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ENERGY AND CLIMATE CHANGE
ENVIRONMENT AND SUSTAINABILITY
INFRASTRUCTURE AND UTILITIES
LAND AND PROPERTY
MINING, QUARRYING AND MINERAL ESTATES
WASTE RESOURCE MANAGEMENT

International Seminar - Innovations in the lithium supply chain. Views from Latin America and the United Kingdom.

Santiago & Buenos Aires - April 2018

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BRITAIN & NORTHERN IRELAND

THE DRIVE FOR LITHIUM

Dr Chris Broadbent
Research Director, Wardell Armstrong

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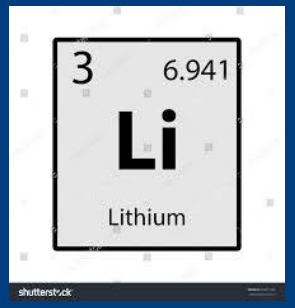
CONTENTS



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IOM3 VISION

To be recognised as the global leader for professionals involved with the materials cycle

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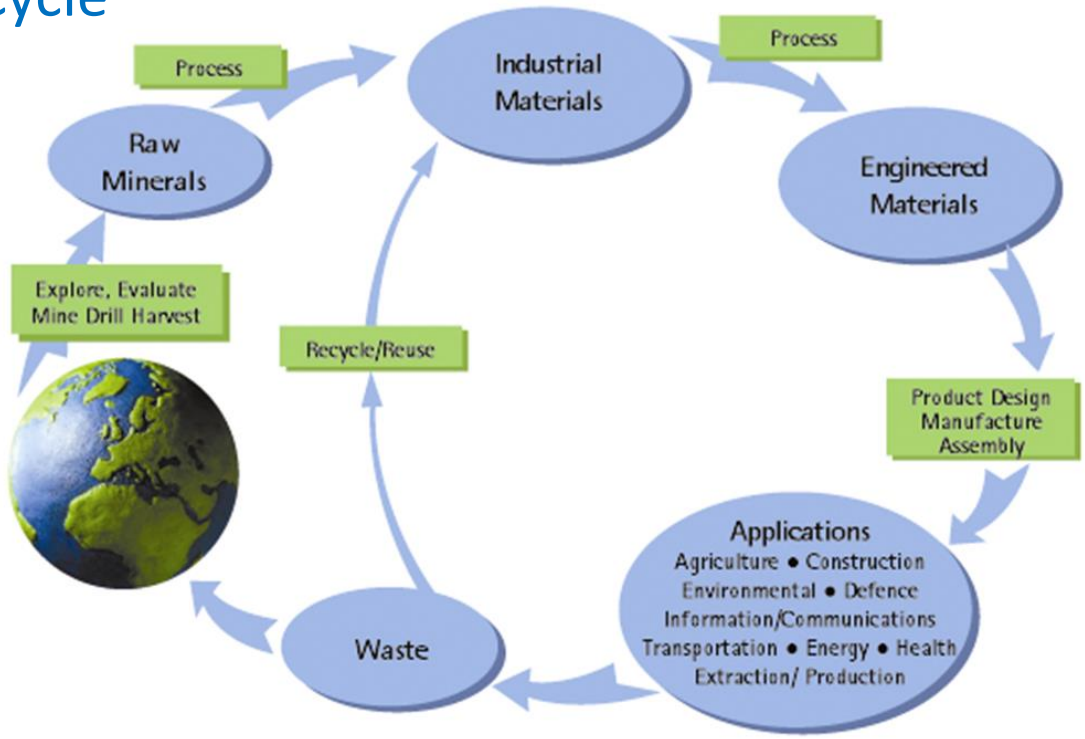
Materials Cycle



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IOM3 AT A GLANCE

- 16,000 members – 20% outside the UK
- 90 IAS members (Company members)
- 1,200 SAS members (School members)
- 50 members of staff
- 3 UK offices
- 54 Local Societies
- 8 International Local Societies

IOM3 Technical Communities

Materials Divisions

- The Polymer Society
- The Ceramics Society
- The British Composites Society
- Light Metals Division
- The Iron & Steel Society
- Materials Science & Technology Division
- The Wood Technology Society

Minerals & Mining

- Mining Technology Division
- Oil & Gas Division
- Applied Earth Science Division
- Mineral Processing & Extractive Metallurgy Division

Applications Divisions

- Automotive Applications Division
- Biomedical Applications Division
- Casting & Solidification Division
- Electronic Applications Division
- The Packaging Society
- Surface Engineering Division

Multidisciplinary groups

- Construction Materials Group
- Energy Materials Group
- Natural Materials Association
- Sustainable Development Group

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FUNDING OPPORTUNITIES

HM Government

UK Government initiatives, e.g. the Faraday Battery Challenge: Industry Strategy Challenge Fund

UK Government will invest £246 Million to support the development of new battery technologies

This will fund: Research, Innovation and scale up facilities for batteries for EV's

https://www.gov.uk/government/collections/faraday-battery-challenge-industrial-strategy-challenge-fund

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 641650.

EU Horizon 2020 Programme
e.g. FAME 7.4 million Euros

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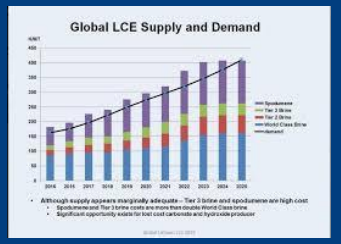
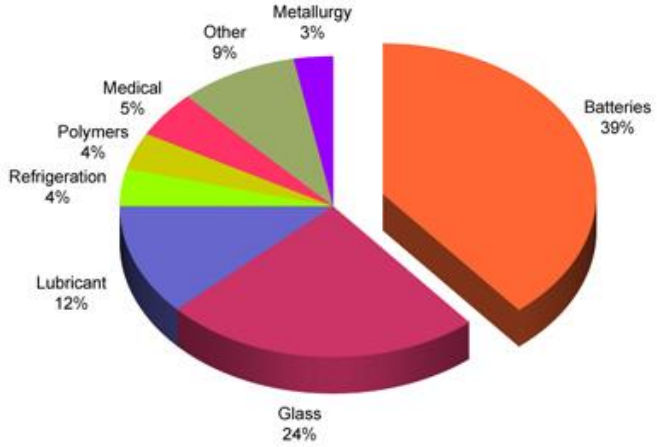
LITHIUM DEMAND



"In terms of new lithium supply the industry needs all the supply it can get. SQM, traditionally conservative of its lithium estimates, is expecting an 800,000tpa LCE market by 2027. These numbers are staggering considering the market was at 180,000tpa LCE in 2017."

Source: Mining Journal – Interview with Simon Moores – MD Benchmark Mineral Intelligence – 5th September 2017



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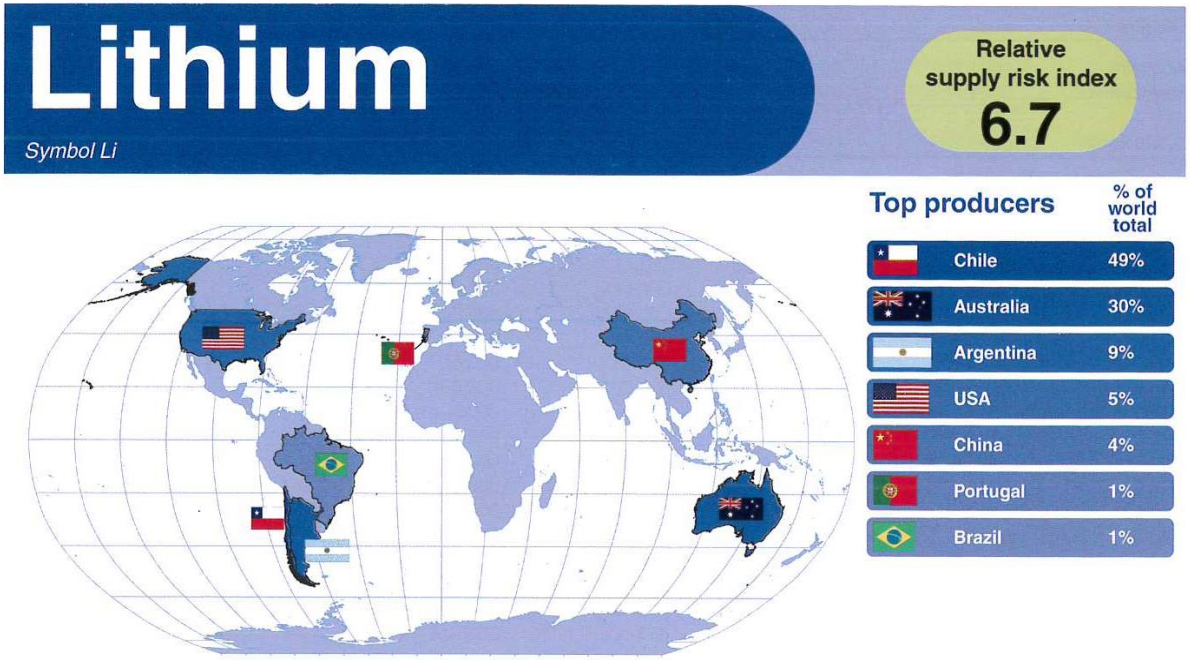
CURRENT LITHIUM PRODUCERS



Source: BGS World Mineral Production

CURRENT PRODUCTION

BRINE (South America)	V	HARD ROCK (Australia)
Low OPEX		High OPEX
Relatively high CAPEX		Relatively low CAPEX
Time to Production		Quick to Production

- Future market increasingly dominated by batteries
- Therefore battery grade needed
- Impurities key
  Carbonate V Hydroxide

COMPOSITION OF LITHIUM MINERALS

COMMON Li-PHASES AND ASSOCIATED MINERALS

Abbreviation	Li-mineral	Mineral formulae
Pt (Lpd)	Polylithionite-trilithionite *	$KLi_2Al[Si_4O_{10}][F,OH]_2 – K[Li_{1.5}Al_{1.5}][AlSi_3O_{10}][(F,OH]_2$
Zwd	Zinnwaldite	$KLiFe^{2+}Al[AlSi_3O_{10}][F,OH]_2$
Spd	Spodumene	$LiAlSi_2O_6$
	Petalite	$LiAl[Si_4O_{10}]$
Lt	Lithiophilite-triphylite	$Li[Mn,Fe]PO_4$
Am	Amblygonite-montebrasite	$LiAl[PO_4][F,OH]$
Brl	Beryl	
Qz	Quartz	
Pl	Plagioclase	
Kfs	K-feldspar	
Ap	Apatite	
Chl	Chlorite	
Kao	Kaolinite	
Tz	Topaz	

UK Li Mineralogy Expertise Available:
Particularly at NHM, London and CSM, Cornwall

** Note: "Lepidolite" is a loosely defined name commonly used for Li-mica of the Pt-series*

NATURAL HISTORY MUSEUM

Camborne School of Mines

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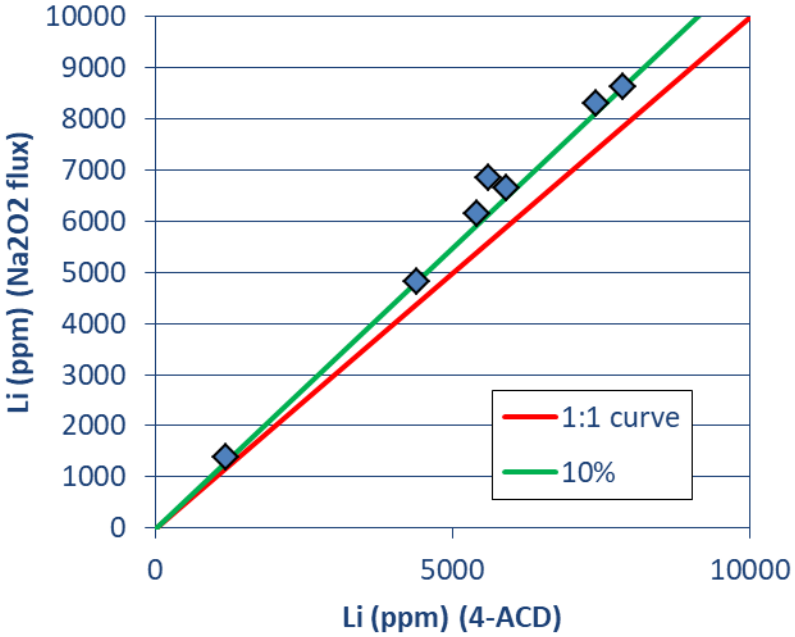
WHOLE ROCK ANALYSIS (Li ASSAYS)

- Li is not that straight forward to analyse in whole rock
  - Its low mass means that there are low fluorescence yields and long wave-length characteristic radiation rule out lab-based XRF and pXRF
  - We cannot use conventional fluxes as these are generally Li-based
  - We can use "older" non Li fluxes such as Na_2O_2 but then there maybe contamination issues in the instruments
  - We can use multi-acid digests ($HF+HNO_3+HClO_4$ digestion with HCl-leach) (FAME used the ALS ME-MS61) however there may still be contamination issues and potentially incomplete digestion.
- It has been noted that the comparability between methods is sometimes poor (>10% difference)

Source: R Amstrong, NHM – The Challenge of Li Determination in Minerals, Geol Soc, London, April 2018

COMPARISON OF METHODS: AN EXAMPLE

- Samples from the Kaustinen area spodumene pegmatites supplied to the FAME project by Keliber Oy Finland.
- 4 acid digestion vs Na_2O_2 flux then acid – both with ICP-AES finish

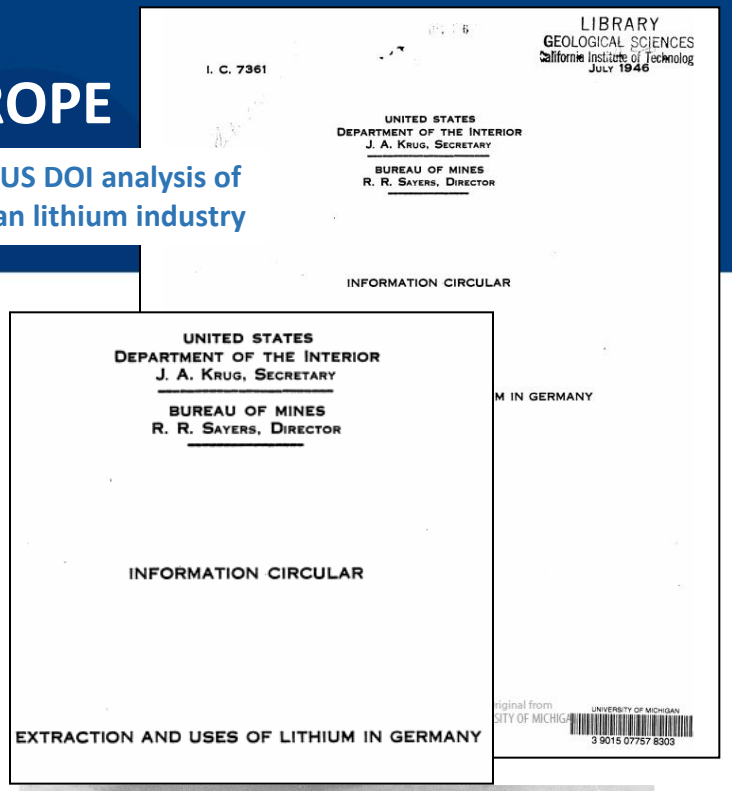


4 Acid	Na_2O_2	
Li ppm	Li ppm	%diff
7410	8300	11.33036
5610	6860	20.04812
7870	8640	9.32768
1180	1380	15.625
5910	6640	11.63347
4390	4820	9.337676
5400	6160	13.14879

Source: R Amstrong, NHM – The Challenge of Li Determination in Minerals, Geol Soc, London, April 2018

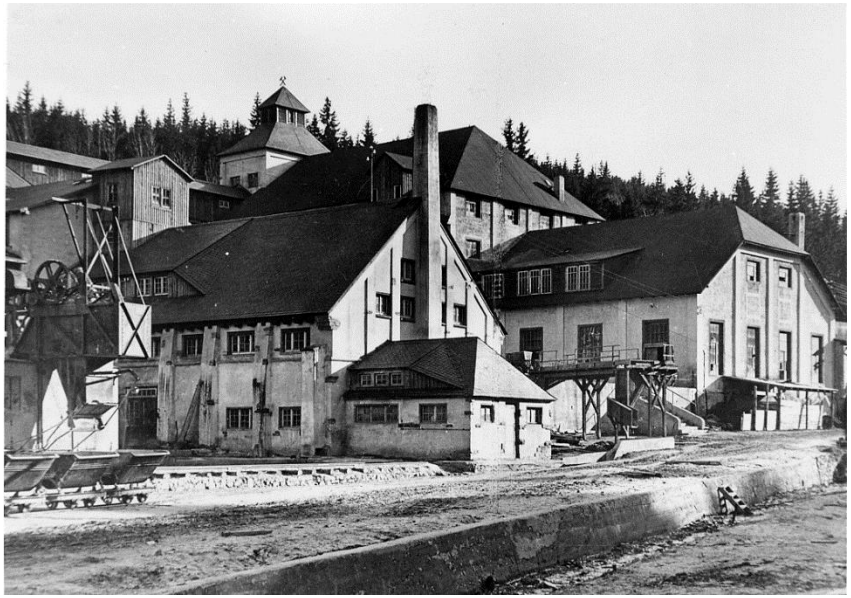
HISTORY OF LITHIUM PRODUCTION IN EUROPE

1945: US DOI analysis of German lithium industry

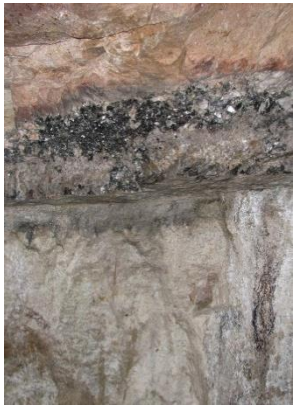


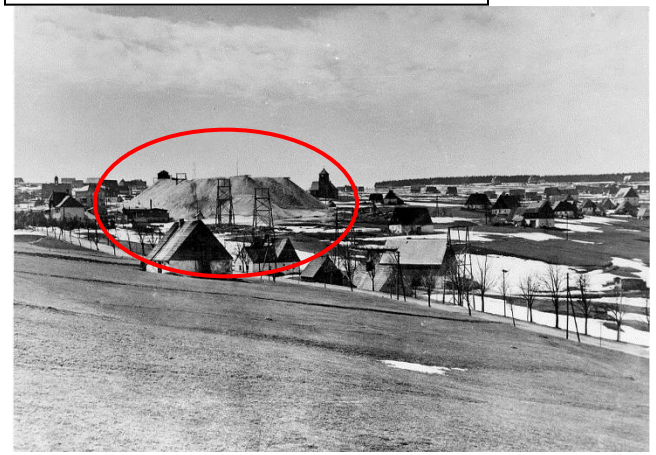
First large scale Lithium production in the world: Zinnwald / Germany

Start in 1922: Re-mining of Tin-Tungsten tailings for lithium mica (Zinnwaldite)



Processing plant





Tin-Tungsten tailings containing Li mica

EUROPEAN Li POTENTIAL (HARD ROCK)

European lithium producers 2016 and advanced (post conceptual study) lithium projects

Country	Company	Deposit	Main mineral	Stage	Production 2016 t LCE	Resources		Reserves	
						Mt	Li2O %	Mt	Li2O %
Austria	European Lithium	Wolfsbeg	Spod	PFS o	-	12.6	1.17	-	-
Czech Republic	European Metals	Cinovec	Zinn	PFS f	-	656.5	0.40	-	-
Finland	Keliber	Several	Spod	DFS o	-	8.1	1.19	4.5	1.10
Portugal	Sociedad Mineira de Pegmatites	Castanho	Spod?	Prod	1200	?	?	?	?
Portugal	FELMICA	Gondiães	Pet	Prod	150	?	?	?	?
Portugal	Imery Ceramics Portugal SA.	Imery Ceramics Portugal SA.	Spod	Prod	190	?	?	?	?
Portugal	José Aldeia Lagoa Et Filhos	Gonçalo Sul	Lep	Prod	50	?	?	?	?
Portugal	Sociedade Mineira Carolinos	Alvarrões	Lep	Prod	150	?	?	?	?
Serbia	Rio Tinto	Jadar	Jad	PFS o	-	136.0	1.80	-	-
Spain	Imerys	Alberto	Lep?	Prod	100	?	?	?	?
Total					1840	813.2	0.65	4.5	1.10

Minerals: Spod = Spodumene, Zinn = Zinnwaldite, Pet = Petalite, Lep = Lepidolite, Jad = Jadaite.

Stage: DFS o = Definite Feasibility Study on-going; PFS f = Pre-feasibility study finished, PFS o = Pre-feasibility study on-going, Prod = Production

Source: Lamberg & Broadbent – Materials World, February 2018

LITHIUM IN CORNWALL

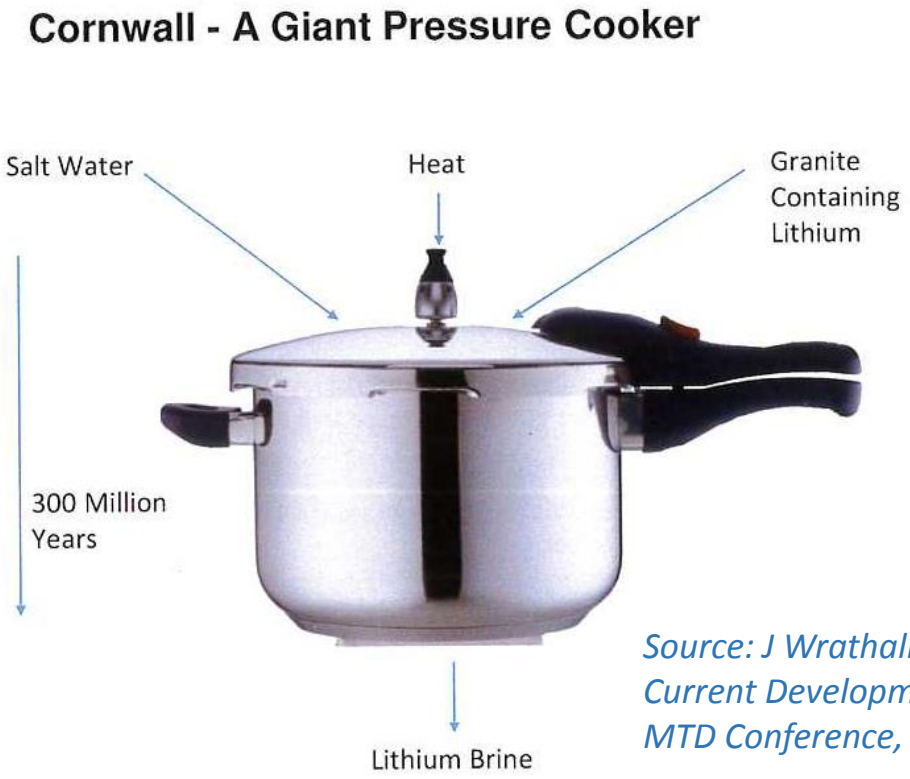
- A long history of mining and mineral extraction
- Cornwall has hosted 2000 mines over the last 400 years
- There is a "pro-mining" culture and the county still hosts the world renowned Camborne School of Mines
- Excellent infrastructure – grid power, road, rail, airport etc.
- Cornwall is increasingly becoming a centre for renewable energy (wind and solar)
- UK government is focussed on increasing UK industrial activity post Brexit vote
- Underground mining in Cornwall was plagued by upwelling hot water which made working conditions very challenging. It is this same water that contains lithium

South Crofty Tin Mine

Source: BusinessCornwall.co.uk

Source: J Wrathall, A New Metal from an Old Mining Area Current Developments in the UK Mining Industry, MTD Conference, October 2017

CORNWALL A GIANT PRESSURE COOKER



Source: J Wrathall, A New Metal from an Old Mining Area Current Developments in the UK Mining Industry, MTD Conference, October 2017

CORNISH BRINE PROCESSING

Cornish Lithium

Processing

Old Technology

New Technology

BRINE FROM DRILLHOLES

⇩

REVERSE OSMOSIS PLANT

⇩

Concentrated brine

⇩

ION EXCHANGE

⇩

LCE PRECIPITATION

New processes to extract lithium directly from brine have been developed by the following companies

posco · energi group · VEOLIA · tenova · PurLucid · ERAMET

Source: J Wrathall, A New Metal from an Old Mining Area
Current Developments in the UK Mining Industry,
MTD Conference, October 2017

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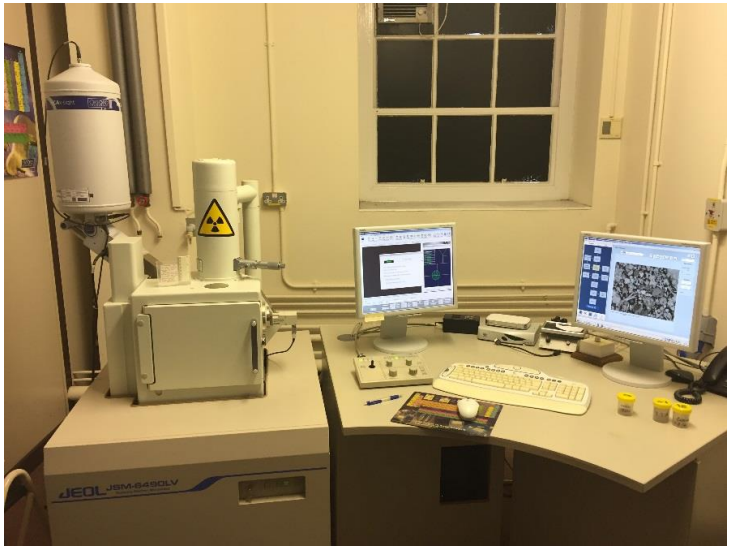
EU FUNDED R&I – FAME (WHAT IS FAME)

- Horizon 2020 PROJECT
  Flexible And Mobile Economic Processing EU Research and Innovation Project co-ordinated by Wardell Armstrong
- 7.4 Million Euros
- 16 Partners – 7 countries
- Start Date 01/01/2015
- End Date 31/12/2018

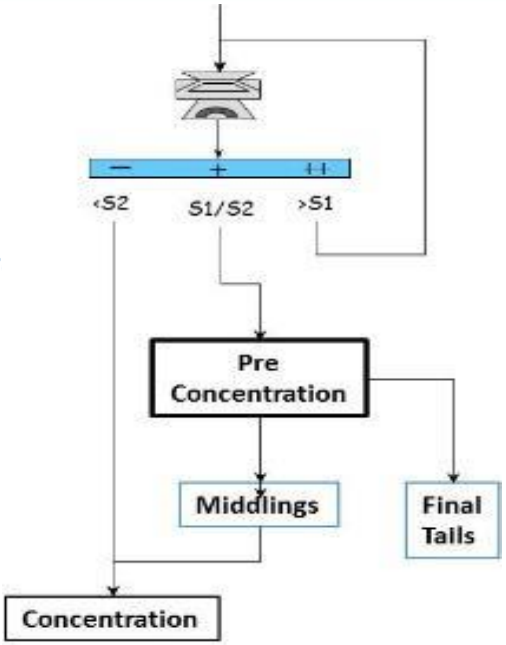


FAME REFERENCE ORES

PRE-CONCENTRATION

- Removal of barren rock (i.e. PRECONCENTRATION) will be important for successful Li Processing
- There may be uses for the barren rock (gangue) – otherwise tailings for disposal with low Li content
- If pre-concentration is possible at coarse sizes, the reduced amount of or going for crushing leads to significant energy savings and increases head grade (Li Content) of feed
- A number of Different Sorting Techniques Considered:

Good results using Optical sorter (colour differences between Li-rich minerals and gangue)



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Pre-concentration of Lepidolite using an optical sorter

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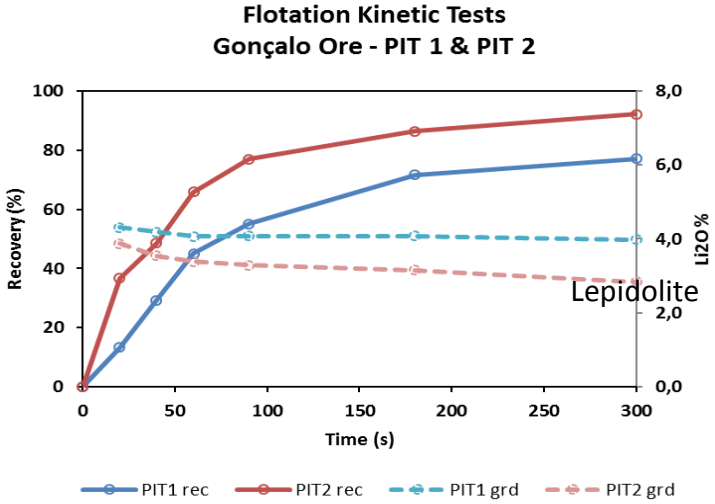
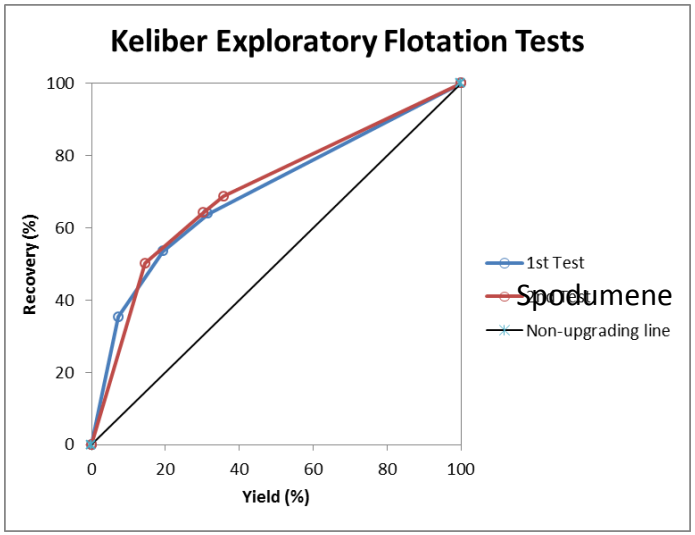
FLOTATION

- (Almost all) Li minerals can be upgraded to Concentrates of Higher Li content using Froth Flotation (However – Max Li Content 6-8%)
- FAME has developed intensive Flotation to improve Li recovery from lepidolite and spodumene ores close to a 100% recovery aim





- Comminution down to k_{80} ~ 150µm;
- Flotation in acidic media, using specific collectors
- Li recoveries = 80-90%; concentrates upgrade above 4.5 – 5 %Li_2O

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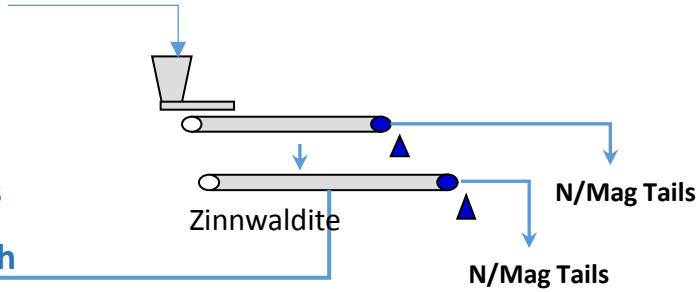
MAGNETIC SEPARATION

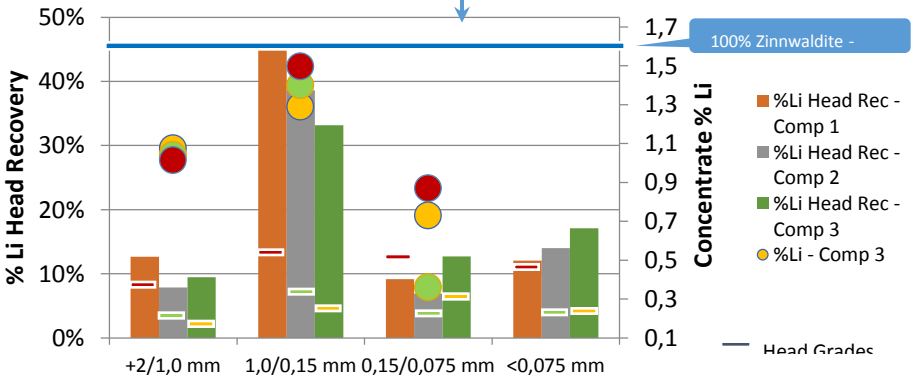
SAMPLES FROM CINOVEC

Lithium Recovery:

- Fraction 1/0,5 mm collects 40% Li
- Recovery decreases with size
- Fines (<0,075mm) represent 14% Li losses



Concentrate of size fraction 1/0,5 mm is a high purity zinnwaldite product



Particles crushed to around 1mm

Higher entrapment in size fractions below 0,5 mm leads to low grades and low recoveries

Dry Medium Intensity Magnetic Separation (Permroll type) seems to be suitable for zinnwaldite recovery

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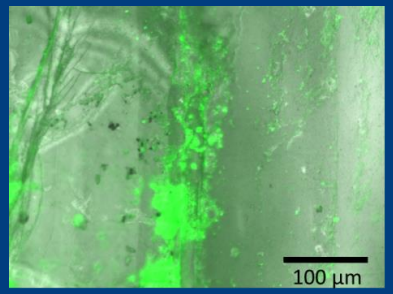
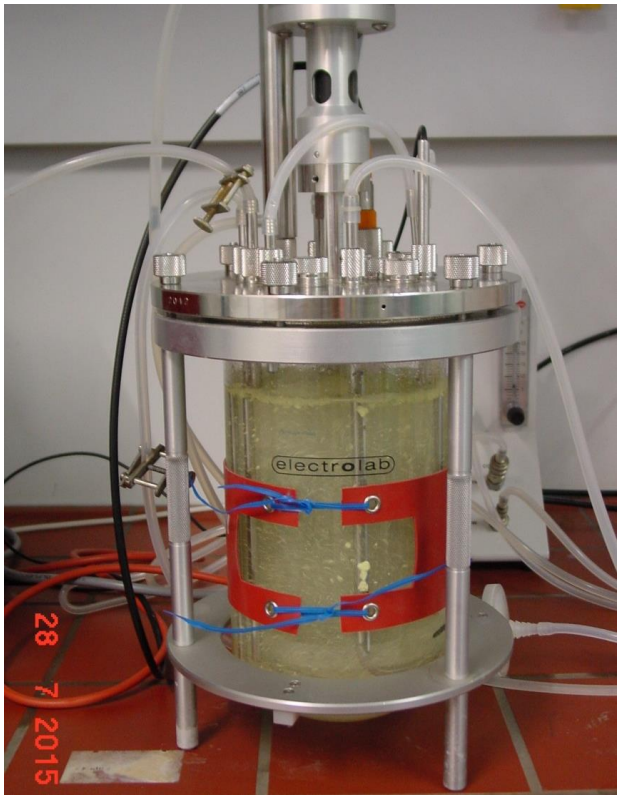
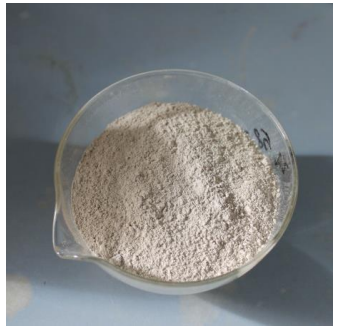
BIOLEACHING – BATCH BIOREACTOR





Volume:	2 to 4 l
Pulp density:	5 % (zinnwaldite added at exponential growth phase)
Temperature:	30 °C
Medium:	DSMZ 71 + elemental sulfur (5 g/l)
Grain fraction:	<45 µm
Innoculation:	acidophilic mixed culture (6.5 10^{-7})

Pure minerals (mica blade and crystalline sulphur) added to investigate biofilm formation)



Zinnwaldite (mica) ground < 45 µm

Zinnwaldite (blade) and sulfur

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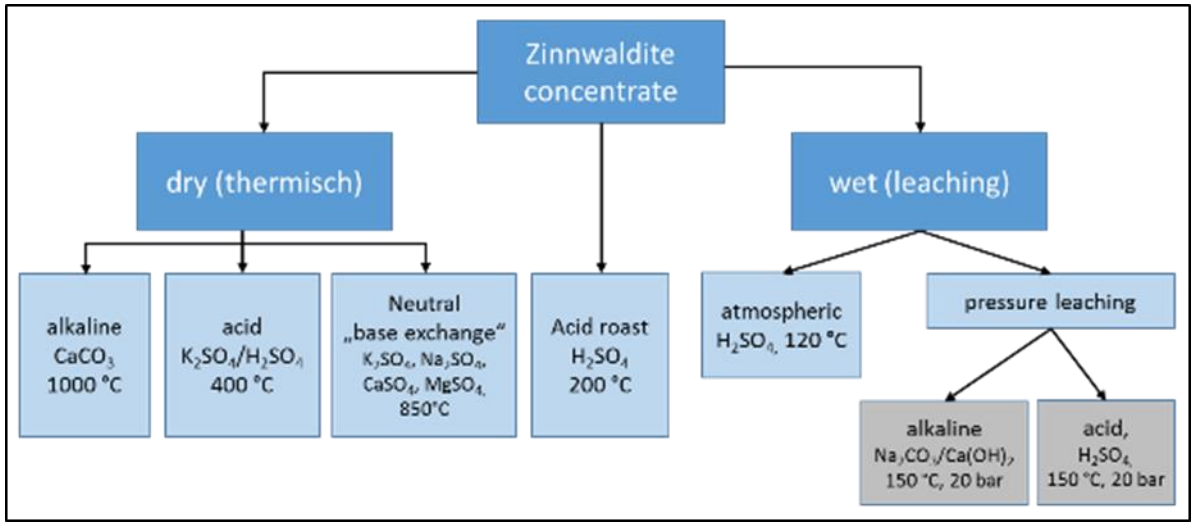
OVERVIEW OF POTENTIAL CHEMICAL PROCESSING ROUTES FOR LITHIUM PROCESSING FROM MICAS OR SPODUMENE



Overview of the technologies for lithium silicate digestion

FAME EXAMPLE: SULPHURIC ACID LEACHING TESTS ON ZINNWALDITE MICA:

	Leach recovery (%)
Li	96
Fe	73
K	58
Ga	78

→ **Good Li recovery**

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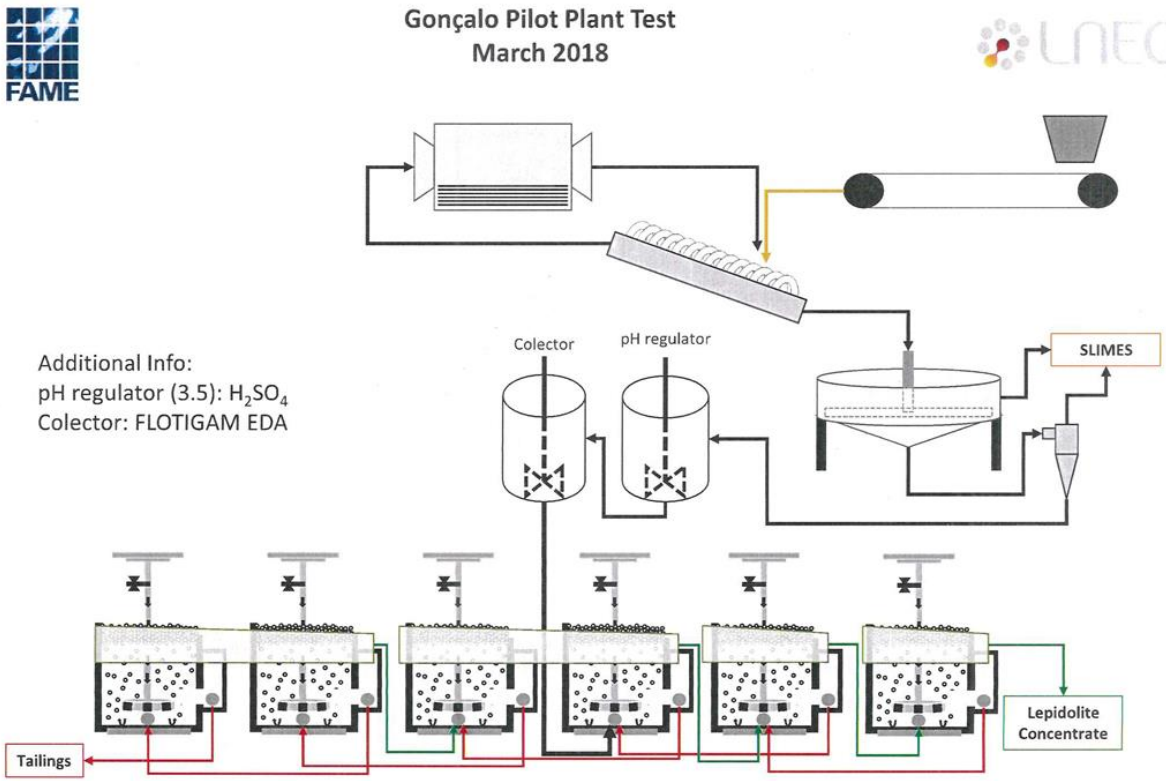
FAME PILOT TESTS WITH GONÇALO ORE



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PILOT PLANT – Li MICA FLOTATION TESTS AT LNEG

LNEG Wednesday 28 March 2018 lepidolite flotation tests

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Li RESEARCH

- Mineral Processing
- Chemical Processing
  e.g. SiLeach® – Australia

- Brine Purification Technologies
  - Reverse Osmosis
  - Membranes

- Battery Developments Grade
  - Impurities?
  - Hydroxide or Carbonate or Other?

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CONCLUSIONS

- Room for Brine and Hardrock producers, dramatic growth in Lithium demand due to Electric Vehicles
- Brine – always lower OPEX but often longer to production than Hardrock Projects
- Li analysis
  - Issues with historical data
  - Caution
  - Li Analysis Difficult
- Work with Battery Manufacturers – impurities etc?
- Other issues to be aware of:
  - Source of "Ethical" supply of Cobalt
  - High Purity Ni
  - Li is not designated a Critical Raw Material BUT is very strategic
  - Security of Supply?

THANK YOU FOR YOUR ATTENTION

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