ALTERNATIVE TECHNOLOGIES FOR RADIATION SOURCES FOR WELL LOGGERS

ROADMAPPING WORKSHOP REPORT

JANUARY 2018

An IfM Education and Consultancy Services Report

ROADMAPPING WORKSHOP FOR IDENTIFYING ALTERNATIVE TECHNOLOGIES FOR RADIATION SOURCES IN THE ENERGY INDUSTRY

January 2018

This workshop is commissioned by NuSec and AWE and supported by BP. The report was prepared by:

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EXECUTIVE SUMMARY

The energy industry (principally oil and gas) has been using radioactive sources as well loggers to obtain geological information about subsurface rocks. The UK Home Office has identified the use of radioactive or nuclear (RN) material in well loggers as being an issue for UK security. While the use of RN material as part of terrorism is less likely than other terror activities, the societal and financial consequences are very high if such an event takes place. Even where RN materials are kept under tight regulatory control, their existence adds complexity to the task of maintaining UK border and homeland security. Thus, reducing the availability of RN materials is a route to reducing the risk of RN terror activities.

AWE and the Nuclear Security Science Network (NuSec) organised a workshop with participants from the public sector, industry and academia to identify possible alternative technologies for radiation sources for well loggers. The workshop had the following aims:

- To identify a potential list of alternative technologies for well loggers;
- To scope out the best alternative technologies and identify the required developments, including the identification of any specific enablers (e.g. partner organisations, funding) and barriers;
- To provide to policy and programme stakeholders (e.g. regulatory bodies, the UK government, RCUK) evidence for the feasibility of change and evidence for funding requirements.

The most important drivers, trends and industry needs identified during the workshop were as follows.

- Provide suitable alternatives to radioisotope sources with compact, lower-cost technologies.
- Demonstrate quality of measurement uncertainty and identify methods to reduce it.
- Productise the solutions and offer to the wider industry; educate and inform of risks, solutions and benefits.
- Regulatory alignment and similar regulatory regime in multiple countries, not just UK.
- Understand the true costs of current technology and increase cost efficiency of prospecting and well logging.

Overall, 24 alternative technologies were assessed in detail using pre-selected criteria of opportunity and feasibility. The following five technologies were selected for further exploration during the workshop based on their detailed scores:

- Acoustic;
- Pulsed neutron generators;
- NMR;
- Data analytics and modelling;
- X-rays.

These technologies were scoped and explored in more detail in small focus groups. The technology developments required for their commercialisation were explored, as well as the milestones and the energy industry adjustments required for their adoption. Current and anticipated enablers were identified, as well as barriers that limit the worldwide adoption of each technology.

The following actions were considered important for reducing and eventually eliminating the use of radiological or nuclear material by the energy industry.

- Continuation of engagement of all actors, including the UK Home Office, BEIS and the US government;
- Communication of results to SPWLA Nuclear Logging SIG, Nuclear Threat Initiative (NTI) and the individual organisations that participated in the workshop;
- Identification of a project with industry and operators to compare data between different techniques;
- Promoting more education of industry (especially drilling engineers) about the risks of using RN sources;
- Generating more topic roadmaps on other technologies that were not assessed during the workshop.

WORKSHOP GOALS

BACKGROUND

The Nuclear Security Science Network (NuSec) [1] promotes research and technology in nuclear security science, with an emphasis on radiological detection techniques and systems. The Network is open to all academic, industrial and government scientists and engineers working in nuclear security, and acts as a forum to encourage collaboration, networking and capability for all stakeholders. The UK Home Office, Ministry of Defence (MoD), the Department of Health and DEFRA, together with several UK universities, provide oversight and sponsorship on NuSec's activities and programmes. The network is a three-year project led by the University of Surrey in partnership with AWE. AWE [2] has been at the forefront of the UK nuclear deterrence programme for more than sixty years. AWE is a centre of scientific, engineering and technological excellence, equipped with some of the most advanced research, design and production facilities in the world. AWE's Nuclear Threat Reduction programme leverages its nuclear weapons expertise to support the Ministry of Defence (MOD) and other Government departments working to identify worldwide and UK-based nuclear threats – using cutting-edge scientific methods and instrumentation to assist with threat reduction and counter-terrorism. Work includes enhancing capability to detect special nuclear material at the UK's borders; nuclear forensics to identify the origin of materials and 24/7 nuclear accident response as part of the Government's national emergency response arrangements. The energy industry has been using RN sources and measurement methods to determine oil well characteristics such as porosity, elemental composition and the presence of oil or water [3]. The threat to the UK from terrorism as assessed by the Joint Terrorism Analysis Centre (JTAC) is currently set as "SEVERE" meaning that an attack is considered highly likely. Whilst there is no indication that any individual or group has any of credible plans to use RN material in a terrorist attack today, it is known that some terrorist groups aspire to acquire and use RN materials. This has therefore generated an impetus for identifying alternative technologies that could be adopted by the energy industry to reduce the risk of RN material being acquired by terrorist groups.

Previous work by the US Department of Energy has provided guidelines [4] and the US Government Accountability Office has authored additional actions [5] to increase the security of industrial radiological sources. Some early alternative technology exists but has not been widely adopted by the energy industry. There remains the challenge of replacing RN sources with alternative technologies.

[1] www.nusec.uk

[2] http://www.awe.co.uk

[3] Radiation source use and replacement, Chapter 9, page 151 (2008). National Research Council, The National Academies Press, https://doi.org/10.17226/11976

[4] Security and Control of High Activity Well Logging Sources, Guidelines, co-authored by the US Department of Energy and the Oilfield Services Industry, 8 August 2008.

[5] Additional Actions Needed to Increase the Security of US Industrial Radiological Sources, UnS Government Accountability Office, June 2014.

AIMS

The primary aim of the workshop was to identify suitable alternative technologies for well logging to reduce the risk of RN threats through reducing the presence and availability of RN materials. The desired workshop output was collected evidence for industry, academia and government to facilitate policy, programme and investment decisions. The evidence was structured so that progress towards the goals can be demonstrated and verified.

The workshop was a collaborative partnership project between the University of Surrey (the NuSec network), AWE and its Strategic Alliance with the University of Cambridge and BP.

The workshop's specific aims were to:

- Identify a potential list of alternative technologies for radiation sources for well loggers;
- Scope out the best alternative technologies and identify the required developments, including the identification of any specific enablers (e.g. partner organisations, funding) and barriers;
- Provide evidence for policy, industry, academia and government to facilitate policy, programme and investment decisions.

The workshop was designed to capture and prioritise the industrial requirements, identify and select the most suitable alternative technologies for radiation sources and to explore these technologies in more detail. Aspects such as technology developments, and enablers and barriers, were discussed and summarised for each selected alternative technology.

Overall, 26 participants contributed to the workshop. The participants were from industry, academia and government, with many diverse organisations represented, such as: NNSA, BP, GE-Baker, Haliburton, Schlumberger, Society of Petrophysicists and Well Log Analysts (SPWLA), Ocean Drilling Programme, nuclear and radiation science community, Quantum sensing community, National Physical Laboratory, Science and Technology Facilities Council, Knowledge Transfer Network.

WORKSHOP DETAILS

This workshop was commissioned by NuSec and AWE, supported by BP and delivered by IfM Education and Consultancy Services Limited.

DATE

17 January 2018, 9.30am–5.00pm

VENUE

The Maxwell Centre
JJ Thomson Ave
Cambridge
CB3 0HE

FACILITATORS

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IfM Education and Consultancy Services

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BP plc.

WORKSHOP SPONSOR

Neil Gaspar,
Nuclear Threat Reduction
AWE

ACKNOWLEDGMENT

Editorial work to this report by some of the participants is gratefully acknowledged.

*Workshop participants are listed in Appendix I

WORKSHOP METHODOLOGY

The Roadmapping Workshop methodology consisted of three parts: scoping and design; the workshop; and the reporting of the workshop outcomes.

SCOPING AND DESIGN

During the scoping and design phase, the following activities took place:

- Confirming and detailing the aims and scope of the workshop.
- Discussing and designing the workshop methodology and process. The workshop used the **S-Plan** framework that was developed by the IfM over a period of several years [6, 7, 8]. The framework has been configured to support universities and research organisations to align their research activities with industry needs, supporting decision-making and action. The workshop also used a scoring method [9] developed by the IfM, which provided a systematic way of assessing the different technologies.
- Designing the templates necessary to support the workshop activities.
- Agreeing on the selection criteria that are important for NuSec in assessing the different technology options.
- Agreeing the detailed workshop agenda.

WORKSHOP

The workshop process brought together 26 participants from government, academia and industry and had the following structure:

- Welcome and introductions by Neil Gaspar, Nuclear Threat Reduction, AWE;
- A presentation by Richard Cronie, Office for Security and Counter Terrorism, UK Home Office, on the UK context and challenge;
- A presentation by Nick Butler, Office of Radiological Security, US NNSA, on the US context and previous work;
- A presentation by Ahmed Badruzzaman, Society for Petrophysicists and Well Log Analysts and advisor to US NNSA, on the energy industry context;
- A presentation by each participant about suitable alternative technologies to address the main requirements;
- Prioritisation of government and industry requirements;
- Prioritisation of alternative technologies using pre-defined criteria;
- Selection of the most appropriate technologies for further exploration;

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[6] http://www3.eng.cam.ac.uk/research_db/publications/rp108

[7] Phaal, R., Farrukh, C.J.P. and Probert, D.R. (2004), "Customizing Roadmapping", *Research Technology Management,* 47 (2), pp. 26–37.

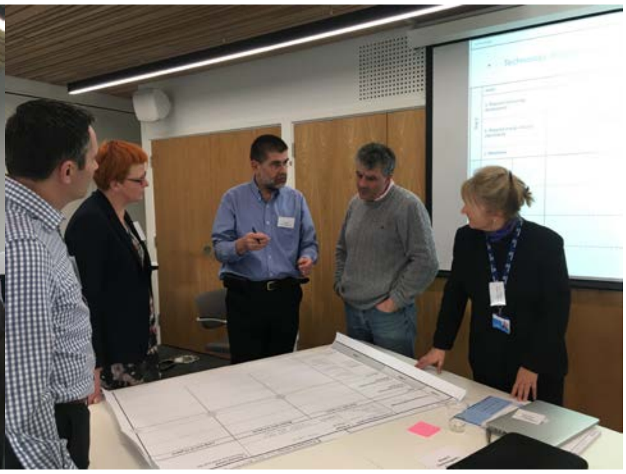
[8] Phaal, R., Farrukh, C.J.P. and Probert, D.R. (2007), "Strategic Roadmapping: A workshop-based approach for identifying and exploring innovation issues and opportunities", *Engineering Management Journal,* 19 (1), pp. 16–24*.*

[9] Rick Mitchell, Rob Phaal, Nikoletta Athanassopoulou, (2014), "A scoring method for prioritizing and selecting innovation projects", Proceedings of the Portland International Conference on Management of Engineering and Technology (PICMET), Kanazawa, 27–31 July.

- Exploration of the selected technologies in small groups, and clarification of the enablers and barriers for their adoption by the energy industry;
- Feedback and review;
- Closing remarks and next steps by Neil Gaspar.

REPORTING OF OUTCOMES

Finally, IfM ECS transcribed all the output from the workshop in electronic format, drafted the current report and distributed it to NuSec for review and wider circulation.

WORKSHOP INSIGHTS

LANDSCAPE SUMMARRY

The landscape covers three time periods: the short term (0–3 years, i.e. up to 2021); the medium term (3–5 years, i.e. up to 2023); and the long term (5–10 years, i.e. up to 2028). It includes two broad layers: (1) government and oil industry requirements; and (2) alternative technologies for radiation sources in the oil industry.

The first layer, “government and oil industry requirements”, is further subdivided into six sub-layers following the STEEPLE classification, namely, social, technological, economic, ethical/political/legislative, environmental and other.

The second layer, “alternative technologies for radiation sources in the oil industry”, is further subdivided into four sub-layers: alternative ways of producing ionising radiation, passive measurements, active techniques and other.

In total 29 government and industry requirements and 25 alternative technologies were prioritised.

Figure 1 (below) shows the government and industry requirements and alternative technologies that received votes during the workshop. Darker shaded items indicate a larger number of votes.

Alternative technologies for radiation sources for well loggers		Short term 0-3 years	Medium term 3-5 years	Long term 5-10 years
Requirements	Social		Productise the solutions and offer to the wider industry, educate and inform of risks, solutions and benefits	
	Technological	Provide suitable alternatives to radioisotopes sources with compact, lower cost technologies		
		Improved accuracy and precision, faster logging speed, robust measurements in complex conditions	Data mining for enhanced prospecting methods	
			Multiple and deeper depths of investigation	Productise the solutions and offer to the wider industry
	Economic	Understand true costs of current technology and increase cost efficiency of prospecting and well logging		
		Provide financial incentives for an orderly transition to new technologies		
				Develop expertise, technology and capability for UK manufacturing hub
	Environmental	Eliminate the use of radioactive materials to minimise environmental impact		
			Low cost detectors, reduction in costs for dedicated radioactive sources	Look to move to induced sources, X-ray or NMR and the solution
	Political/Legal/Ethical	Minimise regulatory burden and costs across all parties		
		Regulators alignment and similar regulatory regime in multiple countries, not just UK		
		Ensure high level of public confidence in government's ability to mitigate the threat of terrorism		
	Other		e-tagging: Encourage all logging companies operating in the UK to test and adopt the PNNL-developed technology (or similar technology) to e-tag the source container	
		In general, consider, collectively, the state in the UK of the four major source risk mitigation options noted: regulations, industry protocols, e-tagging of sources, and Alt-Tech, and identify gaps to improve source security.	Regulations/protocols: Encourage small/regional logging companies to adopt the practice of background check of personnel handling sources and the protocol of two-person entry to source vaults. International logging companies have adopted both.	
		Demonstrate quality of measurement uncertainty and identify methods to reduce it		
Alternative technologies	Alternative ways of producing ionising radiation	High energy X-ray generators		
		Accelerators and small linacs		
		Pulsed Neutron generators		
		Radiological sources		
		Data analytics and modelling		
		Centrifugal source		
	Passive measurements	Gravimetry and Gravity gradiometry		
		Muon High Energy Particles		
		Super high resolution gamma spectroscopy		
		Seismic data		Quantum II electromagnetic or gravitational techniques
	Active techniques		Electromagnetic techniques (Dielectric dispersion MHz to GHz only)	
		NMR		
		Acoustic methods (sonic, ultrasonic etc.)		
		Thermal	Chemical tracer replacements for short-lived radioactive tracers	Data fusion and integration
		Acoustic methods (Radiation induced acoustic techniques)		
		Combination of non-nuclear and radiation technology (e.g. NMR and Cs-137 density) to reduce use of only radionuclide-based tools	Enforce porosity gathering even in bad hole conditions	
	Other		Dielectric laser acceleration (gamma)	
		Coring / SideWall coring / Digital coring		
		Large scale - surface land response		Micro-robotics - swarm sensors
		Control and Security Techniques		Biological techniques

Figure 1: Summary of workshop output of priority government and industry requirements and alternative technologies for radiation sources

GOVERNMENT AND ENERGY INDUSTRY REQUIREMENTS

Prior to the workshop, most participants contributed their perspectives on the most important government and energy industry requirements. In total 29 requirements were put forward, which are listed in Appendix IV.

The requirements were classified under six areas: social, technological, economic, environmental, political/legal/ethical and other. Most requirements fell under the "technological" and "other" categories. The breakdown of the requirements across the different categories is shown below.

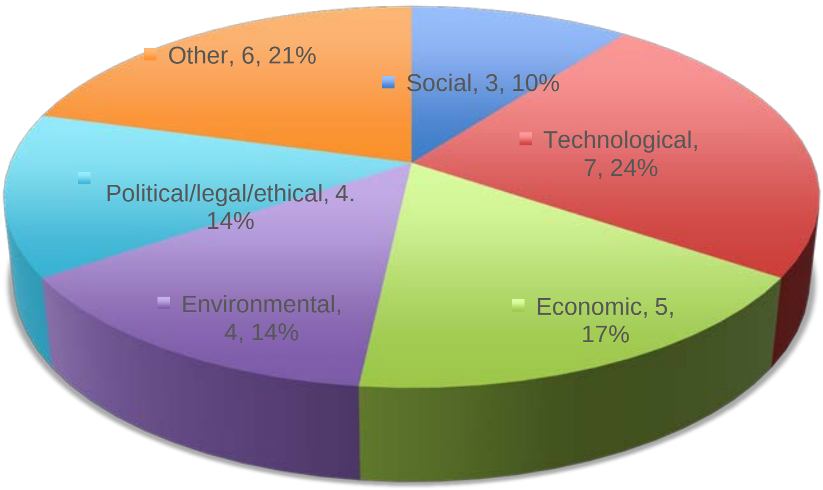


Figure 2: Breakdown of government and energy industry requirements proposed for each different category

These requirements were reviewed at the beginning of the workshop. They were prioritised by providing each participant with four sticky dots and asking each of them to select a maximum of four requirements that they considered to be the most important. Different colour votes were provided to government, industry, and science and technology participants to understand the priority needs of the different stakeholders. The 14 priority requirements (voted by 2 or more stakeholder groups) are shown in Figure 3 (below).

Government and energy industry requirements	Roadmap layer	Time-frame	Indu-stry votes	Science and tech. votes	Govern-ment votes
Provide suitable alternatives to radioisotope sources with compact, lower-cost technologies.	Technological	ST-LT	2	4	4
Demonstrate quality of measurement uncertainty and identify methods to reduce it.	Other	ST-MT	3	4	2
Productise the solutions and offer to the wider industry, educate and inform of risks, solutions and benefits.	Social	MT-LT	5	1	1
Regulatory alignment and similar regulatory regime in multiple countries, not just UK.	Political/legal/ethical	ST-LT	2	2	2
Understand the true costs of current technology and increase cost efficiency of prospecting and well logging.	Economic	ST-LT	2	2	1

Eliminate the use of radioactive materials to minimise environmental impact.	Environmental	ST-LT	1	3	1
Data mining for enhanced prospecting methods.	Technological	MT-LT	1	3	0
Look to move to induced sources, X-ray or NMR and the solution.	Environmental	LT	2	2	0
e-tagging: Encourage all logging companies operating in the UK to test and adopt the PNNL-developed technology (or similar technology) to e-tag the source container.	Other	MT	3	1	0
In general, consider, collectively, the state in the UK of the four major source risk mitigation options noted: regulations, industry protocols, e-tagging of sources, and Alt-Tech, and identify gaps to improve source security.	Other	ST	2	2	0
Regulations/protocols: Encourage small/regional logging companies to adopt the practice of background checks of personnel handling sources and the protocol of two-person entry to source vaults. International logging companies have adopted both.	Other	MT	0	1	2
Develop expertise, technology and capability for UK manufacturing hub.	Economic	LT	1	1	1
Productise the solutions and offer to the wider industry.	Technological	LT	2	0	1
Minimise regulatory burden and costs across all parties.	Political/legal/ethical	ST-MT	0	1	1

Figure 3: Prioritised government and energy industry requirements

Some requirements were important for one stakeholder group only. These are shown below.

Government and energy industry requirements	Roadmap layer	Time-frame	Indu-stry votes	Science and tech. votes	Govern-ment votes
Improved accuracy and precision, faster logging speed, robust measurements in complex conditions.	Technological	ST	0	3	0
Low-cost detectors, reduction in costs for dedicated radioactive sources.	Economic	MT	0	3	0
New measurements with focus on brown fields and marginal fields.	Technological	LT	1	0	0
Ensure high level of public confidence in government's ability to mitigate the threat of terrorism.	Political/legal/ethical	ST-LT	0	0	3
Public perceptions of the oil industry.	Social	ST	1	0	0
Assess the broad Industry landscape in the UK, technical and non-technical (small vs small companies, etc.), in the context of the above, especially assessments and studies completed or reported elsewhere.	Other	ST	1	0	0
Continued need for offshore scientific investigation to understand climate and sea-level change.	Environmental	LT	0	1	0
Multiple and deeper depths of investigation.	Technological	MT	2	0	0

Figure 4: Requirements important for single stakeholder groups only, namely, the government, energy industry or science and technology

ALTERNATIVE TECHNOLOGIES FOR RADIATION SOURCES IN THE ENERGY INDUSTRY

Prior to the workshop, participants were asked to propose alternative technologies that could be used as radiation sources for the energy industry. In total 25 technologies were put forward. The technologies were classified under four areas: alternative ways of producing ionising radiation, passive measurements, active techniques and other.

Most technologies proposed fell under the "active technologies" category, although there was good balance across all categories. The breakdown of the technologies put forward by the participants across the different categories is shown below.

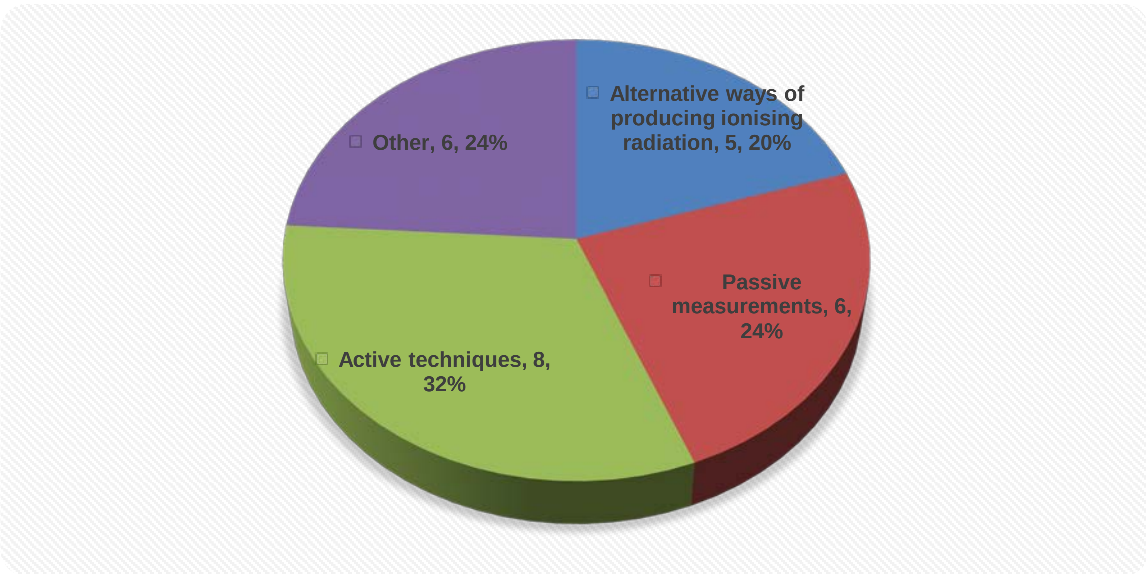


Figure 5: Breakdown of alternative technologies proposed for each different category

All technologies were prioritised by the participants using two different and broadly separate considerations: feasibility and opportunity. Feasibility was defined as how well prepared the energy industry is to exploit the technology. Opportunity was defined as the magnitude of the opportunity plausibly available to the energy industry in terms of cost versus benefit, risk reduction potential and data/information gains.

The opportunity and feasibility criteria were selected prior to the workshop by NuSec and AWE; they are shown in Figure 6 (below), together with the detailed scoring framework used during the workshop. The scoring framework was designed with a linear scoring scale of 0–12, and specific statements under each score to improve consistency.

Feasibility criteria		**Scaling statements for feasibility**				
	Definition	**0**	**3**	**6**	**9**	**12**
Technical challenge	Confidence that the proposed technology is technically feasible.	Key features not yet demonstrated for prospecting.	Some key features not demonstrated but we are confident they can be.	Key features have been demonstrated in prototype, but other features and system	All features have been demonstrated in prototype, some system integration established.	All features and integration have been tested and are fully functional

		TRL 0-2 as applied to prospecting.	TRL 3-4 as applied to prospecting.	integration remain to be demonstrated. TRL 5-6 as applied to prospecting.	TRL 7-8 as applied to prospecting.	TRL 9-10 as applied to prospecting.
Timeliness	How quickly can this technology completely remove radioactive/ nuclear materials?	No clear view of when.	Will be ready to replace all use of RN materials in 10 years OR replace worst radioactive/ nuclear materials in 5 years.	Will be ready to replace all use of RN materials in 5 years OR replace worst radioactive/ nuclear materials today.	Will be ready to replace all use of RN materials in 3 years.	Technically ready to replace all use of RN materials today.
Adoption by industry	Fit to industrial/ commercial/ regulatory systems	Companies AND their relationships need significant restructure. OR New regulations required.	Companies OR their relationships need significant restructure. OR New regulations needed but can be based on existing regulations.	Companies OR their relationships need minor changes. OR Notable changes needed to existing regulations or regulatory control.	Companies AND their relationships need minor changes OR Minor changes needed to existing regulations or regulatory control.	New technology fits directly into existing commercial and industrial environment. OR No new regulations or regulatory control needed within energy industry.

Opportunity criteria		**Scaling statements for opportunity**				
Operational cost efficiency	Same or improved cost to benefit efficiency in prospecting.	Operational cost to benefit efficiency is sufficiently negative to affect business practice.	Operational cost to benefit efficiency is slightly negative but within current business envelope.	Operational cost to benefit efficiency is same as existing technology.	Operational cost to benefit efficiency is slightly better but within current business envelope.	Operational cost to benefit efficiency is sufficiently better to change business practice.
Reduce risk and regulation	Technology reduces risks from regulatory change.	Technology is subject to an imminent high-impact regulatory change.	Technology will be subject to risk of high likelihood AND high-impact regulatory change.	Technology will be subject to risk of high-likelihood, low-impact OR Low-likelihood, high-impact regulatory change.	Technology will be subject to risk of low-likelihood, low-impact regulatory change.	Technology is not subject to any foreseeable regulations.
Data enhance-ment	Obtaining higher-value data versus current options.	New data doesn't cover all existing measurands AND where it does with higher uncertainty.	New data covers a few existing measurands with same uncertainty OR all measurands with higher uncertainty.	New data is the same, with the same uncertainties.	New data covers existing measurands at lower uncertainty OR all existing measurands at same uncertainty, plus additional useful measurands at any useable uncertainty.	New data covers existing measurands at lower uncertainty AND additional useful measurands at any useable uncertainty.

Figure 6: Feasibility and opportunity criteria used to assess the different technologies

The participants were split into six groups (shown in Appendix I) according to their expertise. Each group assessed between three and five different technologies and provided a score for each feasibility and opportunity criterion. The scores were summed up and are shown in Figure 7 (below).

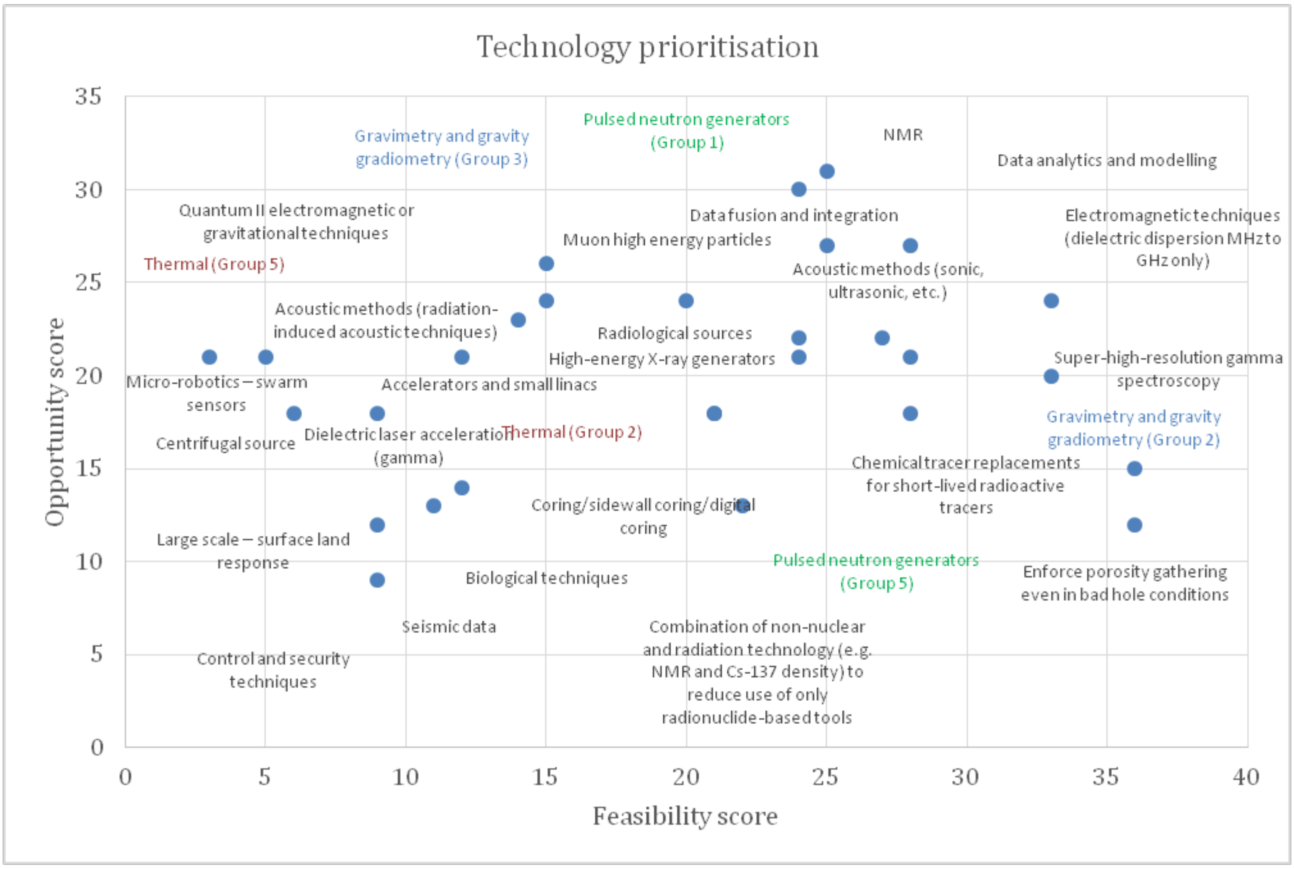


Figure 7: Technology prioritisation chart using feasibility–opportunity axis. Three technologies were assessed by different groups. These are highlighted in different colours.

The technology "correlated particle techniques" was not assessed as there were no experts with the relevant knowledge in the workshop. Three technologies were assessed by two different groups (highlighted with different colours in the graph above). These were:

- Pulsed neutron generators;
- Thermal;
- Gravimetry and gradiometry.

There are variations in scoring for the same technology between groups. This may be because of the specific group's technical expertise and perspective (industrial or academic).

Two technologies were grouped together at this stage, as they were considered to be similar. These were:

- High-energy X-ray generators;
- Accelerators and small linacs.

The 23 technologies were reviewed in relation to their relative scores and position in the opportunity/feasibility chart (Figure 7) and the timeline of their application (short, medium or long term). Consequently, the following five technologies were selected for further exploration:

- Acoustic;
- Pulsed neutron generators;
- NMR;
- Data analytics and modelling;
- X-rays.

These technologies were scoped and explored further during the day in small groups (shown in Appendix I). Summaries of the discussions and the topic roadmaps that were developed are presented in the next section.

PRIORITY TECHNOLOGIES

The summaries and high-level roadmaps for the five technologies are described in the next sections. The high-level roadmaps include the following fields:

- Detailed description of the technology and its desired future functionality;
- The scope and boundaries of the technology, indicating aspects that are included and excluded from further development;
- Key technological goals and developments required in the short, medium and long terms;
- Technical milestones;
- An assessment of what adjustments the energy industry should make to adopt this technology;
- Key enablers that governments, industry and academic and research institutes should promote to enable the adoption of the technology by the industry;
- Key barriers in the further development and commercialisation of the technology.

ACOUSTIC TECHNOLOGY

This technology is mature enough to be considered a viable alternative to RN sources. Improvements could be considered such as extracting information on matrix porosity, or Stoneley permeability. The bigger barrier is that the energy industry prefers nuclear logging for porosity estimation. Currently, most of the acoustic data is taken in high profile wells (exploration and appraisal) while in development wells acoustic technology is used only when there is a high risk of using radioactive sources. There is insufficient data to compare the acoustic technology with the existing nuclear method; therefore, more data using the acoustic method needs to be acquired and there needs to be calibration across the two methods. Attention should be paid to legacy data for further comparative studies by fields and reservoir type (i.e. sandstone versus carbonates; soft sediments versus older rocks).

Following on from this, data integration will be important, possibly through a pilot study of different geologies, for example, sandstone against limestone type reservoirs, and density against sonic porosity under various borehole conditions (mud type, borehole size, reservoir pressure and temperature). The way in which data is handled and used is important in order to compare the outputs from the two methods and to build confidence in using the new acoustic technology. Note that the acoustic technology can be run through casing and offer reliable data if good quality cement is present behind the casing.

Some complementary technologies, in particular microgravimetry and NMR, could reduce the uncertainty in some challenging environments. In particular acoustic and microgravimetry technologies can offer long term surveillance (time lapse) as both can be deployed in both open hole and cased hole. A deadline from the government would help the industry to prepare and adopt new technologies. It would be beneficial if the government and energy regulators [10] request operators to submit white papers on alternatives to radioactive sources that will be the starting point of conversations and initiate the transition process.

Standards and rules, as well as providing a green licence to operators to incentivise them to adopt and use these brand-new technologies, would also be important. These initiatives will cause the energy industry to react and invest appropriately. Academia could work in collaboration with industry and the vendors in developing these workflows and methods.

Figure 8 (below) shows the roadmap for this topic.

[10] https://www.ogauthority.co.uk/

Technology	Acoustic		
Technology description/scope **O π/CH ↓ Low risk**	**Technology summary description** •**Compressional** •**Shear** •**Stoneley** •**↓ Ø Gas Øsec Kston Geomechanics,** •**Fractures** •**Seismic**	**Scope** What's IN: Time lapse •Interwell properties change •Combine with other technologies What's OUT: Calibration soft sedim •Vertical resolution •Matrix Ø only	**Desired future** What success would look like •Reduce uncertainty in Ø •Introduce rigour in process

WHEN		***Short term (0–3 years)***	***Medium term (3–5 years)***	***Long term (5–10 years)***
Required technology development		•Use fieldwide calibration •Benchmarking the nuc density or PN den	•Data analytics (acquisition calibration)	•Miniturisation?? •Reduce length •Reduce ID •∝g & sonic
Required energy industry adjustments		•Change practice •(Currently ex-appraisal) ↓ •Every well	•Industry change ↓ •Lower cost •Provide all raw data	•Complementing technologies on same instrumentation ↓ •∝gravimetry
Milestones		•Interogate a "basin" (SS/LS) •ØΔ vs Øs (Feasibility study) •Pilot	•What works •What be improved •Stop?	
Enablers	What governments should do?	Deadline? Standards → •Allow time to develop new technology	•Rules •Green licence	
	What industry should do?	•React → •Invest	•Rigour	
	What academia and research institutions	•JRC (Joint Research Consortium)		
Barriers		•"Nuclear Density" inertia		

Figure 8: Roadmap for the acoustic technology

PULSED NEUTRON GENERATORS

There are two types of pulsed neutron generator (PNG) technology: deuterium-tritium (D-T) PNGs and deuterium-deuterium (D-D) PNGs. The D-T PNG is a mature technology that has already been in existence for many years, although improvements are possible, such as increasing neutron output and new pulsing sequences. The D-D PNG is currently a research project yet to be developed for the oilfield industry. In the medium term of three to five years, the D-D PNG may be considered a suitable replacement for the AmBe radioisotope technology, as it generates neutrons of similar energy (2.5 MeV).

For the D-T PNG technology, improvement in the use of the data in complex conditions is necessary, especially in completions with multiple tubings. These products need to be more robust in terms of operating at high temperatures and pressures. Additionally, extending the D-T applications to measuring formation bulk density measurement – something that has not yet been done – would be very valuable.

The required technology developments are improved instrument formation response characterisation and ruggedisation of sensors. The main barriers to adoption by the industry could be financial - the perception that this technology is expensive, political lobbies from multiple small service companies that object to technology changes, and from users who need to develop new technical skills.

The government could facilitate the uptake of this technology through funding innovation projects in the area, and by implementing regulations that prohibit the use of radioisotope sources for well logging.

The industry could participate in collaborative R&D, and perhaps more importantly to pilot projects involving operators, service suppliers and academia to both source the services and conduct the operations. Among other topics, collaboration in the calculation of uncertainties and their propagation over the successive tasks of data acquisition, processing and interpretation would be instrumental in convincing oilfield operators to adopt these new technologies. Additional instrument response modelling would also be necessary, in order to take advantage of the improved resolution of the measured GR energy spectrum, to identify new elements, and to obtain better precision of the measurement.

Figure 9 (below) shows the roadmap for this topic.

Technology	Pulsed neutron generators			
Technology description/scope		**Technology summary description** - D-D gen (low energy n) to replace AmBe bulk porosity information - D-T gen (high energy n) for epithermal neutron porosity and GR for elemental information - Also: Pulsed mode for GR die-away from D-T and Activation measurements	**Scope** What's IN: D-D and D-T pulsed generators, powered via cable or battery packs What's OUT: Any radioisotope n-sources (Cf, AmBe)	**Desired future** What success would look like •To introduce D-D generator to industry to replace AmBe porority measurements •To improve characterisation of neutron data in complex configurations •More robust generator for high temperature & pressure •Extend PNG to gamma density measurements
WHEN		***Short term (0–3 years)***	***Medium term (3–5 years)***	***Long term (5–10 years)***
Required technology development		•Improved instrument characterisation facilities and techniques (e.g. TOTAL facility in France) •Improved ruggedisation of existing D-T machines •Improved use/analysis of higher-resolution gamma spectral data	•High flux D-D generator, increasing flux from 10^5 to 10^7 cps •higher tube voltage •higher beam current	•Super-compact "neutristor" n generators •*In situ* and long timescale measurements •Improved precision of GR measurement, e.g. saline vs fresh water
Required energy industry adjustments		For open hole measurements: industry acceptance to move from AmBe to PNG measurements		
Milestones		Ruggedised DT prototype at TRL (Technology Readiness Level) = 5-6	Prototype high flux D-D machine for commercial adoption	Demonstration of first prototype neutristor generator to low TRL with sufficient neutron flux
Enablers	What governments should do?	•Government investment in R&D for new well logging technologies, e.g. KTN programs, Innovative programs. •Catapult centre in "Source Removal Technologies"	→	Forced regulation to prohibit use of AmBe sources
	What industry should do?	•Engage in collaborative R&D for neutron generator technologies •*Pilot projects to explore (1) sourcing services, (2) operational	→	
	What academia and research institutions should do?	•Improved modelling and data analytics, reduced errors and uncertainty - machine performance and reliability - enhanced interpretation of data •*Pilot projects, as above •Masters/PhD programmes to train students	→	
Barriers		Industrial inertia to adopt generator technologies, in the absence of mandatory regulation •financial •political lobby •technical skills		

Figure 9: Roadmap for the pulsed neutron generator technology

NMR

Of all technology that could be used to replace RN sources, NMR is by far the most mature. Currently every major logging service provider has both a wireline and LWD NMR capability offering real choice in the market. However NMR has not taken off as a measurement because it is seen as slow, and complex to acquire and process and far more expensive than current nuclear source tools. Encouragement of NMR uptake could follow a multi thread approach examining standard and more efficient tool designs, more robust processing of the data and increased costs for using the more traditional nuclear sourced tools.

The scope for the use of this technology in well logging is to measure total porosity and pore fluid type. It would be possible to partition the porosity into different pore size distributions which offers additional value and assesses fluid types, such as gas, oil water or tar. There is an issue with this technology in terms of quantification of gas. The NMR data can also be used to provide an indication of permeability particularly when calibrated against core. So there is the opportunity to obtain some additional data that is not easily derived otherwise.

This technology is difficult to use where pores are extremely small such as shale. In addition it is also challenging in gas and also carbonates environments. Furthermore, if the rock or drilling mud contains materials that are magnetic then the use of NMR could become problematic.

The NMR measurement depends on the use of permanent magnets of the tool to help polarise the hydrogen in the rock and uses RF frequencies to tilt the orientation through 90 deg and 180 deg to generate a signal. This process takes time and hence logging data acquisition speeds are slow. In future, the ideal situation would be to increase the speed of measurement and have faster polarisation, inversion, as well as faster data processing. Each logging service company has generate a different configuration of permanent magnet and different RF frequencies measuring different sensitive volumes. There could be scope to perform fundamental R&D on the optimal configuration of permanent magnets and RF frequencies to enhance tool design. NMR will need to be combined with other measurements to obtain all the necessary information.

Currently, conventional measurement logging speed is approximately 1800 foot per hour. NMR logging is acquired at 800 to 900 feet per hour. Neutron or other technologies can achieve 3,600 foot per hour, so an increase of a factor of 2 to 4 would be required, in the first instance.

Regarding technology development, in the short to medium term an increase in the speed of measurement would be important, as well as stronger polarisation, through either polarising more hydrogen or better sensors, or both, and better and faster processing, potentially incorporating machine learning methods. The main technology milestones would be starting from independent measurements, for example, in universities, determining the research required, establishing feasibility studies to speed up the key parameters, developing prototypes, and finally developing faster and more accurate tools.

In order for this tool to be adopted by the industry a change in culture is required, as today this is not a standard tool. Education on how to use and process the measurement is also necessary. There also needs to be considerable investment in order to make it a standard tool, so that it can be adopted more easily, in addition to enhancing interpretational capability and automation of the tools.

The government could fund the requisite R&D, in addition to announcing a legislation change within a reasonable timeframe (e.g. 5–10 years), establishing collaboration with the US for this purpose and potentially providing tax breaks for early adopters.

The industry should establish a steering group, upskill its staff on the new technology and join academic projects to scope out and influence the product development. Providing access to field testing in the medium term would be essential before adopting and using the tools.

Academia and research institutions could lead the technology development project initially and form the best consortium to drive this project forwards before handing it over to industry in the medium term.

The main barriers to adoption are definitely the culture, the technology and the cost.

Figure 10 (below) shows the roadmap for this topic.

Technology	NMR			
Technology description/scope		Technology summary description Polarisation of hydrogen nuclide to determine formation Ø	Scope What's IN: Measuring: porosity (fluid porosity) Partition the porosity Fluid typing, solids (TAR), (GAS) Permeability indication What's OUT: Micro Ø Carbonates Gas issues	Desired future What success would look like Faster logging Combine with other measurements *Interpretation and processing* AI (for clays) and other elements??
WHEN		***Short term (0–3 years)***	***Medium term (3–5 years)***	***Long term (5–10 years)***
Required technology development		•Stronger polarisation (logging speed) Ø	•Better and faster processing •Scope for machine learning	•?Better sensors
Required energy industry adjustments		•Change in culture. NMR vs D/N •↓ $$ Greater availability/demand	•Interpretational capability automation	
Milestones		JIP Independent lab measurements to look at polarisation (and detection) *University work*	Prototypes	Better faster, more accurate tools
Enablers	What governments should do?	•Fund R&D •Announce legislation charged in future (IAEA) •UK and US work together •Steering group, lobby for funding	•Tax breaks for (prototypes)	•Tax, AmBe C1 •Legislation change (international IAEA)
	What industry should do?	•Education of staff •JIP participation •Scope the project ← operators	•Access to field testing •Variety of environments	•Buy and run the tools!!
	What academia and research institutions should do?	•Establish who will do the work •Distribute the funding	•Further work!!	
Barriers		•Inertia •Culture •Technology •$$	Cooperation (JIP)	

Figure 10: Roadmap for the NMR technology

DATA ANALYTICS AND MODELLING

The development of new wireline logging technologies that are RN-free has the potential to create interpretative uncertainties within oil companies as they aim to increasingly take-up these new technologies. This situation may be exaggerated by the current economic climate as researchers are increasingly expected to do more with their heritage datasets in an effort to save costs. As a consequence, oil companies need to be able to integrate RN-free and heritage datasets within one common earth model. This integration has the potential to compound interpretive uncertainties. The topic defined in this Chapter defines how we could interrogate these disparate data sets using data analytics to see if common patterns or interpretative paradigms can be realized from these integrated data sources. As an example, it is recognized that sonic logs contains a multitude of waveforms that are currently unused in interpretation. The ability to facilitate analyses of these can then be used to assess whether more information about specific rock- or fluid-properties can be recognized or to see if new anomalies can be uncovered to gain informed insight into the subsurface. These insights will aid the interpretation and integration of any new-generation logging technologies.

One significant technological development to assist integration could focus around the comparison and algorithmic modelling of RN-free and the heritage datasets to help reduce interpretative uncertainties. As a short term action, such modelling can be facilitated through the creation of a validated, QC'd database of typical high-quality log data, that are publically available, and are intended to be used as training data for machine learning. This database can also be used to generate algorithms for integration. The main intent of machine learning will be to replicate RN-free responses in other datasets in order to deliver more informed earth models from these data. Computationally, it is anticipated that any derived algorithms will need to be ran through large data sets in order to better facilitate interpretation, calibration, optimization and discovery. Therefore, during the creation of this publically available resource, this needs to be considered. Collaboration is required and an industry group should possibly be set up to maintain focus in this activity. Academic and industrial liaison will be essential. In the medium term, it is suggested that the creation of such a resource will enhance the acceptance of the RN-free logging tools. In the long term, it is expected that analytical algorithms will become more refined with new data patterns being identified to provide an enhanced understanding of existing data sets. Close engagement with technology groups in this area should be encouraged and it is hoped that relevant conferences, meetings and data sharing initiatives should result.

At the time of discussion it was recognized that the BGS may already have elements of a 3D earth model for the UK. One pertinent question is whether the energy industry could utilise this framework and build on it or deliver something similar with its well logging data set, enforcing endorsement from UK government and companies invested in the UK.

Three main barriers to the delivery of this resource are identified. The first and main barrier is confidentiality of the database. In most instances, the component data could be used to generate insight into commercially sensitive, high-value subsurface assets for a company. The second is related to this and reflects the suggestion for unrestricted access to the use of these resources. The final barrier is the industry investment that will be required to develop and implement this idea. Figure 11 (below) shows the roadmap for this topic.

Technology	Data analytics and modelling			
Technology description/scope		**Technology summary description** **Human/algorithmic modelling to help reduce use and/or replace excessive logging methods (inc. RA)**	**Scope** What's IN: Big data: data management (storage, QC, availability etc) interpretation, interrogation, optimisation, discovery Limited data: algorithms, modelling What's OUT: Discussions on individual tools or responses. Specific petrophysical answers/results	**Desired future** What success would look like: A recognition of the range of uncertainties surrounding new non-nuclear tools compared with traditional (RARN) tools
WHEN		***Short term (0–3 years)***	***Medium term (3–5 years)***	***Long term (5–10 years)***
Required technology development		•Training data sets for machine learning for formation evaluation or earth modelling •Algorithms to run through large data sets (tool specific) for interpretation, integration, optisation and discovery. •A combination of the above	•Generate new uses/concepts from old data for delivering new integrated insights from logs •Improve our understanding of the uncertainties of new tools	Software update based on: •Emerging new measurements •New data patterns that uncover data in new/enhanced ways
Required energy industry adjustments		•Collaboration (industry group to govern data sets) •Build and prepare training data sets	Release database web portal → grow and develop and analytical portal	Close enguagement with tech conference group (see below)
Milestones		Draft scoping document and terms of reference	Technology conference series on new concepts for wireline logs Year *1, Year *4	Technology conference series on new concepts for wireline logs Year *6, Year *8
Enablers	What governments should do?	•Mandate OGA to drive data collaboration and the creation of training data sets	Enforce?/endorse UK and UK interests →	→
	What industry should do?	•Buy into the notion of creating training data set that includes the supply and release of data	Maintain/support/evolve →	→
	What academia and research institutions should do?	•Include organisations that may already be working on modelling of data, e.g. BGS	Maintain/support/evolve →	→
Barriers		•Confidentiality or protection of investment by oil industry •The perseption that like-for-like measurement are not possible •No legal restriction to the utilisation of RA sources (i.e. the lack of driver) •Lack of inertia from the industry		

Figure 11: Roadmap for the data analytics and modelling technology

X-RAYS

The original topic was accelerators and small linacs, which, after discussion, was split into two technologies, X-rays and particle accelerators. X-rays were explored in detail as a source, as particle accelerators were considered to be a very immature technology, and currently too unreliable.

The ultimate aim is to use X-ray technology to replace the current density measurements using caesium 137. X-ray technology has the potential to match the performance of the density tools currently being used.

In the short term (within the next three years), one can investigate the existing X-ray generators that are readily available and have the appropriate dimensions, and possibly build some prototype tools. In the longer term, it would be important to make these prototypes consistent and reliable enough to enable the development of a commercial product within a 5- to 10-year period.

The industrial strategy should be to take the opportunity to operate both the existing and new technology as it is developed, and to build a database of both sets of data to establish confidence in the new technology. Tests for the X-ray technology should be encouraged in a wide range of boreholes, and environment formation. The X-ray tool should be able to operate at temperatures of 300 F and pressures of up to 15,000 psi initially, and temperatures of 400 F and pressures of 20,000 psi in the medium to long term.

In the short term, the government should set up the overall objective and timeframe (e.g. 10 years), within which no more nuclear sources will be used downhole for well logging. This would also include the Am241Be sources used for Neutron Porosity. The government should incentivise people using funding research and the necessary investment to try and bring this technology forwards. Potentially, the government should also consider making the use of nuclear sources prohibitively more expensive the closer the final deadline is approached. For example, within the next 3 years the cost of using a radioactive source could be 10,000 dollars, in 5 years the cost could be 50,000 dollars, and in 10 years the cost could be 100,000 dollars. This will incentivise the industry to start changing and provide the early adopters with real benefit.

The industry will have to realise and accept that there will be some investment in time and money to operate and compare the two technologies in order to build confidence. Academia could be influential in terms of how to use the new source of data, where to put it in the workflow, and what additional information could be extracted. This could be facilitated by the industry in sharing some of this information early, rather than trying to keep it proprietary.

Presently, the main barrier is that the industry is not in the best financial condition. It is the wrong time to encourage a change in practices and people as this bears more cost. This is something that everyone needs to be realistic about.

Figure 12 (below) shows the roadmap for this topic.

Technology	X-rays			
Technology description/scope		**Technology summary description** **Accelerators and Small Linacs**	**Scope** What's IN: X-rays, electrons What's OUT: Particle accelerators	**Desired future** What success would look like Particle accelerator to fit down bore hole that is capable of interpreting the environment around the hole. Will provide replacement for CS137 sources. For instance likely to generate 10 Photons per second monochromatic 500 keV-1
WHEN		***Short term (0–3 years)***	***Medium term (3–5 years)***	***Long term (5–10 years)***
Required technology development		•Ruggedisation of existing systems •Monochromatic beam energy •Develop processing workflow	•Miniturisation of current X-ray generators	•Particle accelerator research
Required energy industry adjustments		•Develop optimum short-term temperature and pressure ranges •Deployment of parallel techniques •Develop processing workflow	•Extend temp. and pressure optimum ranges •Benefits of scale by medium adoption •Consolidation of best practice •Training	•Develop potential for further applications
Milestones		Prototype deployment	Begin to reduce CS137 sources. Commercialised product 50%	Developed commercialised product. Reduce CS137 sources
Enablers	What governments should do?	•Help educate industry •Fund research •Engage internationally •Engage with United States government to	•Gain industry buy-in •Provide incentivisation schemes •Develop incremental regulatory control International standards (i.e. ISO)	•Increasingly punitive licencing costs for Cs 137
	What industry should do?	•Help educate industry	Develop industry expertise and knowledge to drive development ⟷	
	What academia and research institutions	•Help educate industry	Develop data interpretation ⟷	
Barriers		•Lack of sufficiently developed existing technology •Current implementation and development costs too high •Resistance to change. At present industry is focused on reducing costs		

Figure 12: Roadmap for the X-ray technology

CONCLUSIONS AND NEXT STEPS

NuSec organised a Roadmapping Workshop with 26 delegates from industry, academia and the government to assess and explore alternative technologies to radio-nuclear sources for well logging.

The workshop assessed in detail 25 alternative technologies and explored five of those in more detail to understand the technology developments required, their potential impact and the enablers, barriers and risks from an implementation perspective. The five technologies shortlisted and explored during the workshop were:

- Acoustic;
- Pulsed neutron generators;
- NMR;
- Data analytics and modelling;
- X-rays, accelerators and small linacs.

Two technologies, acoustic and data analytics and modelling, were considered to be ready for implementation by the industry now.

The **main barrier** to the adoption of alternative technologies by the energy industry was predominantly inertia and resistance to change, which is facilitated by the absence of mandatory regulations and no restriction to radioactive sources. Lobbying, especially from industrial groups representing small operators, also has an impact on maintaining the status quo. Another barrier to change is also the lack of technical skills and/or education in new methods. The industry perception that implementation and development costs for alternative options were currently too high is also a barrier change. Finally, confidentiality and data protection issues of well logging data by the oil industry creates difficulties in validating alternative technologies against the current methods.

A list of actions (shown below) was derived at the end of the workshop to raise further awareness of the issue within the energy industry and to promote positive change. These are summarised below and are predominantly around communication (both within organisations and with governments and relevant interest groups), continuing engagement of all actors and raising awareness of the risks of using RN sources.

Actions/Next steps	Owner	Timing
Consistent follow-on – brief Home Office and BEIS	Neil Gaspar	3 months
Continuation of engagement between all actors	AWE	6 months
Need to engage US government	Nick Butler	3 months
Report back to 1 nuclear SIG	Ahmed Badruzzaman	1 month
Report back internally (within organisation) – upon receipt of report	All industry participants	1 month
Identify a project with operators and industry to compare data with different techniques	Michel Claverie	2 weeks
Collection of UK stakeholders	Anke Lohmann	4 months
Report to the NTI	Nick Butler	

More education of industry (especially drilling engineers) about the risk of using RN sources	Neil Gaspar, Nick Butler, Ahmed Badruzzaman	6 months
Generate more topic roadmaps on other technologies	e.g. Quantum measurements of gravity. Kai Bongs	

APPENDIX I: LIST OF PARTICIPANTS

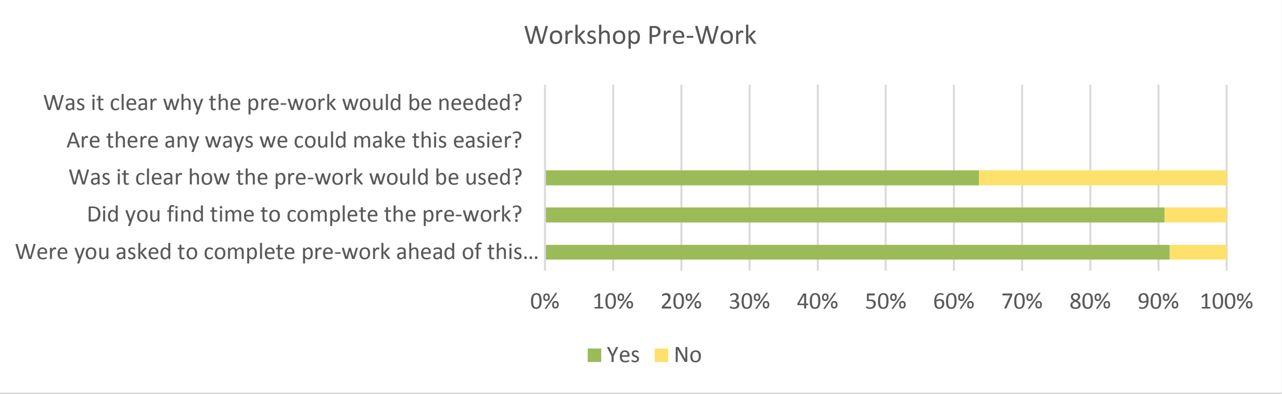
	Name	Role	Organisation
Industry	Adrian Zett	Reservoir Development, Advisor	BP
	Ahmed Badruzzaman	USDoE, SWPLA Nuclear SiG, SME Adviser	SPWLA Nuclear SIG
	Alec Latimer	Formation Reservoir Solutions, Consultant	Halliburton
	Andrew Woods	Head of BP Institute	BP Institute University of Cambridge
	Ashwin Seshia	Professor of Microsystems Technology	University of Cambridge
	Ian Draper	Global Service Delivery Manager	GE-Baker
	Michel Claverie	Technical Director – Wireline Petrophysics, Petrophysics Advisor	Schlumberger
	Mike Webster	SPWLA Regional Director	SPWLA
	Owen Sutcliffe	Head of Stratigraphic Research	Halliburton & Petroleum Group of the Geological Society
	David Moss	Wells Discipline Team	Shell
Science and technology	Andy Parker	Head of Physics	University of Cambridge
	Caroline Barrett	Nuclear Threat Reduction Technical Sponsor	AWE
	Ian Marshall	Distinguished Specialist	AWE
	Kai Bongs	Head of National Quantum Technology Hub for Sensors and Metrology	University of Birmingham
	Lee Thompson	Professor of Experimental Particle Physics	University of Sheffield
	Paul Sellin	Head of Nuclear Security Science Network	University of Surrey
	Sally Morgan	Technical Manager and Logging Specialist	Ocean Discovery Programme
	Simon Jerome	Head of Radiochemistry	NPL
	Peter Williams	Senior Acclerator Scientist	STFC
	Anke Lohmann	Founder and Director	Anchored In Ltd
Government	Liqun Yan	Knowledge Transfer Manager, Sensors, KTN	KTN
	Neil Gaspar	Outreach Lead, Nuclear Threat Reduction	AWE
	Nick Butler	NNSA Program Director	NNSA
	Richard Cronie	Radiological and Nuclear Policy Advisor, Office for Security and Counter Terrorism	Home Office
	Stephen Loader	External Innnovations Programme Manager	STFC

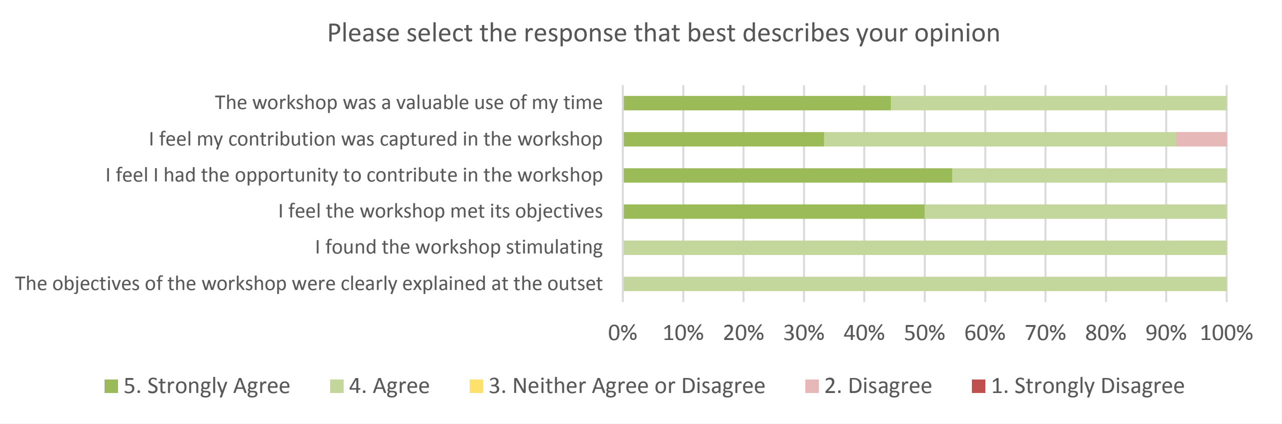
Technology group assessed	Participants
1. Particle and photon generation	Ahmed Badruzzaman Michel Claverie Ian Marshall Peter Williams Liqun Yan
2. EM, gravity and Quantum II	Andy Parker Kai Bongs Stephen Loader David Moss
3. HEP, NMR and spectroscopy	Adrian Zett Alec Latimer Lee Thompson
4. Acoustic, seismic, chemical and radiological	Ian Draper Owen Sutcliffe Simon Jerome
5. Coring, robots, thermal and other	Ashwin Seshia Caroline Barrett Paul Sellin Nick Butler
6. Data analytics, modelling, control and security techniques	Andrew Woods Mike Webster Sally Morgan Neil Gaspar Richard Cronie

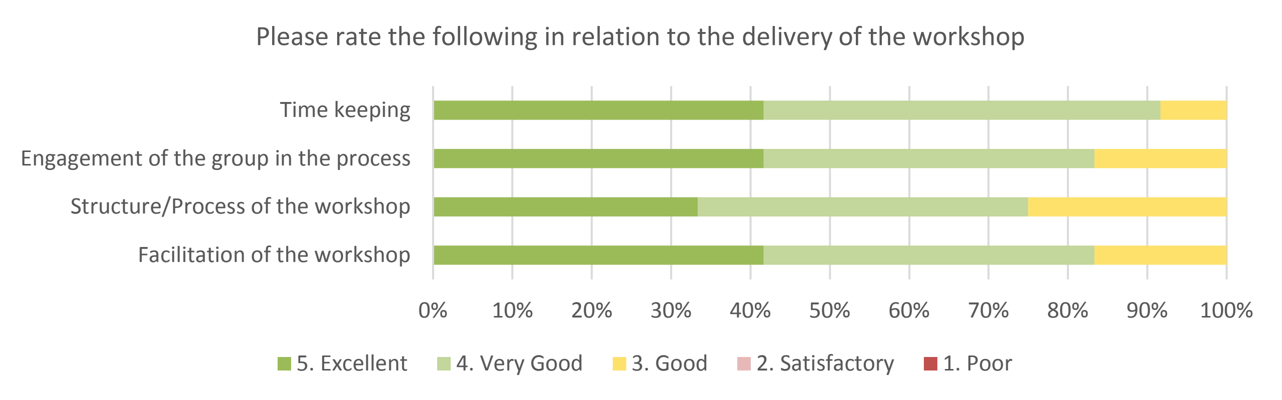
Technology roadmap group	Participants
1. Acoustic	Nick Butler Adrian Zett Anke Lohmann Andy Woods
2. Pulsed neutron generators	Lee Thompson Paul Sellin Ian Marshall Michel Claverie
3. NMR	Caroline Barrett Mike Webster Kai Bongs Ahmed Badruzzaman Sally Morgan
4. Data analytics, modelling	Neil Gaspar David Moss Owen Sutcliffe Alec Latimer Liqun Yan
5. X-rays	Andy Parker Simon Jerome Richard Cronie Ian Draper

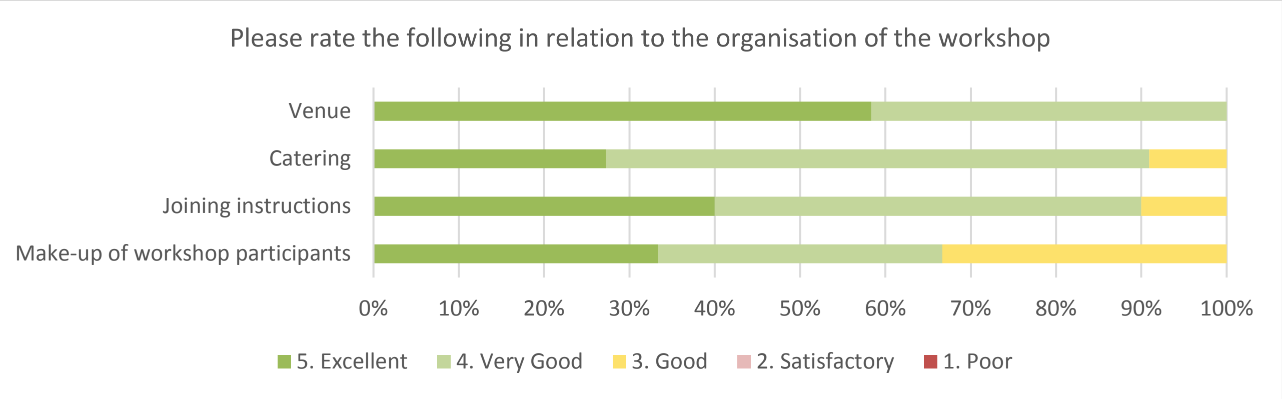
APPENDIX II: PARTICIPANT FEEDBACK

Feedback was received at the end of the workshop from 13 participants. All participants considered the workshop to be Excellent, Very Good or Good, as well as useful and stimulating. All considered their participation to be worthwhile and their participation in the workshop to be a valuable use of their time. The detailed feedback is shown below.









APPENDIX III: WORKSHOP AGENDA

08.30	**Arrival**	
09.00	Welcome and Introductions	Neil Gaspar, Nuclear Threat Reduction, AWE and IfM ECS
09.05	UK context and challenge	Richard Cronie Office for Security and Counter Terrorism, UK Home Office
09.25	USA context and previous work	Nick Butler Office of Radiological Security, US NNSA
09.45	Energy industry context	Ahmed Badruzzaman Society for Petrophysicists and Well Log Analysts and advisor to US NNSA
10.10	**Break**	
10.20	Step 1: Individual presentations of suitable alternative technologies to address the main requirements	All (plenary)
11.30	Step 2: Prioritisation of requirements and alternative technologies using pre-defined criteria	All (plenary)
13.00	**Lunch**	
13.30	Select four to five technologies for further exploration	AWE/NuSec
14.00	Step 3: Explore the selected technologies (one per group)	All (in groups)
15.50	**Break**	
16.00	Review and feedback	All
17.00	**Close**	

APPENDIX IV: LIST ALL OF GOVERNMENT AND ENERGY INDUSTRY REQUIREMENTS

Government and energy industry requirements	Roadmap layer	Time-frame	Indu-stry votes	Science and tech. votes	Govern-ment votes
Provide suitable alternatives to radioisotope sources with compact, lower-cost technologies.	Technological	ST-LT	2	4	4
Understand the true costs of current technology and increase cost efficiency of prospecting and well logging.	Economic	ST-LT	2	2	1
Provide financial incentives for an orderly transition to new technologies.	Economic	ST-LT	1	0	1
Low business development and implementation costs.	Economic	LT	0	0	0
Improved accuracy and precision, faster logging speed, robust measurements in complex conditions.	Technological	ST	0	3	0
Well understood muon flux means straightforward calibration.	Technological	MT	0	0	0
Low-cost detectors, reduction in costs for dedicated radioactive sources.	Economic	MT	0	3	0
Eliminate the use of radioactive materials to minimise environmental impact.	Environmental	ST-LT	1	3	1
Data mining for enhanced prospecting methods.	Technological	MT-LT	1	3	0
Look to move to induced sources, X-ray or NMR and the solution.	Environmental	LT	2	2	0
New measurements with focus on brown fields and marginal fields.	Technological	LT	1	0	0
Minimise regulatory burden and costs across all parties.	Political/legal/ethical	ST-MT	0	1	1
Regulatory alignment and similar regulatory regime in multiple countries, not just UK.	Political/legal/ethical	ST-LT	2	2	2
e-tagging: Encourage all logging companies operating in the UK to test and adopt the PNNL-developed technology (or similar technology) to e-tag the source container.	Other	MT	3	1	0
Is PN considered chemical n/s in the UK? (Not in the US.)	Other	ST	0	0	0
Regulations/protocols: Encourage small/regional logging companies to adopt the practice of background checks of personnel handling sources and the protocol of two-person entry to source vaults. International logging companies have adopted both.	Other	MT	0	1	2
Ensure high level of public confidence in government's ability to mitigate the threat of terrorism.	Political/legal/ethical	ST-LT	0	0	3
Public perceptions of the oil industry.	Social	ST	1	0	0
In general, consider, collectively, the state in the UK of the four major source risk mitigation options noted: regulations, industry protocols, e-tagging of sources, and Alt-Tech, and identify gaps to improve source security.	Other	ST	2	2	0
Assess the broad industry landscape in the UK, technical and non-technical (small vs small companies, etc.), in the context of the above, especially assessments and studies completed or reported elsewhere.	Other	ST	1	0	0
Productise the solutions and offer to the wider industry, educate and inform of risks, solutions and benefits.	Social	MT-LT	5	1	1

Demonstrate quality of measurement uncertainty and identify methods to reduce it.	Other	ST-MT	3	4	2
Continued need for offshore scientific investigation to understand geohazards.	Social	LT	0	0	0
Continued need for offshore scientific investigation to understand climate and sea-level change.	Environmental	LT	0	1	0
Multiple and deeper depths of investigation.	Technological	MT	2	0	0
Develop expertise, technology and capability for UK manufacturing hub.	Economic	LT	1	1	1
Geophysical ground proofing, particularly in relation to shale.	Political/legal	MT	0	0	0
Passive flux interrogation method yields density variation information.	Environmental	MT	0	0	0
Productise the solutions and offer to the wider industry.	Technological	LT	2	0	1

APPENDIX V: LIST OF ALL PROPOSED TECHNOLOGIES

Technology	Roadmap layer	Timeframe	Opp. votes	Feas. votes	Total votes
Electromagnetic techniques (dielectric dispersion MHz to GHz only)	Active techniques	MT-LT	24	33	57
NMR	Active techniques	ST-LT	31	25	56
Data analytics and modelling	Alternative ways of producing ionising radiation	ST-LT	27	28	55
Pulsed neutron generators	Alternative ways of producing ionising radiation	ST-MT	30	24	54
Super-high-resolution gamma spectroscopy	Passive measurements	ST-LT	20	33	53
Data fusion and integration	Active techniques	LT	27	25	52
Gravimetry and gravity gradiometry	Passive measurements	ST-LT	15	36	51
Acoustic methods (sonic, ultrasonic, etc.)	Active techniques	ST-LT	22	27	49
Chemical tracer replacements for short-lived radioactive tracers	Active techniques	MT	21	28	49
Enforce porosity gathering even in bad hole conditions	Active techniques	MT	12	36	48
Radiological sources	Alternative ways of producing ionising radiation	ST-LT	22	24	46
Centrifugal source	Alternative ways of producing ionising radiation	ST-LT	22	24	46
High-energy X-ray generators	Alternative ways of producing ionising radiation	ST-LT	21	24	45
Muon high-energy particles	Passive measurements	ST-LT	24	20	44
Quantum II electromagnetic or gravitational techniques	Passive measurements	LT	24	15	39
Coring/sidewall coring/digital coring	Other	ST-LT	18	21	39
Acoustic methods (radiation-induced acoustic techniques)	Active techniques	ST-LT	23	14	37
Combination of non-nuclear and radiation technology (e.g. NMR and Cs-137 density) to reduce use of only radionuclide-based tools	Active techniques	ST	13	22	35
Accelerators and small linacs	Alternative ways of producing ionising radiation	ST-MT	21	12	33
Dielectric laser acceleration (gamma)	Other	MT-LT	18	9	27
Biological techniques	Other	LT	14	12	26
Thermal	Active techniques	ST	21	5	26
Seismic data	Passive measurements	ST-MT	13	11	24
Micro-robotics – swarm sensors	Other	LT	21	3	24
Large scale – surface land response	Other	ST	12	9	21
Control and security techniques	Other	ST	9	9	18
Correlated particle techniques	Passive measurements	MT	0	0	0

APPENDIX VI: LIST OF FIGURES

IfM Education and Consultancy Services

IFM EDUCATION AND CONSULTANCY SERVICES (IFM ECS)

IfM ECS is owned by the University of Cambridge and is the research dissemination arm of the Institute for Manufacturing (IfM), which is part of the Department of Engineering at the University of Cambridge.

IfM ECS provides consultancy and executive and professional development – based on the new ideas and approaches developed at the IfM – to help policymakers and manufacturing and technology companies around the world create and capture value more effectively. Our profits are gifted to the University of Cambridge to fund future research.

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