An overview over some new extraction chromatographic resins and their application in radiopharmacy

Steffen Happel
10/07/2020
Overview

- **TrisKem International**
  - **Products**
  - **R&D**
  - **Networks**
- **Extraction Chromatography**
- **Domains of application**
- **ZR Resin** *(e.g. Zr-89, Ga-68, Ge-68, Ti-44/5)*
- **TK200 Resin** *(Ga-68, Zn/Cu, Pt/Ir, Sc/Ca)*
- **TK201 Resin** *(Cu-64 from solid Ni targets)*
- **CU Resin** *(Cu from Zn and liquid Ni targets)*
- **Lanthanide separation** *(Lu-177, Tb-161)*
- **TK221** *(LN, Ac purification)*
- **TBP Resin** *(e.g. Zr-89, Sc, Ga)*
- **TK400 Resin** *(Pa, Nb, Ga)*
- **CL Resin** *(Ag, Pa, I removal)*
- **TK202** *(Tc/Mo)*
- **DGA Sheets**
- **PAN based resins**
- **TK-TcScint**
- **On-going developments**
TrisKem International

- Based in Rennes (France)
- Independent company since 02/07
  - Formerly part of Eichrom Europe
  - ISO 9001 since 2007
- Staff: 19
- R&D and TechSupport group:
  - 3 RadChem PhD, 2 OrgChem PhD, 4 Technicians
- R&D: Development of new resins, techniques and applications
- Several domains

Radiopharmacy and Nuclear Medicine
Environment and Bioassay
Geochemistry and Metals Separation
Decommissioning
➢ Production and trade of selective resins and accessories
   ➢ Mainly extraction chromatographic resins
   ➢ PAN embedded inorganic compounds
   ➢ Functionalized polymers and silicates
   ➢ Analytical and chelating ion exchange resins

➢ Distribution (Europe):
   ➢ LSC cocktails et al. (Meridian)
   ➢ PEEK columns
   ➢ Raddec Pyrolyser (H-3 & C-14)
   ➢ ICP & AAS standards (Labkings)
   ➢ New: Radioactive standards (NPL)
   ➢ Accessories (Zr crucibles, empty columns & cartridges, funnels, vacuum boxes,...)
R&D TrisKem International

- **Two R&D labs:**
  - **Synthesis Lab (new resins and extractants)**
    - Incl. grafted resins (silica or polymers), macrocycles,...
  - **Application Lab**
    - Preparation of extraction chromatographic resins
    - Resin characterisation and method development

- **Equipment:**
  - ICP-MS, IC, TOC, TGA, IR, moisture analyzer, surface area and pore size/volume analyser, particle size and shape analyser, pycnometer
  - Production and packing lab with four 20L reactors

- **No handling of radioactivity => R&D cooperation**
  - Resin and method development “cold” => R&D partner
Networks

- Isotope4Life / Atlanpole Biotherapies ID2 Santé
- Nucleopolis
- Prometia

- Several projects financed by the BPI
  - Radiopharmacy (Pb-212 => PSPC CARAT/LU-177)
  - Member of BPI Excellence
  - Lauréate Vague d’innovation BPI (C.L.I.P.S. 2020)
Organic extractant impregnated onto inert support

➢ « Supported Solvent Extraction » / « Solvent Impregnated Resins »

- Distribution between two non-miscible phases
- High density of functional groups
- Fast kinetics/small volumes => rapid separations
- High variety of selectivities:
  - Pure extractants, synergetic mixtures, solid extractants in diluents
- Aim: selectivity for product, no selectivity for target material
- Combining several cartridges can allow obtaining better product quality
- Elution under ‘soft‘ conditions in small volume => labeling/injection
- Bleeding might need to be addressed (Prefilter, AIX, CEX,...)
# Products and applications

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+Resin available worldwide in orange
| *main application in blue

**Coming soon:**
- **TK202** (Tc from Mo)
- **TK222** (Ac purification)
Examples of domains and applications

• Analytical
  • Radiochemistry
    – Environmental monitoring, bioassay, waste monitoring, decommissioning
    – Actinides, fission and activation products, NORM, methods/resins for DTM's, rapid methods,
      » TK100/1, TK200, TBP, CL Resin, TK201/2, TK300, TK-TcScint, Extractive discs,
  • Mass spectrometry
    – Isotope ratio determination (universities, petrol industry,
      » Dating of geological samples : TK200, TK400, TK300, ...
      » Food provenancing : TK100,
      » Nuclear forensics: TK200, TK400,
      » Biomedical (Cu),... => CU Resin,
Examples of domains and applications

- Decommissioning/decontamination
  - Treatment of effluents / liquid wastes / environmental waters
    - Removal of radioactive contaminants & heavy metals (Cs, Sr, Ra, I...)
  - Inorganic compounds embedded into PAN matrix
    - CS Resins, MnO2-PAN more under development
  - Polymer-based => TK202,...

- Hydrometallurgy
  - Recycling of critical metals
    - Mainly functionalized polymers => under development
Examples of domains and applications

• Radiopharmacy/Nuclear Medicine

• Radionuclide production
  – Cooperation with cyclotrons & reactors (NL, RN producers,...)
  – Equipment provider (targetry, synthesizer,...)
  – Separation of radionuclides from irradiated targets
    » Diagnostics: Zr-89, Cu-64, Ga-68, Ge-68, Ti-44/5, Tc-99m, Sc-43/4...
      • ZR Resin, CU Resin, TK200 Resin, TK400, TK201, TK202,...
    » Therapy: alpha emitters, Lu-177, Cu-67, Sn-117m, Sc-47...
      • TK400, TK200, TBP Resin, CU Resin, TK211/2/3, TK221,...
Examples of domains and applications

- Radiopharmacy/nuclear medicine
  - Purification of generator eluates => under development
  - Decontamination of contaminated effluents => **CL Resin**, ...
  - Quality control
    - Cartridge based methods
    - **DGA sheets** (functionalized TLC, Ra-223, Ga-68, Pb-212, .... => CVUT Prague)

![Chart showing chromatographic separation](chart.png)

_A scheme of chromatographic separation of mixture of $^{227}$Ac and his daughter’s nucides. $^{227}$Th remains on start, $^{227}$Ac has the retention factor ca 0.2, $^{211}$Pb ca 0.7 and $^{223}$Ra ca 0.9._
Applications in RadPharma – new resins

Radiopharmacy

Separation of radionuclides for medical applications

- Rapid, highly specific separation techniques
- Separation of radionuclides from irradiated targets
- Quality control of radionuclides for medical use
- Post-generator purification
- Radioprotection and Radioanalysis
- Easily used in glove boxes or hot cells
- High active samples

Our resins are increasingly finding application in the production and quality control of radionuclides such as Cu-64, Ga-67, Ge-68, Sr-89, Zn-65, Tc-99m, I-131, Ac-225, Pb-210, Ge-68,...

Triskem is now offering a selective chromatography paper (DGA Sheets) for quality control of radionuclides and generator effluents (Ac-225, Pb-210, Ge-68,...).

Triskem International places a strong focus on the development of new resins and separation methods to meet your separation needs. If you’d like to receive more detailed information, or if you’d like to discuss a specific separation problem, please contact us under: contact@triskem.fr

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*the main application is in blue

Our new developments - for information on all our products please visit our web site: www.triskem.com

www.triskem.com
ZR Resin

• Original scope: Hydroxamate based resin
  • Standard for Zr separation from Y targets
  • Ready to use / no activation
  • Facile Zr elution (avoid 1M oxalic acid)
• Zr-89 production via \((p,n)\) reaction from \(^{\text{nat}}\text{Y}\) targets
  – High Zr/Y selectivity necessary
  – Alternative e.g. TBP Resin (=> Graves et al.)
• Application for other separations: Ti/Sc, Ga/Zn, Ge/Ga
ZR Resin – HCl

- No selectivity for Y, Sc
- High Ge/Ga selectivity at elevated HCl
- High selectivity for Zr, Ti, Nb, W over wide HCl conc. range

- No selectivity for alcalines and earth alcalines
- Lanthanides not retained
- Fe retention (dip at 2 – 3M HCl)
Zr Resin – HNO\textsubscript{3}

- High selectivity for Zr, Ti, Nb, W over wide HNO\textsubscript{3} concentration range
  - Loss of selectivity at 6M HNO\textsubscript{3} => Resin shows colour change
- No selectivity for Y, Sc, lanthanides, earth alcalines, most transition metals,…
- High Ge/Ga selectivity at 3M HNO\textsubscript{3}
Zr-89 separation from Y targets

- Load from 2 – 6M HCl
- Rinsing described by Holland may be used
- No activation with acetonitrile

- Quantitative Zr elution in 1.5 - 2 mL ≥ 0.05M oxalic acid
- Clean Fe removal
- Use in commercial systems
  - Taddeo, Pinctada,...
Ti-Sc Separation (Ti-44/5)

- Ti retained from (high) HCl, Sc not retained
- Ti also retained in dilute acid, Sc not => Ti generator?
- Ti elution with 0.1M citric, >0.2M oxalic acid, 0.1M H$_2$O$_2$
- Publications:
  - Malinconico et al.: J Nucl Med May 1, 2018 vol. 59 no. supplement 1 664)
  - Chaple et al. : Appl Rad Isot, Volume 166, December 2020, 109398
Ti-44/Sc-44 production

- 4g irradiated Sc
- 5 mL Zr Resin
- Ti-44 yield >95%
- 65.2 MBq Ti-44
- $D_f(\text{Sc}): 10^5$

Generator been set-up at BNL/SBU => Poster S. Houclier ISRS 2019

Use of ZR Resin as support in Ti-44/Sc-44 generators

- Direct (1 mL ZR) and reverse elution (2 mL ZR)
- 65 column volumes tested up until publication
- High Sc yields, max. Ti-44 breakthrough: $4.1^E\times 4\%$
- Obtained Sc gave labelling yields > 94%
Ge-68 separation from GaNi or GaCo

- Loading from HNO$_3$, HCl or H$_2$SO$_4$
  - Target dissolution in HNO$_3$ or H$_2$SO$_4$ often preferred => GeCl$_4$ volatile
- Ongoing: Cold test on >5g GaNi
- First cycle on ZR (2 mL ZR Resin cartridge):
  - Load/rinse from 5M H$_2$SO$_4$
  - High Ge retention/purification from Ga, Ni & Co
- Elution: 0.1M citric acid (pH 3)
- Second cycle on ZR (1 mL cartridge):
  - Adjustment of eluate to 5M H$_2$SO$_4$
  - Load/rinse from 5M H$_2$SO$_4$
  - Elution with 0.1M citric acid (pH 3)
- Conversion step:
  - Acidification to 9M HCl, load onto Guard Resin
    - Alternatives: TK400 or PF
  - Rinse with 9M HCl
  - Elution with to 0.05M HCl => pH!
Ga-68/Ga-67 separation from Zn targets

- Loading from:
  - dilute HNO₃ (liquid targets)
  - > 6M HCl (solid targets)
- Ga separation on ZR Resin
- Elution with ~1.5M HCl
- Ga conversion step on TK200 (TOPO)
  - TK200 load from 1.5M HCl
  - Better pH control of eluate via rinse with NaCl/HCl before elution=> Gagnon et al.
  - Elution in 2 – 3 BV water

Presentation EANM ’17: Ga-68 from liquid targets by K. Gagnon (GEHS) et al.
Poster ISRS 2019: Ga-68 from solid targets by K. Gagnon (GEHS) et al., Tieu et la. (MITRU)
ARTMS/Odense: 10 Ci production

⇒ New IAEA TechDoc:
https://www-pub.iaea.org/books/IAEABooks/13484/Gallium-68-Cyclotron-Production
Cyclotron production of Ga-68

- Liquid target: 1.7M $^{68}$Zn(NO$_3$)$_2$ in 0.2M HNO$_3$
- GE PETtrace at 12MeV, 32 min, 46 µA
- Modular Lab (EZAG)
- $4.3 \pm 0.3$ GBq EOB
- Separation on ZR Resin and TK200 Resin ($t \sim 40$ min)
  - Loading of ZR Resin at <0.1M HNO$_3$,
  - Rinse with 9 mL 0.1M HNO$_3$.
  - Ga Elution with 5 mL 2M HCl directly onto 100 mg TK200
  - Ga Elution from TK200 with water
- Chemical yield >75%,
  - $2.3 \pm 0.2$ GBq after separation
- Purity: 99.976 ± 0.002% => Ph. Eur.
- Target material recovery 80 – 90%
- For solid targets: single cartridge method (TK400) also under evaluation
Other examples for separations on TK200 (TOPO based)

- **Zn separation from Cu**
  - Zn/Cu separation. Elution study, ICP-MS measurement
  - Zn-65 separation. Data kindly provided by Fedor Zhuravlev, DTU

- **Pt separation from Ir**
  - Pt/Ir separation. Elution study, ICP-MS measurement

- **Sc from Ca**
  - Elution under rather soft conditions
  - Potentially in combination with TBP Resin
Cu separation on TK201 (Cu-64)

- Cu separation from solid Ni targets and conversion usually done using AIX
  - Shrinking/swelling, trace Zn removal, elution volumes

- Use of TK201 (amine)

  - Cu-64 separation from solid Ni on TK201:
    - Load and rinse at 6M HCl => Ni removal => recovery/recycling
    - Co elution with 4 – 5M HCl
    - Gagnon et al. use of NaCl/HCl for better pH control of eluate
    - Cu elution with 0.5M HCl => Fe and Zn remain retained
    - Preferred alternative: Additional use of TBP (or TK400) upfront for Fe/Ga removal
      => allows for Cu elution in 0.05M HCl or lower
CU Resin

• Oxime based resin
• High selectivity for Cu
  – Especially with respect to Zn and Ni
  – Widely used in mass spectrometry (Cu isotope ratio measurement)

• Load from pH >2, elution in high mineral acid (2 – 8M)
  – Suitable for **liquid** targets
  – Used for (large) solid Zn targets (=> Cu-67)
  – Loading not ideal for solid Ni targets (usually high HCl) => TK201
  – Elution in high HCl not compatible with labelling/injection
    • Evaporation or conversion to dilute HCl e.g. via TK201
  – High purity and labelling yields
Cu-67 at BNL (DeGraffenreid et al.)

Purification of $^{67}\text{Cu}$ and Recovery of its Irradiated Zn Target

- Brookhaven National Laboratory, C-AD/MIRP—Upton, NY (USA)
- University of Missouri, Department of Chemistry—Columbia, MO (USA)

- 13.7g Zn metal dissolved to give 312 mg ZnCl$_2$/mL solution at pH 2
- Loading of 60.6 mL $\Rightarrow$ 18.9g ZnCl$_2$ onto 2.4g CU Resin column $\Rightarrow$ 8 mL
- Rinse with 80 mL pH2 HCl
- Eluiton in 2 x 20 mL 6M HCl
- Evaporation to dryness
- Chemical yield $\sim$100%
- Single column $D_f$ for Zn $\sim$10 000
  - Additional removal indicated
- Ideally further Zn and Co removal
- Original suggestion: AIX

Alternatives to AIX:
- TK201: prefered option. Cu elution from CU Resin with 6M HCl directly onto TK201, followed by Cu elution from TK201 in dilute acid
- TK200: Cu eluted from CU Resin in 2M HCl, direct load through TK200 (Zn retained, Cu passes)
Lanthanide separation on LN series or TK211/2/3

Product sheet: 

\[
M^{3+} + 3(HY)_2 \leftrightarrow M(HY_2)_3 + 3H^+
\]
$k'$ Am(III) on LN, LN2 and LN3 vs HNO$_3$

50-100 μm, 1 hr equilibration, 22(1)°C

Main difference: acidity

$k'$ Relative to La on LN2 = 1

$[\text{HNO}_3]$

- Allows for nca Lu-177 separation from 300 mg Yb targets
- Lu and Yb chemically very similar
- Based on LN2 and DGA, N
- Large amounts of Yb introduce peak tailing
  - The more Yb the stronger the tailing
- Multi-column method needed
- Lu yield ~73%
- Rapid (<6h) but difficult to automize method
- Under optimization and upscale
• On-going developments Lu-177 et al.

• Separation of nca Lu-177 from Yb-176 targets (300 – 2000 mg)
• Simplification via sequential separation steps
  – ‘Sequential separations’ approach also applicable e.g. to Tb separation
• New resins: TK211/2/3
  – On-bead mix of different extractants for improved selectivity
  – Higher extractant load
  – Small amount of long-chained alcohol and use of inert support containing aromatic groups => aim: improved radiolysis stability
  – 35 µm beads
    • Originally developed as 15µm beads => too small for large scale separations
    – Resins also applicable to Horwitz method (TK212 & TK221)
• Prepacked PE columns under development
  – 29 mL, 53 mL, 150 mL, 375 mL and 750 mL
• Simplified method for Lu separation from 500 mg Yb – TK211/2 & TK221

Sequential separation step (direct load from TK212 onto TK211 for polish)
• Simplification of Horwitz method
• Can be upscaled to 1g or 2g (larger columns)
Lu separation form 500 mg Yb - TK212/TK221/TK212/TK211

- Large tailing due to high Yb content
- Improved separation through use of 1.25M HNO₃ / 10% EtOH (v/v)
- Higher Lu yield at similar residual Yb compared to LN2 based method (cf. LN Resins product sheet)
- Additional benefit from use of EtOH => improved radiolysis stability
- Higher flow rate possible e.g 25 mL/min
- Online separation: switch at start of Lu fraction
Lu separation from 500 mg Yb - TK212/TK221/TK212/TK211

- 2nd separation step on smaller TK212 (53 mL) after TK221 for conversion from high HNO₃ to dilute HCl
- Separation with e.g. 1.25M HNO₃ (with or without 10% EtOH)
- Direct loading of obtained Lu fraction onto TK211 Resin
Lu separation form 500 mg Yb - TK212/TK221/TK212/TK211

- Lu / Yb separation on TK211 (29 mL) => Lu fraction directly loaded onto TK211 from TK212
- Overall Lu recovery of process approx 85%
- Remaining Yb in single digit to low double digit µg, under further optimisation
- Flow rates may be optimized (rule of thumb: column diameter in mm => flow rate in mL/min)
Tb separation from 500 mg Gd targets

- Initial separation on TK213 and TK212 under testing – 150 mL columns
- TK212 method – fine tuning ongoing (e.g. adjustment of eluents to 10% EtOH)
- Separation easier than Lu/Yb
- Polishing via direct load on TK211 (29 mL)
• Direct load of Tb fraction from TK212 onto TK211 (29 mL)
• Gd breakthrough during load & rinse with 0.5M HNO₃
• Method optimisation ongoing
• Conversion to dilute HCl via TK221
• Next: TK213/TK211 method development
• On-going developments Lu-177 – new TK221 Resin

• DGA well suited for ‘conversion’ and purification (Ca, Al, Fe,... removal)
  – Convert Lu from high nitric acid to dilute HCl
• Elution of heavy lanthanides needs elevated volumes
  – small volume preferred => high activity concentration
• Optimisation of DGA Resin => new TK221 Resin
  – Lu eluted in smaller volume
  – Should also work for Ac-225 conversion/purification => better: upcoming TK222 Resin
  – Also improved U retention
Zr-89 separation on TBP Resin

- Method published by Graves et al.
- 400 mg Y foils irradiated at 14 MeV (50 µA)
- Dissolution in 10 mL conc. HCl
- Separation on 220 mg TBP Resin
- Load from 9.6 M HCl, rinse with 20 mL 9.6 M HCl
- Zr elution with 1 mL 0.1 M HCl
- Zr yield: 89 ± 3%, Y decontamination: 1.5 x 10⁵
- Zr elution with oxalate, citrate, phosphate...

- Other applications of TBP Resin:
  - Sc isotope production from Ca targets (=> presentation EANM’18, Polatom)
  - Sn-117m from Cd targets
Use of TK400 for Fe/Nb removal

- On-going work – initial testing
- On TBP only:
  - Fe and Nb follow Zr
    - Test on vacuum box, 2 mL TBP cartridge
- Removal of Fe & Nb upfront possible using TK400 Resin
- Test with stacked 2 mL TK400/TBP cartridges
  - Load and Rinse: TK400 stacked above TBP
  - Elution: splitting of cartridges and separate elution
    - TBP => ZR
    - TK400 => Fe & Nb
  - Use of TK400 before TBP seems efficient
TK400 Resin

- Long chained alcohol
- Retention only at high HCl concentration, elution in low HCl, water,...
- Main application: Pa separation (Pa-231 determination by MS/Pa-230 for medical use)
  - NPL (no selectivity for actinides, Ac, Ra, Pb,...=> Pa-230 purif.)
  - Also retains Mo, Po, Ga (= single column Ga-68 from solid targets => Tieu),...
  - Under testing for At separation and Ge conversion to dilute HCl
  - Nb separation from Zr possible (Nb-90)

Knight et al.
Chromatographic separation of the theranostic radionuclide $^{111}$Ag from a proton irradiated thorium matrix


*Chemistry Division, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545, USA
b Nuclear Security and Isotope Technology Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

**Highlights**

- Chromatographic recovery of medical isotope $^{111}$Ag from proton irradiated thorium targets.
- First-time measured equilibrium distribution coefficients for silver and ruthenium on CL resin.
- $^{232}$Th (p, fission) cross-section data for the formation of $^{110}$Ag and $^{110m}$Ag.

**Graphical Abstract**

Separation of protactinium employing sulfur-based extraction chromatographic resins


†Chemistry Division, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545, USA
‡Nuclear Security and Isotope Technology Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

§Current Address: Life Sciences Division, TRIUMF, 4004 Wesbrook Mall, Vancouver, BC, V6T2A3, Canada
Decamp et al.: Iodine removal from elevated sample volumes

- Treatment of complex process effluents
  - > 10 L radioactive effluent (1M HNO₃)
- Issues with rad. waste storage
  - Storage as liquid waste challenging
  - Preferably stored as solid waste
- Use of mixed-bed columns
  - 3g Ag loaded CL resin (plus 4g XAD-4 resin)
- Flow rate up to 180 mL/min
- Radio-iodine retention: 89% - 98%
- Retention of up to 2000 GBq radio-iodine per 7g column

Decontamination of effluents e.g. nuclear medicine departments

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Beta testing: TK202 Resin

• Based on Polyethylene Glycol (PEG) grafted on inert support
• Tc retention from high NaOH (preferably 5M NaOH)
• Tc retention increased by Mo
• Separation from high masses of Mo
• Elution with water
• Potential uses:
  – Radiopharmacy => direct Tc-99 production by irradiation of Mo targets
  – Decommissioning => Tc determination in decommissioning samples after sample fusion
Tests show Re-Tc have similar behaviour in tested conditions

Clean separation of Re-Tc and recovery in 5BV H₂O

Tests at Polatom with simulated Mo targets

Poster presentation at ISTR2019, Vienna, 28/10/19 – 01/11/19

- Tc recovery > 90% for 6 – 8g Mo per g of TK202
- Tc recovery > 80% for 12g Mo per g of TK202
DGA Sheets

• QC of radionuclides and generator eluents (p.ex. Ra-223, Ac-225/Bi-213, Pb-212, Ge-68/Ga-68 ...)
  – TLC scanner or radiometer/LSC after cutting
  – Therapy: alpha emitters
  – Diagnostics e.g. generator produced Ga-68

• More types of sheets under development (selectivities, geometry)
  – TK201, LN, UTEVA,...

• 2D TLC under development => use in decommissioning
  – Quadratic sheet, two runs (90° turn in-between) with different acids => 2D pattern
  – Measurement e.g. with Ai4r Beaver system (high res α/β discrimination counting)
TK TcScint

- Scintillating Resins (PSm)
- Developed by Uni Barcelona (Garcia)
- « TK ELScint » range of products
- First: « TK TcScint »
  - Similar to TEVA
- Plastic scintillator beads impregnated with selective extractants
- Direct measurement of cartridges after loading on LS counter
- Environmental/decommissioning monitoring => Tc-99 by LSC
- Chemical yield preferably via Re/ICP-MS in effluents
- Use in QC?
PAN based resins for decontamination

- Laureate ‘1. vague concours d’innovation 2018’ of the BPI
- Range of PAN based resins (other polymers possible - depending on pH)
  - Decontamination of effluents => radionuclides, heavy metals, pollutants...
  - High content of inorganic compounds (~85%)
  - Organic compounds also possible (HDEHP, TBP,...)
  - Mechanical stability
  - Control of particle shape, diameter, porosity
  - High porosity/active surface => fast kinetics

![Graphs showing decontamination kinetics](image)
PAN based resins

• Platform technology
  – Control/choice of wide range of selectivities
  – Variety of inorganic compounds embedded in organic matrix
    • AMP & KNiFC for Cs, SbO for Sr/Y, ZrP for Sr, TiO for actinides and activation products, FeO for Se, CeO₂ or SnO₂ for Ge, NaBiO₃ for Am/Cm separation, MnO₂ for Ra,…
  
  – Organic extractants may be embedded, too

• Large scale production of resins under development
Some other on-going projects

- SE Resin
- Sc separation
- Ac separation (incl. Ra recycling)
- At separation (TK400,...)
- Tl separation
- Improvement of radiolysis stability
- Functionalised polymers & silicates,...
  - e.g. DO-DGA, DE-DGA, macrocycles,...
- Ra separation (TK100/1, CAs)
- Microfluidics
- Impregnated membranes
- Li Resin
- Cs/Rb separation (TK300)
- Rapid tests
  - Test sticks => Uni Southampton
  - DGA Sheets (2D TLC)
  - Spin coated discs
- DGT (Diffusive Gradients in Thin Films) => ’bio-availability’
Thank you for your attention!