Welcome

XENAH: Current status, results and challenges faced

Dr Andrew Petts, EDF, on behalf of XENAH collaboration

Hartlepool Power Station Overview

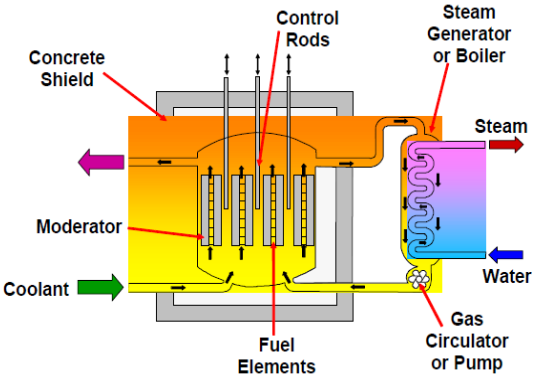
Advanced Gas-cooled Reactor (AGR) design and operation

Hartlepool Power Station – Advanced Gas-cooled Reactor (AGR)

- The Station operates 2 Advanced Gas-cooled Reactors (AGRs)
- Has been on-line since 1983 and is currently licenced to April 2026*
- Each generates ~ 600 MW(e), runs at ~1570 MW(th)
- AGR is a graphite-moderated reactor, an evolution of the MAGNOX reactors
- Utilises low-enrichment uranium fuel, 3.2% - 3.78%
- Pressurised CO_2 as primary coolant

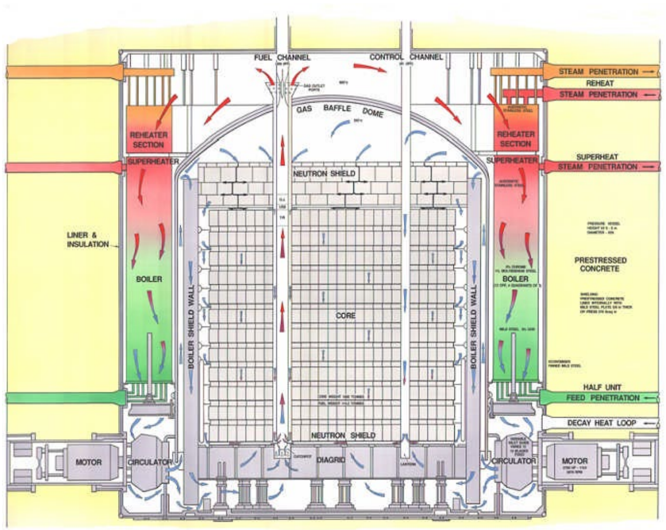
Hartlepool power station, located on the North-East coast of England

Hartlepool power station, pile cap with fuelling machine in background



Cartoon schematic of a typical AGR

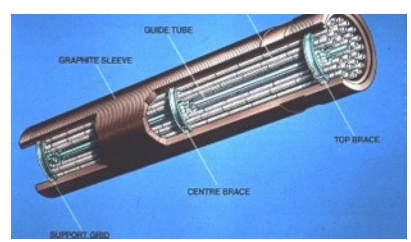
Advanced Gas-cooled Reactor (AGR) Design

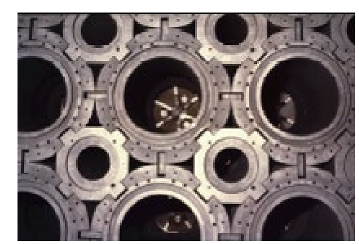


Reactor	
Moderator	Graphite
Primary Coolant	CO_2 @ 41 bar, 3623 kg/s
Number of Fuel Channels	324 with 460mm pitch
Number of Control Rods	81
Active Core Dimensions	9.3m x 8.2m
Mean Temps	T1: 286 °C, T2 648 °C

Fuel design	
Material	UO_2, 3.2 – 3.78% enriched, 130 tonnes per reactor
Disposition	36 pin cluster, graphite sleeve. 8 elements per fuel channel
Cladding	Stainless steel, 0.37mm thick
Average discharge irradiation	30 GWd/tU

Pressure vessel	
Material	Pre-stressed concrete with stainless steel inner liner
Dimensions (Internal)	18.3m x 13.1m
Dimensions (External)	29.3m x 25.9m

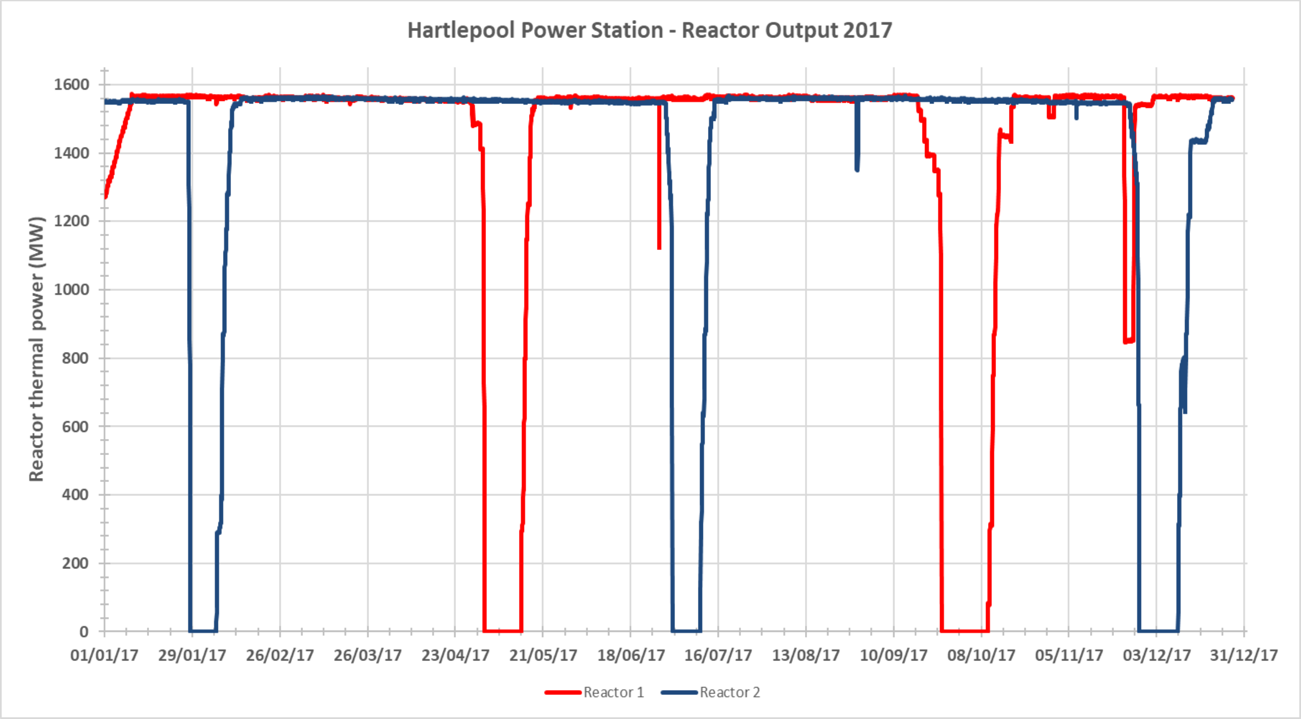




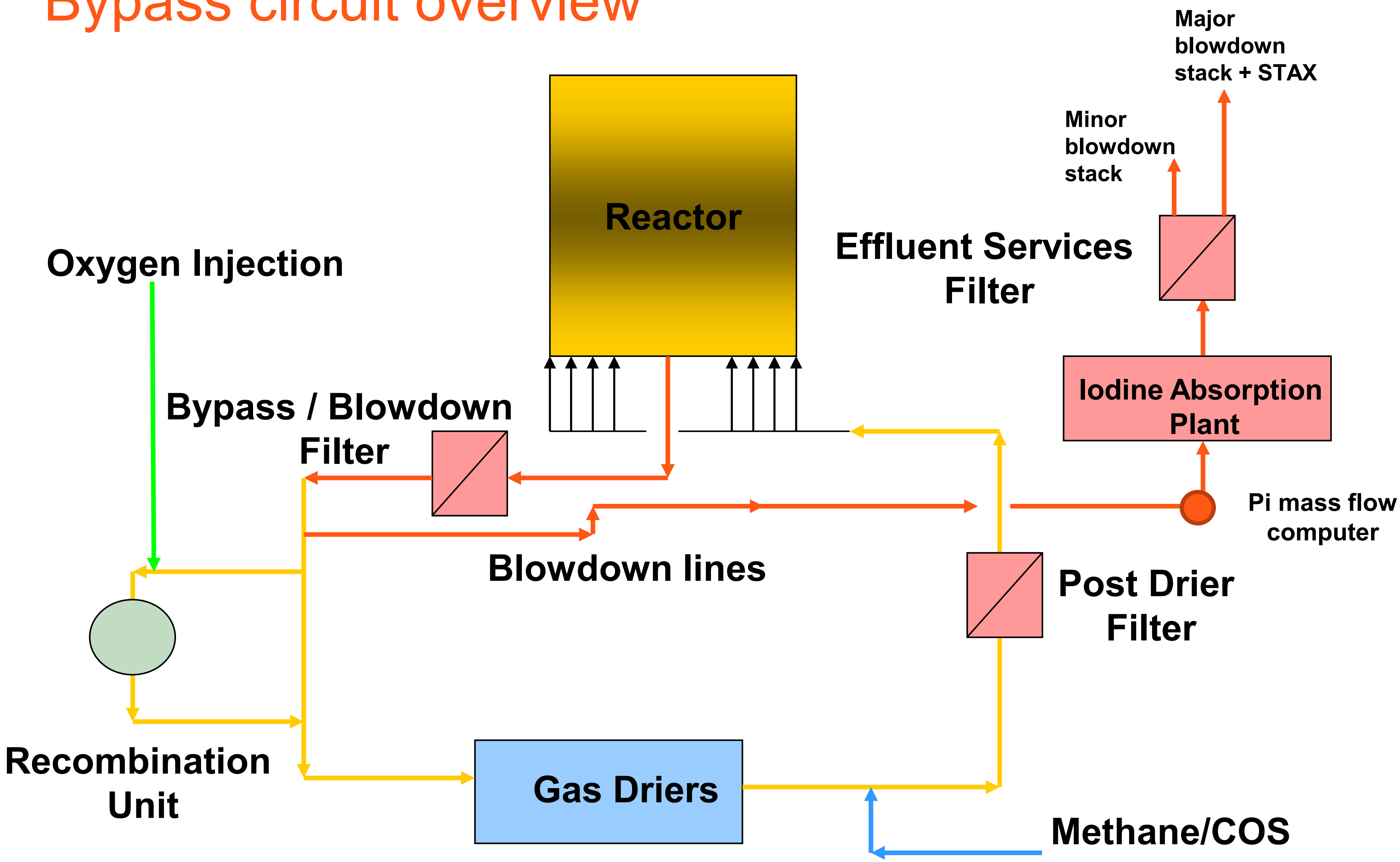
Schematic of a typical AGR fuel element (left) and overhead view of graphite core

Hartlepool power station operation

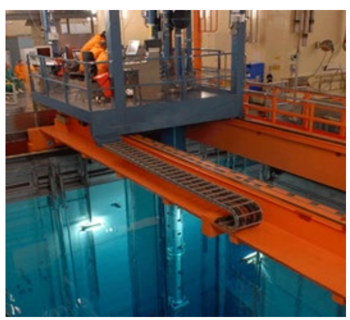
- Reactors operate at full load and are constant – do not change to match grid requirements
- Reactor shuts down approx. every 4-5 months for off-load, depressurised batch refuelling
- Once shutdown, reactor is depressurised over a 24 hour period releasing primary gas coolant though a filtered route. Exhausted gas is routinely monitored for environmental regulation compliance.
- Circa 20 channels from 324 are refuelled during each outage
- Outages last ~14 days, after which load is steadily increased to ~1570 MW(th)
- Usually have 5 refuelling outages across the 2 reactors in a year. Operator avoids having both reactors shut down in coincidence



Bypass circuit overview



Journey of the nuclear fuel



- Fuel spends ~ 8 years in the reactor
- Once out of the reactor, fuel must be below 16 kW before it can be dismantled at the IFDF – this typically takes around 2 weeks, during which the fuel is housed in special ‘buffer stores’
- Once below 16 kW, fuel is dismantled at the IFDF and sent to the cooling ponds
- Fuel must cool to < 12 kW decay heat and spend at least 90 days within the ponds
- Fuel elements are placed in a ‘flask’ for transport
- Flask with irradiated fuel is transported by train to Sellafield for reprocessing and long-term storage

XENAH: Xenon Environmental Nuclide Analysis at Hartlepool

Project overview, results and current status

XENAH - Overview

The Xenon Environmental Nuclide Analysis at Hartlepool (XENAH) collaboration involving scientists from the U.K., U.S and Sweden are performing measurements at Hartlepool Power Station in the North-East of England using a suite of monitoring techniques to better understand radionuclide emissions from a nuclear power reactor and how these might affect the IMS. The XENAH collaboration will perform these measurements with strong cooperation of the reactor operator, EDF Energy.

XENAH collaboration aims to undertake three distinct measurement programs:

- Reactor stack emission monitoring (source)
- Remote detections after atmospheric transport
- Sample measurements and in-core coolant analysis

The aim being to better understand radionuclide emissions from a nuclear power reactor and how these might affect the IMS used for CTBT monitoring.

Collaborators: Atomic Weapons Establishment (AWE), UK, EDF, UK Pacific North-west National Laboratory (PNNL), USA, Swedish Defence Agency (FOI), Sweden, Met Office, UK, STFC Boulby, UK, Durham University, UK

XENAH collaboration standing on top of the Hartlepool Reactor 1 pile cap

Reactor stack monitoring - STAX

STAX system installed at the R6 tower in Hartlepool Power Station on the main blowdown route

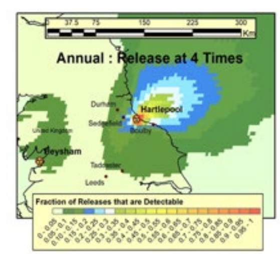
30% HPGe detector
MDC for ^{133}Xe: 270 Bq/m^3
Flow through system: 1.25 m^3/hr
Continuous monitoring (15 minute acquisitions, looped)
System installed at R6 tower on the main blowdown route to monitor emissions just prior to refueling.

In-core measurements and samples

Gaseous Activity Monitoring (GAM) system at Hartlepool power station

Gaseous Activity Monitoring (GAM) measures in-core coolant activity to assess fuel condition ICS cooled, Ortec P-type 40% HPGe detector feeding Ortec DSPEC 50 MCA for isotopic analysis Used to monitor for fuel performance – particularly during blowdowns

Remote measurements after ATM



ATM Q_B sensitivity calculations, using emissions from Hartlepool reactor. Simulations performed using HYSPLIT with GFS 0.25º met data

- Intakes atmospheric sample
  Sample time of 12 hours (includes gas conditioning)
  Qb consists of single beta-gamma detector consisting of 18ml plastic scintillator detector inside a 4 inch NaI crystal
- ^{133}Xe MDC ~ 0.4 mBq/m^3

XENAH - Challenges

Working with a highly-regulated facility can be a challenge. Nuclear operators are required to comply with various regulations and be mindful of what information may be either commercially sensitive or have security implications. The default position is often a conservative one and so there may be an unease in sharing information or resources. **These challenges can be overcome!**

Reactor stack monitoring - STAX

Challenges:

1) Logistics – getting a sizeable piece of equipment onto a nuclear site
2) Potential interactions with existing systems
3) Security implications
4) Data sharing – is it Sensitive Nuclear Information?
5) Resourcing installation of non-essential equipment

Resolutions:

1) Avoid equipment with in-built radioactive sources – advanced warning
2) **STAX was kept "outside of the system".** It was not classed as test equipment and temporary and therefore subject to less stringent installation criteria. The system was also shown not to interact with other systems. This needed to be justified via an "Engineering Change" with particular focus on demonstrating that the claimed monitoring system for environmental release would not be affected by the installation.
3) Security a big concern. **Keeping the system "islanded"** ensured that it did not interact with any plant network and so was not subject to additional justification. Having the system interact with plant network would have required significant qualification.
4) **Early engagement**. Ask ourselves could this information be used by "threat actors" to cause significant harm? **The answer needs to be "No"! It** also helps to identify similar information that is already within the public domain
5) Engage interested parties and pull in favours! Resource can be a challenge – particularly when the work is not required for Compliance or for Commercial benefit. Project needs to peak interest to secure discretionary effort.

In-core measurements and samples

Challenges:

1) **Logistics** – sending radioactive material away from site difficult – particular overseas. Packages needed to be classified as "Excepted" packages under Dangerous goods regs. Receivers need evidence of a permit
2) Regulatory implications – site has process for retaining samples for 3 months
3) Resourcing of non-essential work

Resolutions:

1) Receiver needs to be able to provide evidence of a "Cat 5" permit that allows them to receive radioactive materials. Also settled on shipping within the UK to avoid further complications about shipping material abroad
2) Engaged regulator to ensure they were comfortable with samples being sent and potential not being retrievable. Asked for clarification on exactly what needs to be retained and for how long.
3) Engage interested parties and pull in favours! Resource can be a challenge – particularly when the work is not required for Compliance or for Commercial benefit. Project needs to peak interest to secure discretionary effort.

Remote measurements after ATM

Challenges:

1) **Logistics** – Sending equipment to others for loan – UK tax implications
2) Information sharing

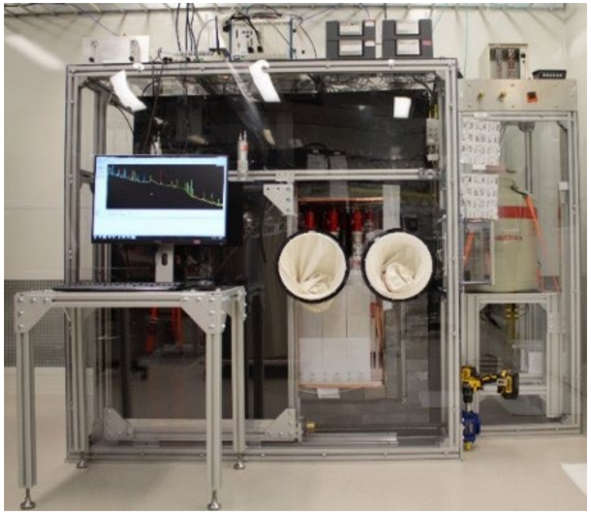
Resolutions:

2) Ensure that information shared is retrospective and based on that which is already publically available.

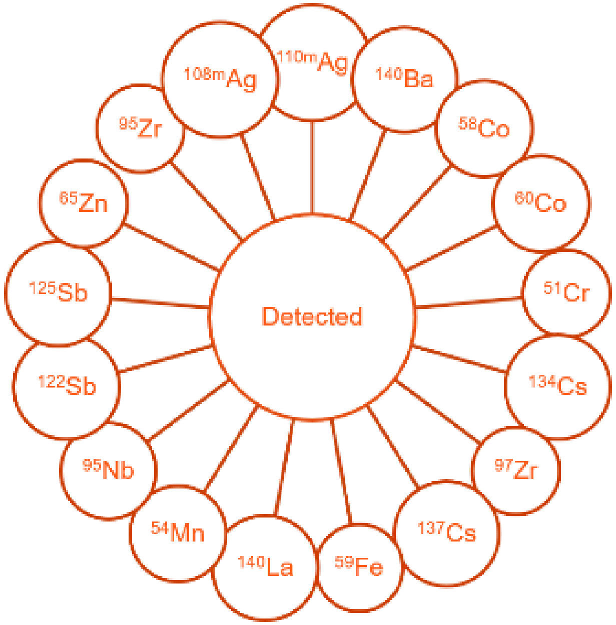
Environmental samples

Environmental measurements

- A portion of stack gas is continuously tapped and passed through maypack filters. At each discharge point. These are exchanged every 2 – 3 days and analysed on-site to demonstrate compliance against environmental discharge limits
- Maypack charcoal and paper filters provided from various locations at Hartlepool where fuel is handled and gaseous effluent discharged (pond stack, R6 and R12 blowdown Stacks, GCMF). Charcoal samples from June 2020 and June 2021 were provided. These were beyond the 3 month retention period* when shipped
- Samples were prepped to consistent geometry by packing charcoal into 200ml plastic sample pots. Each sample contained approx. 39g charcoal.
- Samples were measured at Boulby underground laboratory and the Shallow Underground Laboratory at PNNL
- Laboratories able to perform ultra-sensitive gamma-ray spectroscopy.
- ARGO at PNNL combines low background, cosmic veto, Compton suppression and coincidence functionality

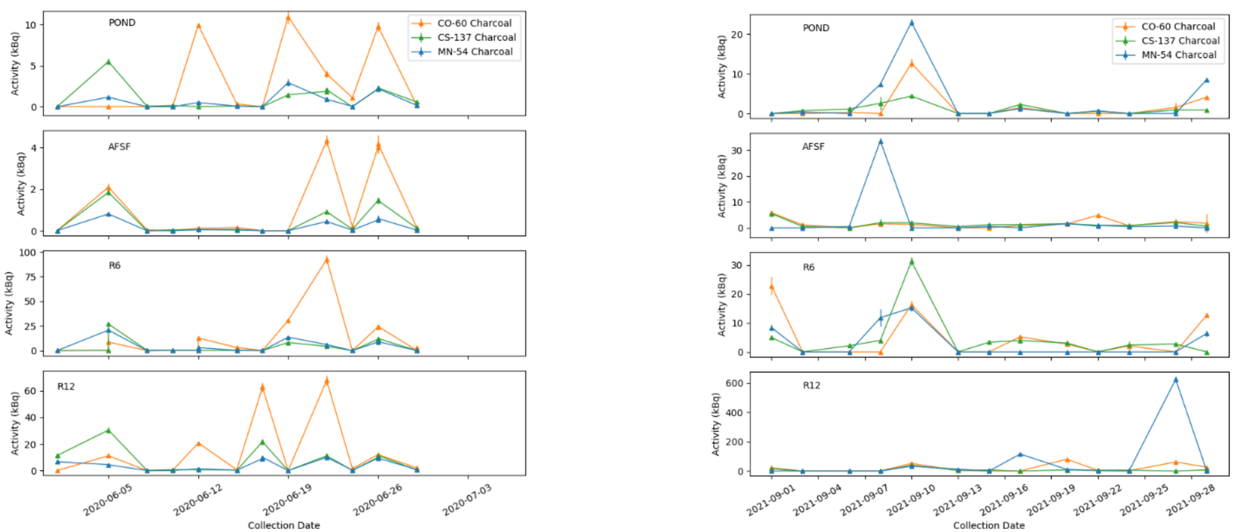


ARGO system at PNNL SUL



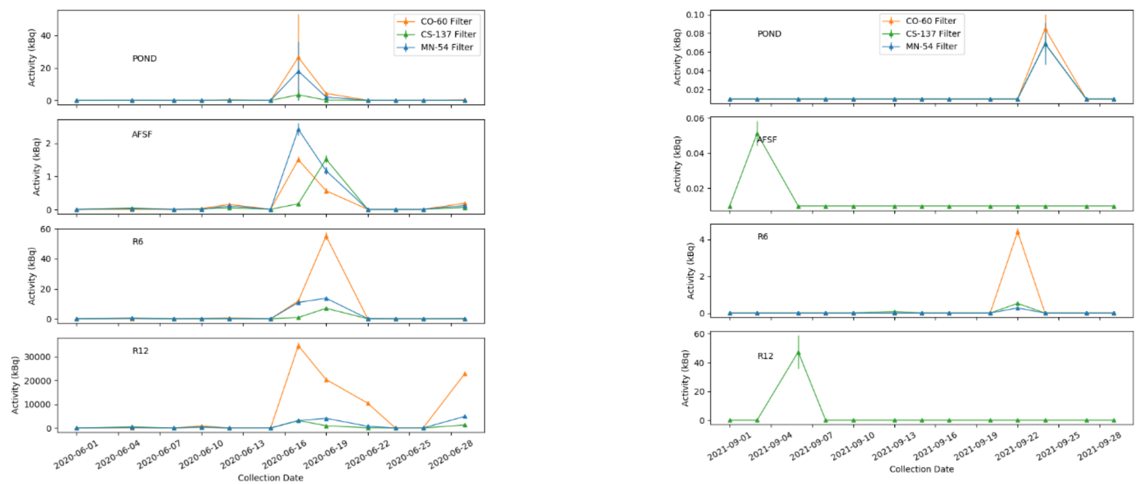
Preliminary results: Environmental samples

Isotope	Production Type	Half-life	Filter detections	Charcoal detections	IMS detections
^{137}Cs	Fission	30.1 a	62 (100)	109 (100)	7739 (31.3)
^{58}Co	Activation	70.9 d	2 (3.23)	18 (16.5)	17 (0.069)
^{60}Co	Activation	5.3 a	41 (66.1)	91 (83.5)	1044 (4.22)
^{54}Mn	Activation	312 d	48 (77.4)	88 (80.7)	62 (0.25)
^{108m}Ag	Activation	438 a	0 (0)	1 (0.92)	NR
^{110m}Ag	Activation	250 d	0 (0)	1 (0.92)	NR
^{51}Cr	Activation	27.7 d	2 (3.23)	4 (3.67)	12 (0.049)
^{57}Co	Activation	272 d	2 (3.23)	0 (0)	2 (0.008)
^{59}Fe	Activation	44.5 d	1 (1.61)	4 (3.67)	17 (0.069)
^{75}Se	Activation	120 d	1 (1.61)	2 (1.83)	NR
^{65}Zn	Activation	244 d	1 (1.61)	13 (11.9)	17 (0.069)
^{46}Sc	Activation	83.8 d	0 (0)	11 (10.1)	4 (0.016)



Time series plots showing measured activities of charcoal samples collected in June 2020 (left) and September 2021 (right) for the three most commonly observed isotopes at four facilities within the Hartlepool NPP.

Preliminary results: Environmental samples



Time series plots showing measured activities of filter samples collected in June 2020 (left) and September 2021 (right) for the three most commonly observed isotopes at four facilities within the Hartlepool NPP.

Conclusions

- Prior to measurement at PNNL and AWE, each sample is measured using conventional gamma-spectrometry systems at EDF Energy for environmental compliance.
- The ultra-sensitive measurements have identified trace levels of fission and activation products, including ^{108m}Ag, ^{110m}Ag, ^{51}Cr, ^{54}Mn, ^{58}Co, ^{60}Co, ^{97}Zr and ^{137}Cs. Some of these isotopes have not been recorded before in IMS data.
- Analysis focused on longer-lived radionuclides (e.g. ^{54}Mn, ^{58}Co, ^{60}Co, ^{137}Cs) at fuel handling locations. These isotopes occurred in a high proportion of the samples measured.
- Activation products have been attributed to the austenitic stainless steel of the fuel pins and reactor internals.
- **Measurements reveal increases in radionuclide activities during fuel handling**
- It is postulated that information from activation-product discharges could possibly infer if a facility is handling nuclear material.

- **Paper submitted to PRA but rejected. Paper to be submitted to JER after revisions**

Radio xenon measurements during blowdowns

STAX measurements

NGM-2000 System

- 30% HPGe detector
- MDC 270 Bq/m^3
- Flow through system: 1.25 m^3/hr
- Continuous monitoring (15 minute acquisitions, looped)

STAX system at R6 tower

- System aims to primarily measure radio xenon isotopes, but is sensitive to all gamma-emitting gaseous fission products
- Air extracted from stack flows through Marinelli. Measured concentration is adjusted by total stack flow.
- Stack flow peaks around 1400 m^3/hr during blowdowns
- System installed at R6 tower (main blowdown route)

In-core measurements

- Gaseous Activity Monitoring (GAM) measures in-core coolant activity to assess fuel condition
- 40% HPGe detector feeding MCA for isotopic analysis and NIM modules for analogue CCR indications and alarms
- 1 hour acquisition, continuous flow of 1 litre/s
- Used to monitor for fuel performance – particularly during blowdowns

GAM system at Hartlepool NPP

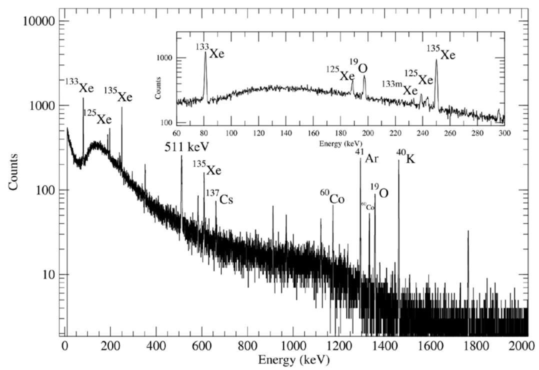
Blowdown route information

- Bypass/blowdown filter remains in service during normal operation and blowdowns.
- Blowdown line is opened via G/8. All gas from reactor goes through bypass/blowdown filter and iodine absorption plant.
- From ~ 30 barg to ~ 5 barg, gas exits through Major blowdown stack. From 5 barg to 0.3 barg, gas exits via Minor blowdown stack

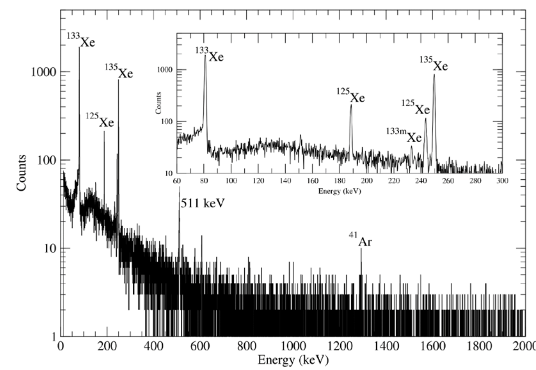
STAX monitor is installed on Major blowdown route at a tapping point within stack just prior to exit, post-filters. STAX gets mass flow data from flow meter installed within stack.

Pi blowdown flow data taken just prior to iodine absorption plant and measures flow to both major and minor blowdown routes. This data is used to scale in-core activity measurements to calculate release.

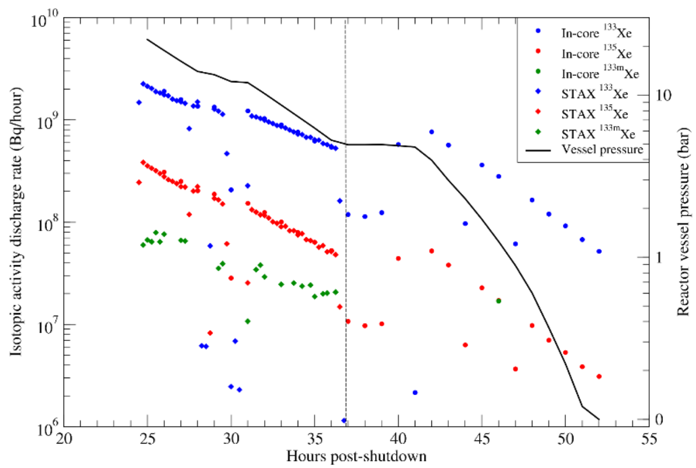
Preliminary results: Blowdown analysis



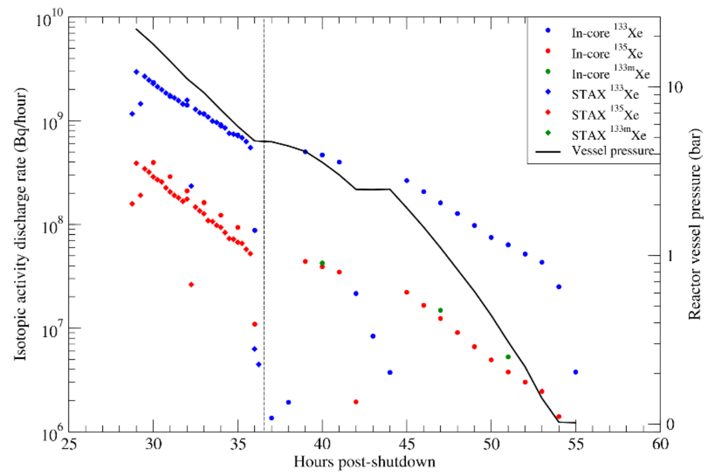
Typical spectrum obtained from a one-hour acquisition on the R1 GAM system whilst on-load at full power. Identified fission products and coolant activation products labelled.



Typical spectrum obtained from the STAX system during a reactor blowdown. Identified fission products and coolant activation products labelled.



Typical spectrum obtained from the STAX system during a reactor blowdown. Identified fission products and coolant activation products labelled.



Typical spectrum obtained from the STAX system during a reactor blowdown. Identified fission products and coolant activation products labelled.

Preliminary results: Blowdown analysis

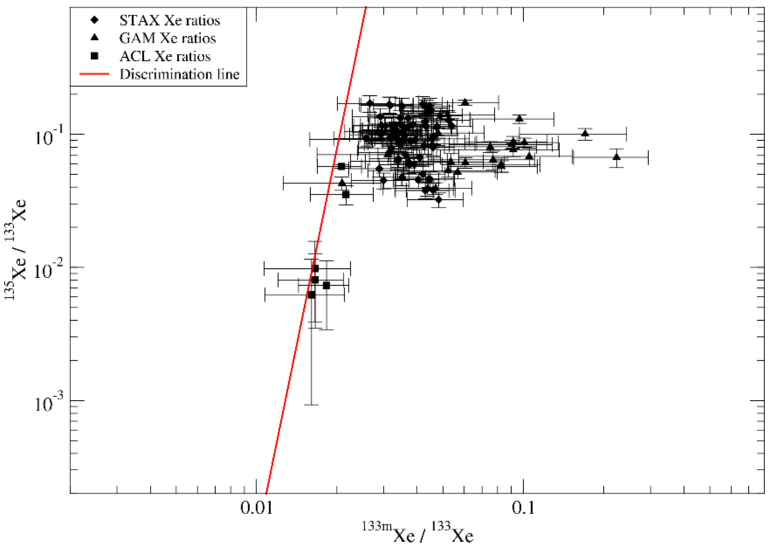
Blowdown period	^{133}Xe (Bq)	^{135}Xe (Bq)	^{133m}Xe* (Bq)	^{131m}Xe* (Bq)
R2 March 22	14.6(5)x10^9	1.4(1)x10^9	1.3x10^9	8.0x10^9
R1 June 22	11.3(4)x10^9	9.7(10)x10^8	1.8x10^9	9.1x10^9
R2 September 22	13.3(4)x10^9	7.8(7)x10^8	1.2x10^9	5.3x10^9
R1 November 22	10.9(5)x10^9	1.5(2)x10^9	1.8x10^9	9.9x10^9
R2 February 23	17.3(5)x10^9	2.2(1)x10^9	1.3x10^9	8.0x10^9
R1 April 23	13.0(5)x10^9	2.2(1)x10^9	1.2x10^9	8.2x10^9
Annual estimate	67(3)x10^9	21(2)x10^9	7.2x10^9	40x10^9

*Calculated total discharge activities, in Bq, for the 4 IMS-relevant xenon isotopes. 133Xe and 135Xe discharge activities are based on measured in-core activity from the GAM system and effluent flow. Upper limits for 133mXe and 131mXe discharged activity during the blowdown periods have been estimate based on GAM system MDAs and are denoted with **

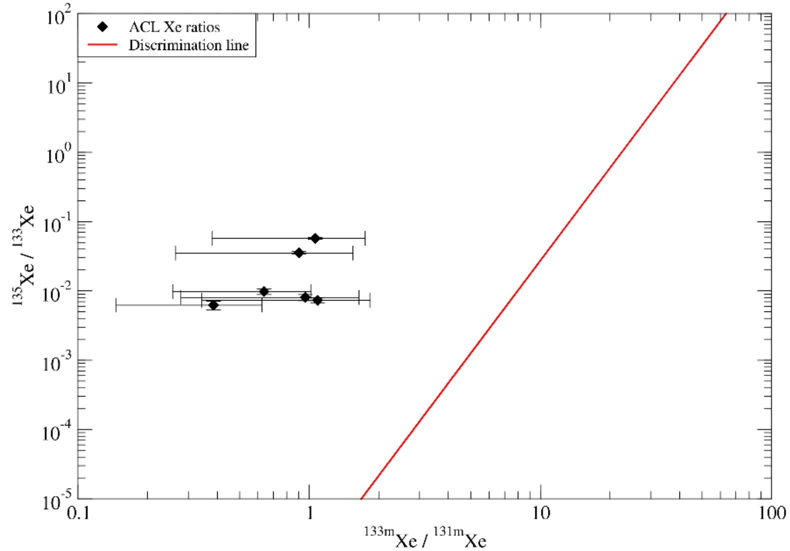
Conclusions

- In-core isotopic measurements are in very good agreement with measured emission activities
- During periods of release, around 10^9 GBq of Xenon activity is released. **Not continuous as previously assumed**
- **Likely that Kalinowksi et al. (JER 100, 2009) overestimate by an order of magnitude.** Upper limit for Xenon release of ~130 GBq for Hartlepool NPP against an assumed batch release of 1010 GBq or 4560 GBq continuous release.
- Other AGRs may be assumed to have similar emission profiles to Hartlepool. MAGNOX reactor design will be similar also.
- AGR emissions several orders of magnitude lower than MIPs and comparable with research reactors

Preliminary results: Blowdown ratio analysis



3-isotope ratio plot for STAX, GAM and ACL data with 'discrimination' line from Kalinowski et al, PAGEO 167, 2010



4-isotope ratio plot for ACL data with 'discrimination' line from Kalinowski et al, PAGEO 167, 2010

Results and conclusions

- When plotting data measured with STAX, GAM and from ACL samples as 3-isotope plots, AGR emissions lie to the right of the nuclear explosion discrimination line
- When the elusive ^{131m}Xe is included (measured in ACL charcoal samples) AGR emissions lie to the left
- **Supports the conclusion that ^{131m}Xe detection is key to discriminating civil emissions from nuclear explosions**

Paper to be submitted to PRA

Next steps…

- Continue to measure emissions during blowdowns using installed STAX system
- Continue analysis of ATM work and Qb array data
- **Publish results**
- Ship and measure ‘fresh’ samples of filtration media immediately after blowdown to measure short-lived isotopes, in particular iodine species.
- Analyse 5 years worth of in-core coolant activity data
- **Bring other UK stations into collaboration – Sizewell B PWR on board**
- Secure Research Council funding to develop novel radiation detection capabilities for use in current and future reactors?

 | EDF Energy Generation| | NOT PROTECTIVELY MARKED |

Thank You

