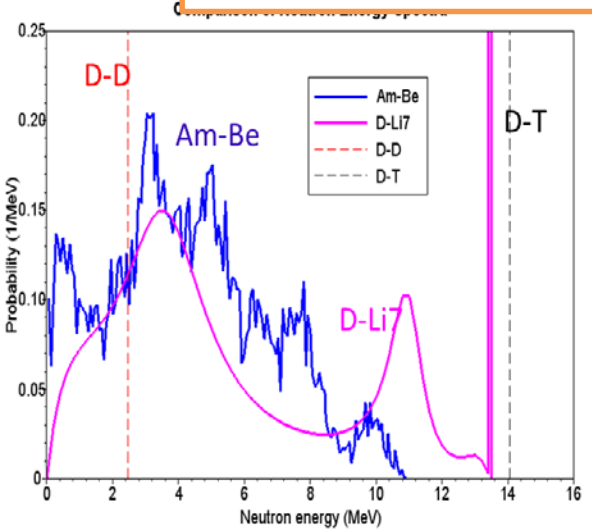
Fusion:

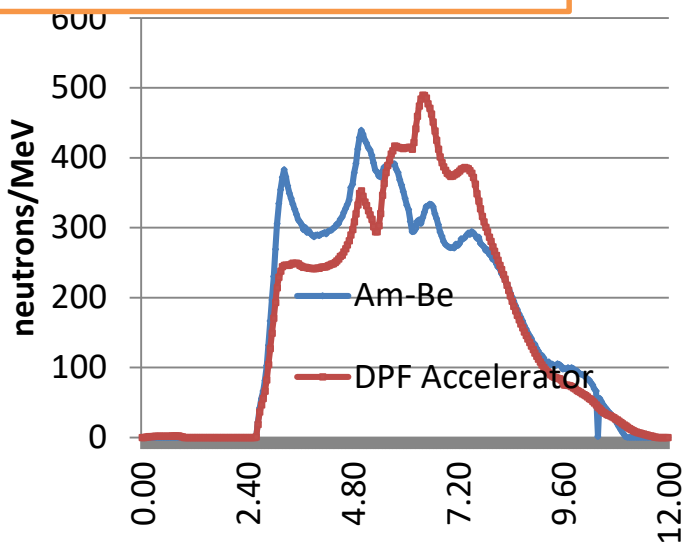
Projectile ⟶ target

⇒ Fused nucleus + n's

DPF: electronic α-Be

Energy Distribution





- Generator output
  ➡ Logging speed
- Proximity to Am-Be neutron spectra
  ➡ proximity to response

Source Type	Nominal n/sec
Am-Be	$2x10^7$
D-T	10^8
D-D	10^6
D-Li7	10^6
DPF	10^7

Neutron Generators Vs. Am-Be Tradeoffs: key attributes

(Conclusions Badruzzaman et al, Petrophysics, 55, February, 2019)

Attribute	D-T	D-D	D-Li7	DPF
Neutrons	Higher energy	Lower energy	Similar	Identical
Porosity sensitivity	**Less; can improve w/ design, but..**	**Greater, but low far counts**	Similar	identical
D.O.I	**Greater**	Lower, but…	Likely similar	Similar
Standoff effect	**Greater**	**Much Less**	Similar	Similar
Am-Be equivalence	A complex algorithm	**Less complex vs. D-T**	Similar	Similar
Mineralogy	**Better: More info**	Capture only	Better: Inelastic & capture?	Similar: Capture
Logging Speed	**Can be faster**	**Slower- but..**	Slower	Similar?
Source Adaptability	**Industry-tested**; T^3 radioactive; dual-use	Likely with research	Challenge	Long term R&D

- No magic bullet yet: will need tradeoff
- D-D tools being tested (US, Ukraine) ⇒ Other advanced generators?

State of Service Companies with Advanced Nuclear-based Logging Technology

- **Am-Be Alternative for porosity**:
  - One large Co: D-T-based, for Wireline and LWD tools (marketed)- LWD tool does well; wireline tool not so well
  - Two large Cos: Tested ideas
  - One SBIR-funded generator co: Designed and tested a slim D-D-based neutron tool for shallow wells in non-petroleum applications
- **CS-137 Alternative for density:**
  - One large co.: INGD (marketed); X-Ray density(experimental)
  - One SBIR-funded Co: Studying 1-MeV Linac-based density
- **Am-Be Alternative for mineralogy: D-T based**
  - It is here: Two major logging companies can supply it, but mostly for special case applications (e.g., shale oi/gas)

Economics

- Somewhat speculative
- D-T generator tools: $50K + $250K+testing
- X-ray density tool: Not clear
- Larger companies can possibly move if business picks up
- Alt-tech ⟺ high-tech: *Unaffordable for small cos- supply 70% logging units in the US,*
  - ❑*Mandating will bankrupt them*
  - ❑*Recommended technology/funding support, but, transition would likely be unaffordable now for them, even with support*

- *Will customer pay for new-tech due to cost?*

State of Alternatives

- Marketed alternatives: Not all are replacement quality yet, economics uncertain, and unaffordable for most, especially now
  - Expect advance in ~ 10 years by major logging companies specially, if mandated

- Novel electronic sources: Promising; to be proven
  - With novel detectors $\Rightarrow$ New parameters likely (see DOE BRN report)

- Generator failure a major concern: Multiple generators!!!?

  $\Rightarrow$Predictive failure diagnostics with AI: suggested in proposed 2020 DOE OS BRN Workshop Report

A Set of Personal Observation

- Application-based risk assessment is missing
  - Cs-137 replacement may not be urgent
  - Replacing 3-5 Ci Am-Be sources used by small companies in some low-cost applications may not be as urgent

- One-size-fits-all approach will not work

- Incentive for replacement should include business drivers, not just security.

Committee Questions

- Q-1: Safety/security issues: Gave examples and noted some issues on current logging risk determination.

- Q-2. Technical Challenges: Discussed- most can be overcome

- Q-3 Progress made in past decade: Discussed.
  - Experimental X-ray density tool
  - Experimental D-D generator neutron tool for shallow applications
  - Much better understanding of response issues- Modeling was key in this.
  - Note that only one major company has hardware for all three types of measurements that they have deployed or tested- ways to go.
  - Other major logging cos. are studying it on the side.
  - Trying to induce the small companies to start looking at the options with modeling- Will need support. Their challenges are huge

Q-4: Evolution of well logging services in next decade, will Alt-tech be adopted

- Will depend on where a given service co is on technology and what the needs of its customers are.
- The major logging co. that has done the most would likely continue to push, can transition in 10-yrs, if mandated
- But some major oil cos., do not appear that eager-feel technology isn't there and their economics may not be there, either.
- Other major cos may follow if their customers want change views.

- Will depend on where national and international regulations go, especially with generators and X-rays.
- Small companies are unlikely to proceed- will definitely need support, but even that may not suffice.

5. Turnover of technologies, duration of phase out likely, Areas of irreversible loss of capabilities?

- Unless mandated to phase out, source use will continue. Source use is inexpensive, gives valuable and reliable info. Will maintain capability, as an option.
- Mandate will bankrupt small cos and drive up cost of business? Is that desirable?
- To transition to source-less logging, technology and funding support is needed. Needs further exploration: National lab-support, tax breaks?
- One major co person an and a large oil co person suggested formation of a consortium, but could not to commit participation in the current economics
- An SBIR-funded non-logging generator company developed a D-D neutron porosity tool for non-petroleum applications. Is looking for clients.
- But is the SBIR approach the correct model for small logging cos, invested in sources with a client base that may not be able afford to or willing to meet the cost associated?
- I am suggesting the above two groups to partner, but D-D has technical challenges for deep wells and the company will have to redesign

6. Cost of neutron sources re-categorized to Cat 2

- Interesting question. Struggled with it. Likely scenarios:
  - Will Reduce activity of meet the new Cat 3 requirement $\Rightarrow$ Repackaging cost, replace current sources and pay for additional rig time to get the counts needed.
  - Could go to Cf-252, etc., but physics will have to be addressed and recalibration would be needed.
  - Each service company would have to do a cost/benefit analysis and look at its business drivers.
  - Some may push back
  - Some may go bankrupt.
  - Not sure if the disruption would be worth it at this point.

7. **How much time, attention, and money put towards rad source security?**

- Hard to get numbers from individual companies.
- One estimated $500k annually across entire industry
- Additional cost for liability, lost-in-hole and fishing operations
- Time and attention: Hard to quantify?

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Thank you

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Extra Slides

Porosity Accuracy: Reserves Uncertainty with 1 Porosity Unit (pu) Error

(Fig: Badruzzaman et al., SPE 123593, 2009)

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

- Some major reservoirs: 5-10 pu; nominal reserve: 50+ billion bbl
- Cs-137 source density: ±1-pu or better in porosity