VOLKER HESSEL

THE CHEMICAL ENGINEERING CHALLENGES OF MINING ASTEROIDS

AUSIMM, ADELAIDE, 15.08.19

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- ❑ **Need of interdisciplinarity and technology disruption**
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- ❑ **Holistic picture – orbital economics & deep space communication**

Hung, Tele-communication

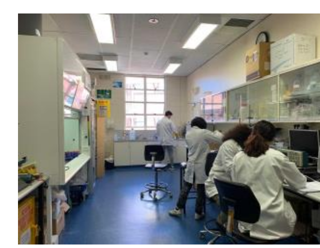
Sanaz, Geology

Mahdieh, IL extraction

Nam, Life cycle manag.

Volker, Chem-Eng disruption

Wendy & Marko, Results fishing



THEMES – PROACTIVE THINK-TANKS

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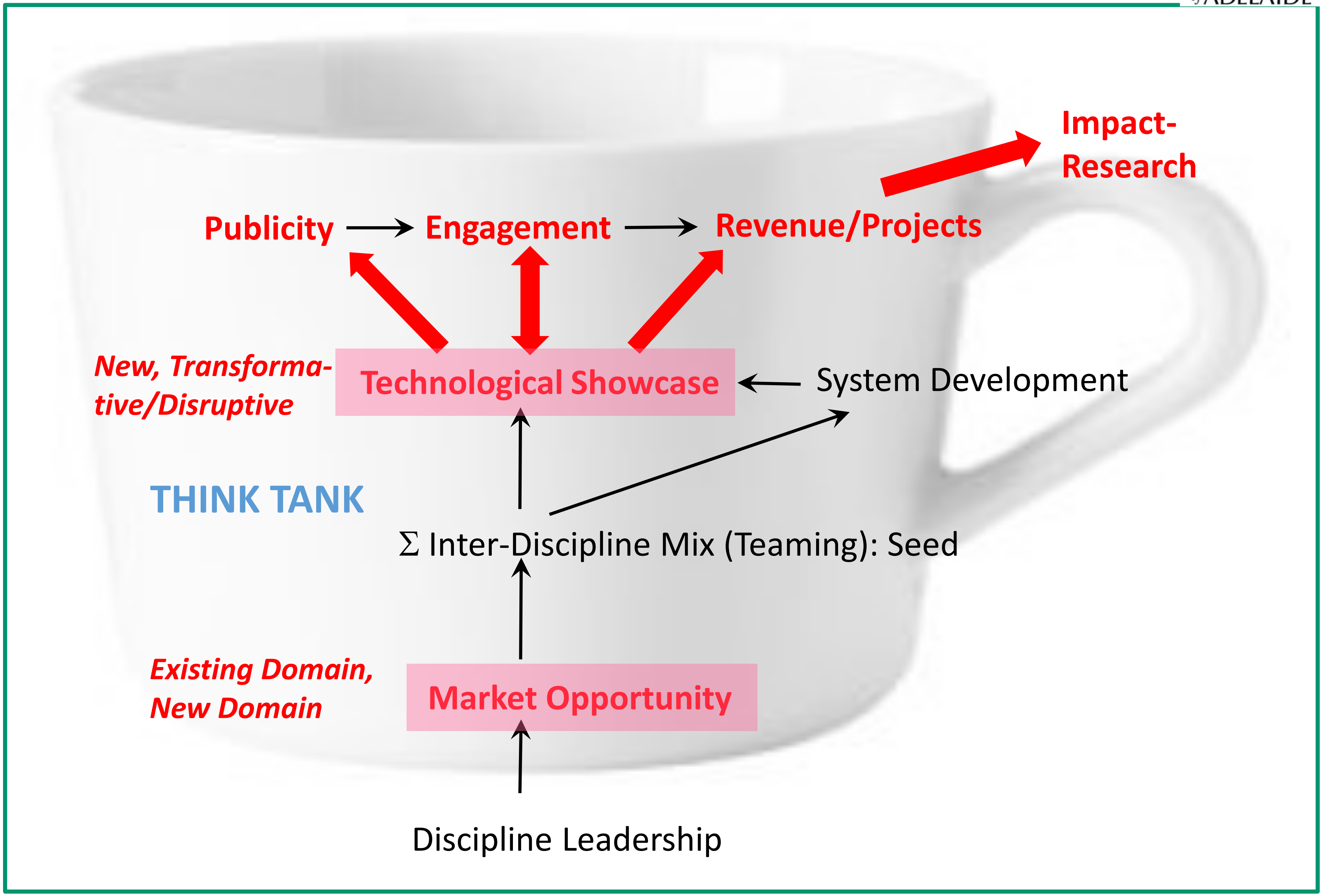

DISRUPTIVE TECHNOLOGY & INDUSTRIAL TRANS-FORMATION OF THE AMERICAS AFTER 1492

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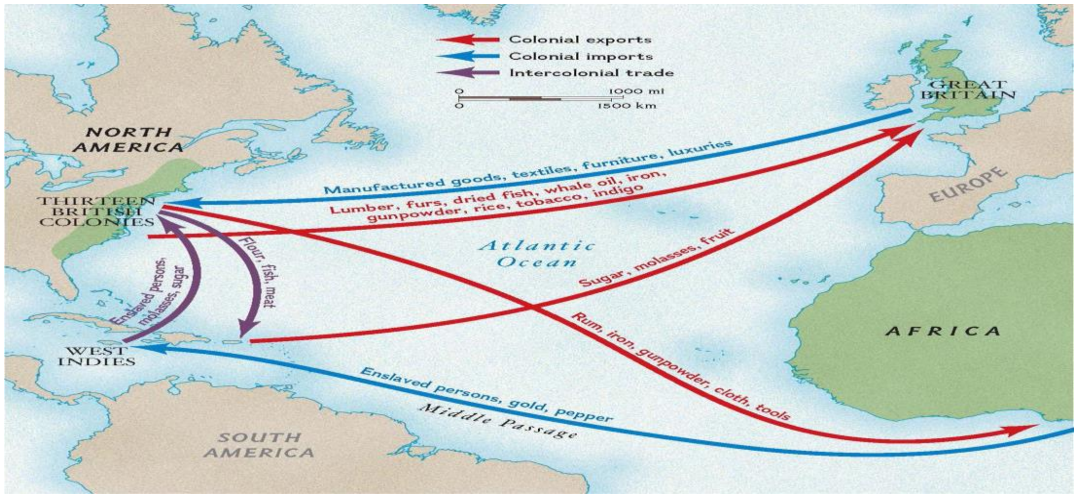
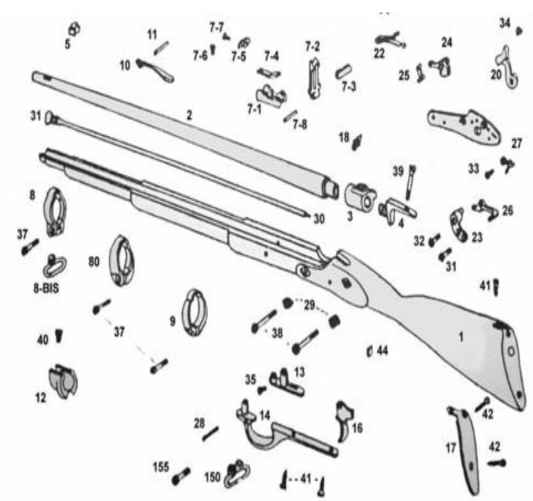


Export through top sales product: 21 million beaver hats (1700-1770)

=> Export 1750: Germany: 16,500, Spain: 110,000, Portugal: 175,000

Invention: Modularisation



Eli Whitney, 1801

Interchangeable parts

Transformed America from **an artisan-based nation to an assembly line style producer**

- **New England** was more far and unknown 400 years than asteroids today
- **Supply chains** and **hubs**
- **New, unknown resources** (eg tobacco & beaver hat): **disruptive technologies**
- **(Semi-) finished goods** & **innovation**
- **Transformative business window: innovations**

CONTINUOUS BECOMES NEW STANDARD

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FDA calls on manufacturers to begin switch from batch to continuous production

D. J. C. Constable, C. Jimenez-Gonzalez, R. K. Henderson, *Org. Process Res. Dev.* **11** (2007) 133-137

... ALSO IN SPACE ... NEW STANDARD

SpaceTango (with Zaiput)

CSIRO

Flow Chemistry in Space–A Unique Opportunity to Perform Extraterrestrial Research

J. Flow Chem. 2017, 7(3–4), 151; Nat. Rev. Chem. 2017, 1, 0055

DECEMBER 1, 2015

Getting into the flow on the International Space Station

by Mike Giannone, NASA

www.spaceflow.org

American Chemical Society

PHARMA GOES SPACE

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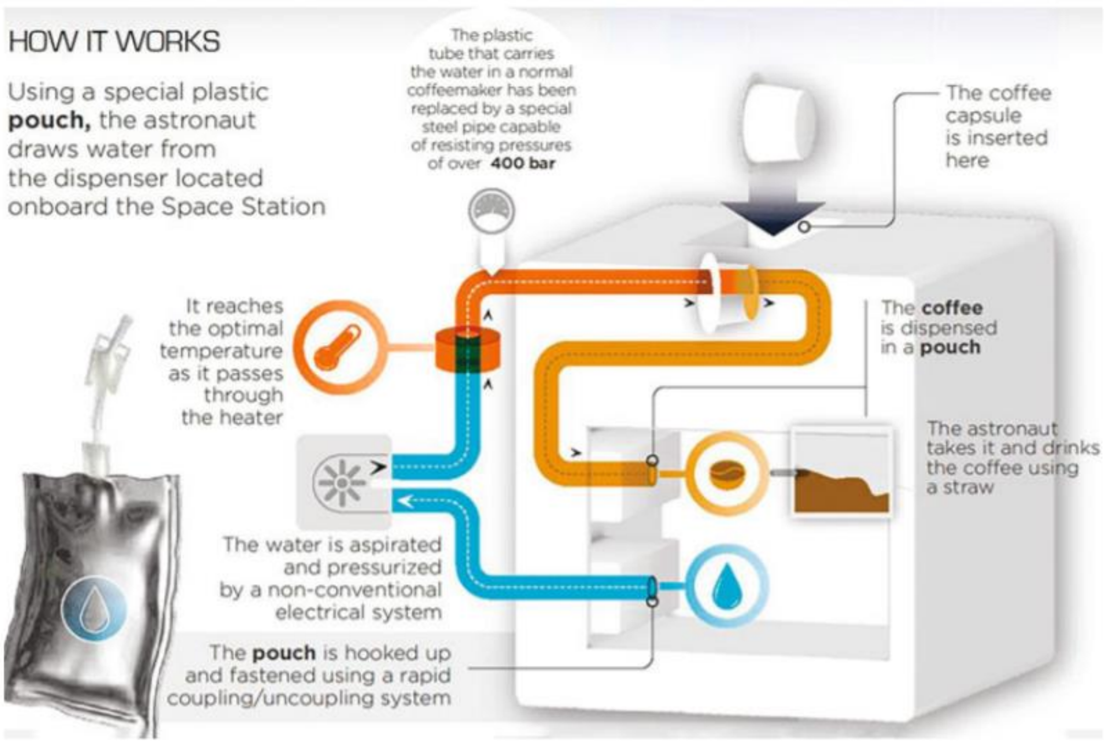
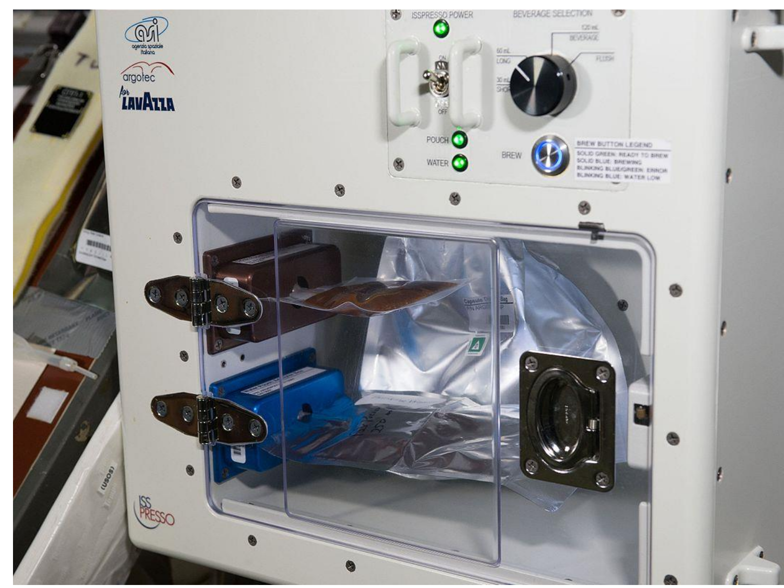
Pharma giants Merck, Procter & Gamble, Amgen and Eli Lilly are on International Space Station

SpacePharma and Space Tango offer ‘space pharma laboratories’

More rodents left the Earth’s orbit than any other mammal



ISSpresso



LENGTH AND TIME: 'MULTI-SCALES'

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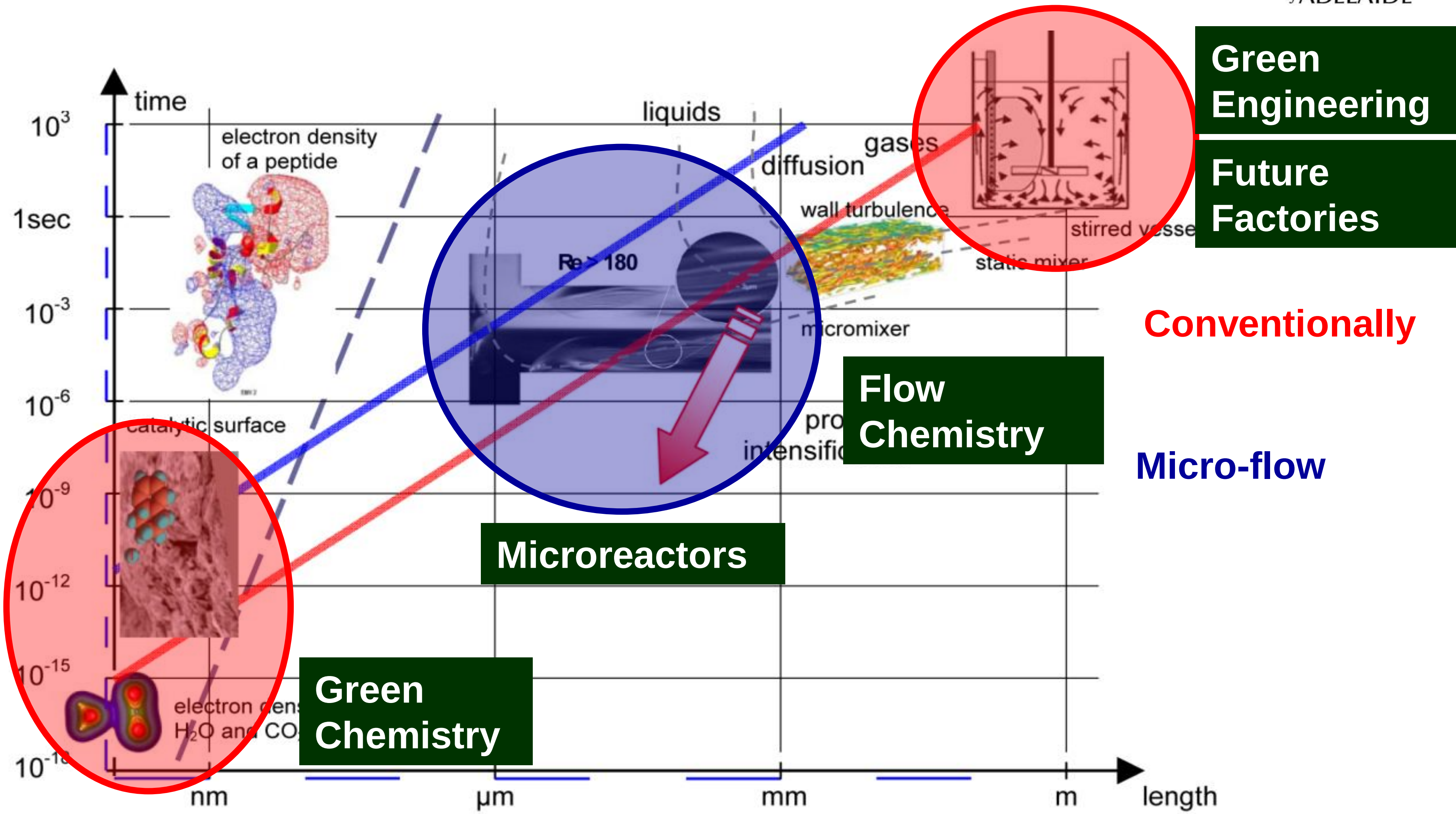

V. Hessel, D. Kralisch, N. Kockmann *Novel Process Windows*, Wiley-VCH, Weinheim, 2014

DISUPTIVE ENGINEERING ON EARTH … & IN SPACE

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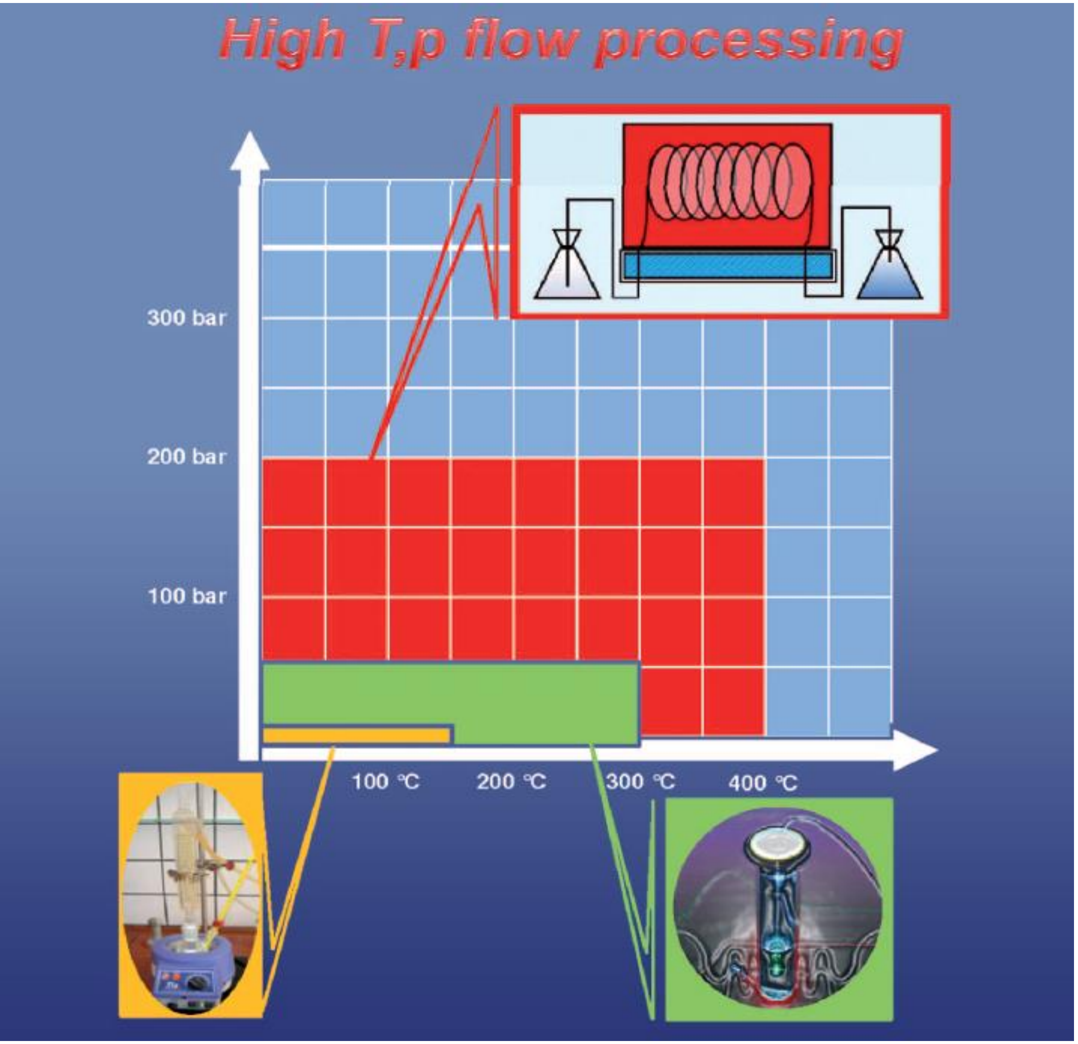
- ❑ Process intensification = processing at first principles
- ❑ Novel Process Windows = Novel Business Windows
- ❑ Lower costs and better environmental footprint
- ❑ Automation = opportunity for artificial intelligence
- ❑ Modularisation = LEGO for space challenges
- ❑ Compactness / Light-weight = low payload
- ❑ Zero gravity processing feasible = capillary forces dominate
- ❑ Vacuum processing feasible = enclosed process chamber; no headspace

S
P
A
C
E

NOVEL PROCESS WINDOWS – HIGH-p,T: SUPERHEATED PROCESSING



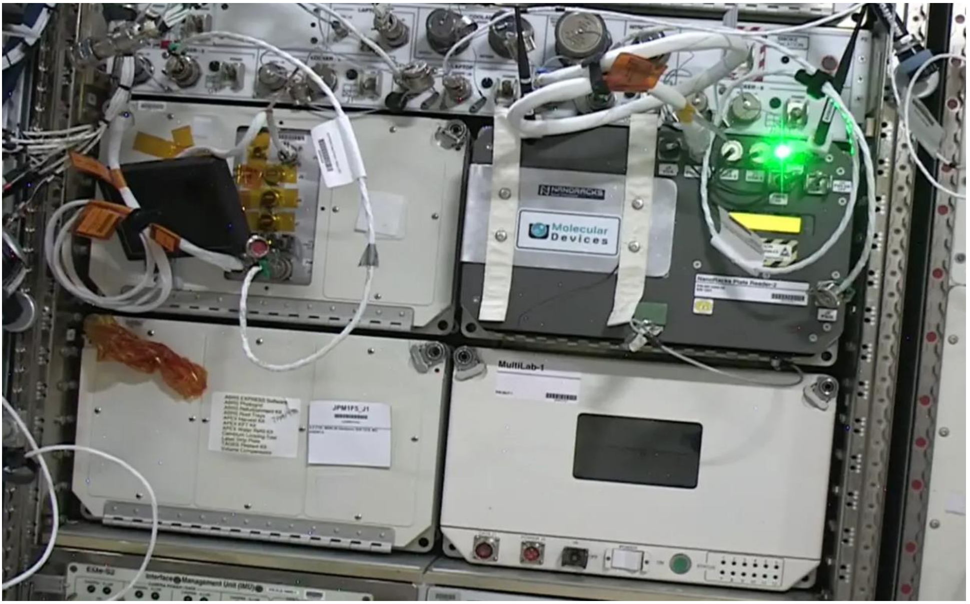
Microreactors expand the p, T process window and more (e.g., concerning c). Microwave did similar, but is difficult to scale-up

NOVEL PROCESS WINDOWS

V. Hessel, N. Kockmann, D. Kralisch, T. Noel, Q. Wang, *ChemSusChem* **65** (2013) 746-789

T. Razzaq, C. O. Kappe, *Chem. Asian J.* **5**, 6, 1274-128

SPACE MINI-LABS



SPACE TANGO

CubeLabs™

Standardized platform

Open architecture

Multiple biomedical applications to run simultaneously and independently

SPACEPHARMA
simply microgravity

DIDO-2

10x10x30 cm

4.5 kg

Medical experiments

SOLVENT EXTRACTION IN MINING INDUSTRY

AUSTRALIAN MINES LIMITED

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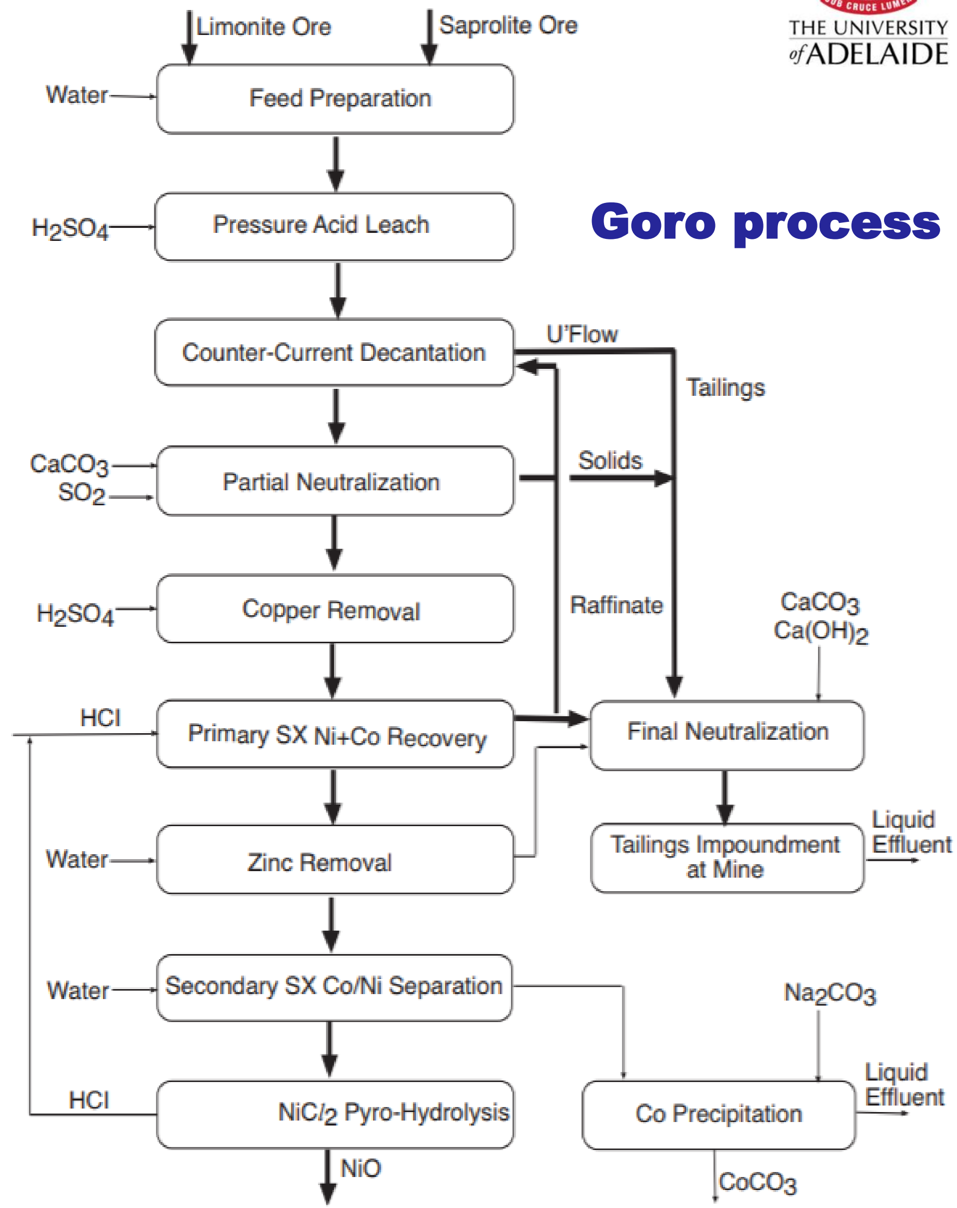
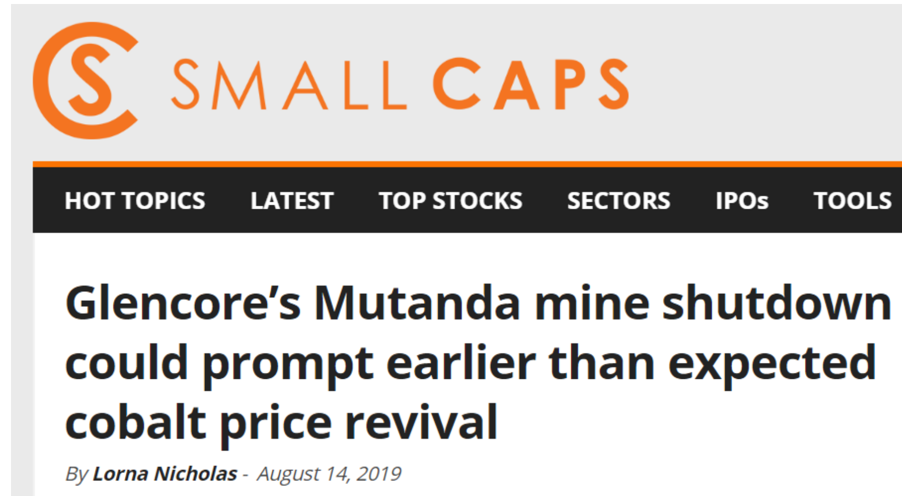
Goro process



GLENCORE'S MUTANDA MINE
- Largest Cobalt Reserve on Earth



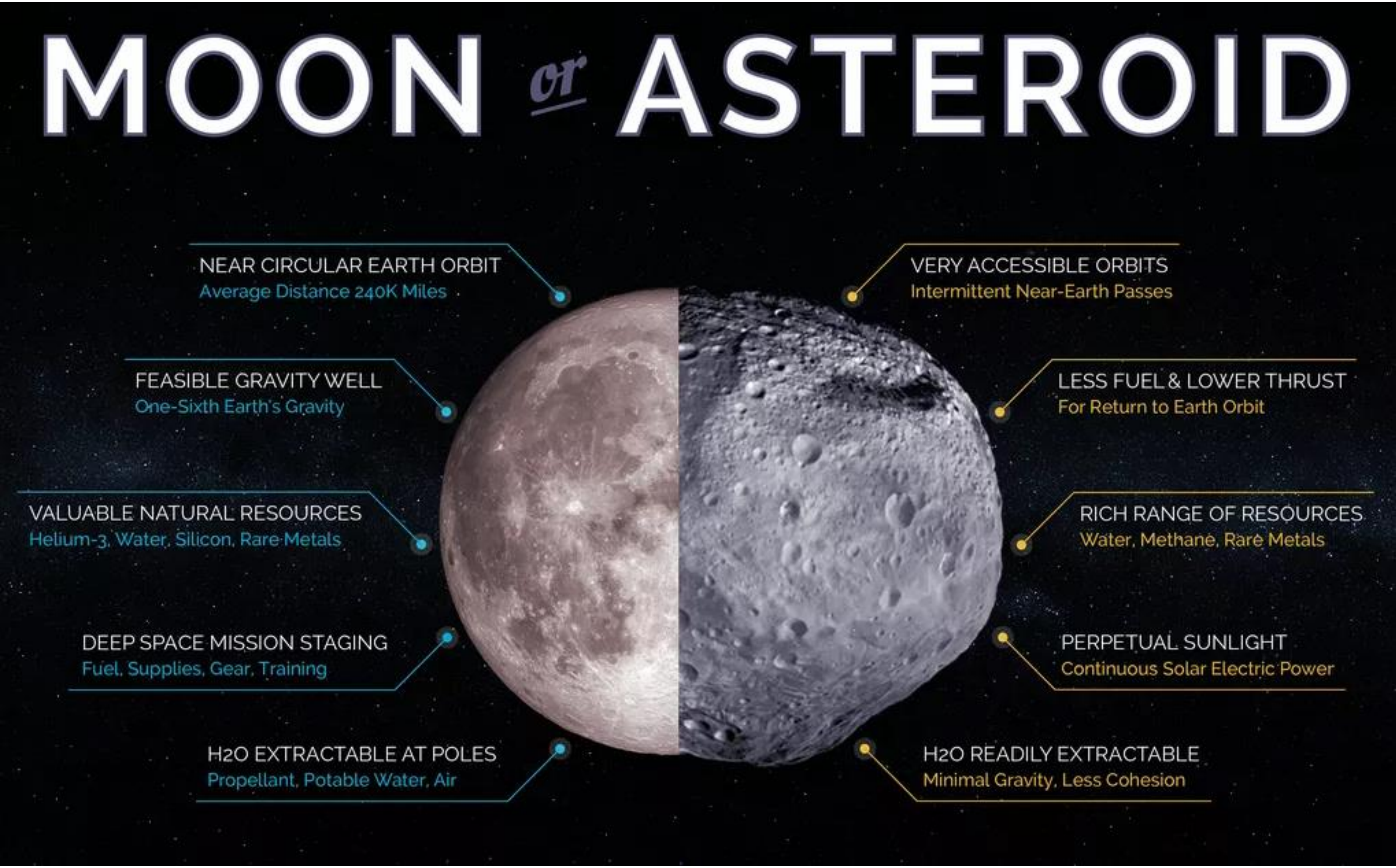
SMALL CAPS

HOT TOPICS | LATEST | TOP STOCKS | SECTORS | IPOs | TOOLS

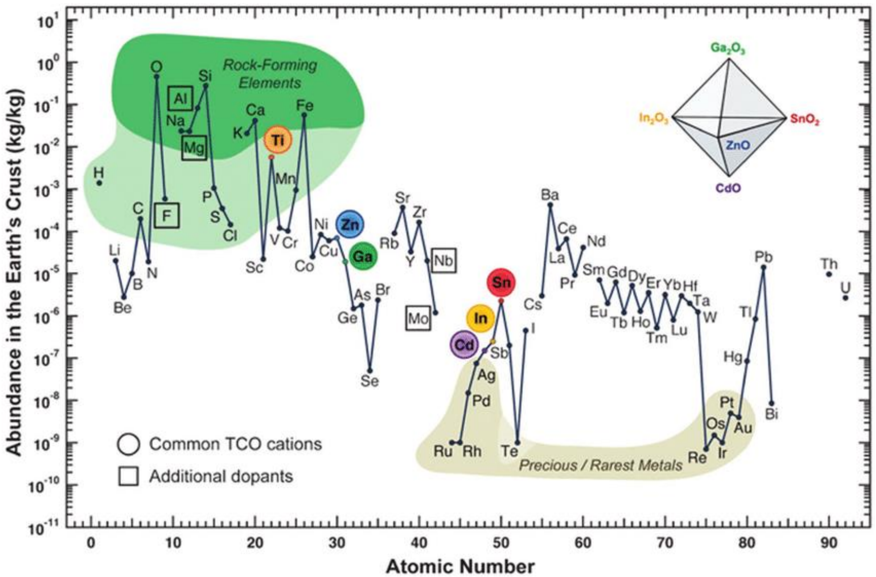
Glencore's Mutanda mine shutdown could prompt earlier than expected cobalt price revival

By **Lorna Nicholas** - *August 14, 2019*

PLANET VS ASTEROID MINING

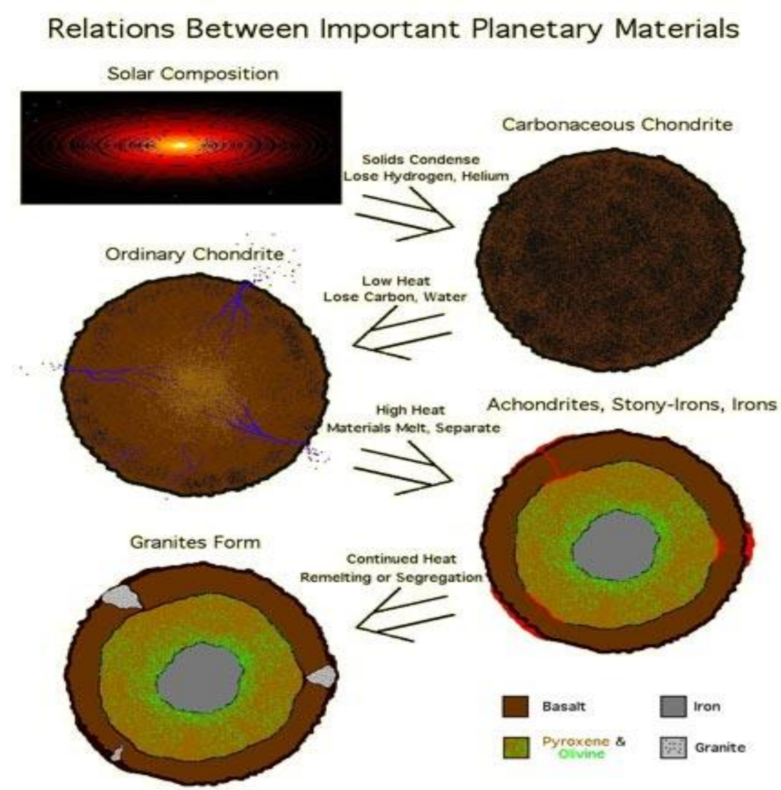


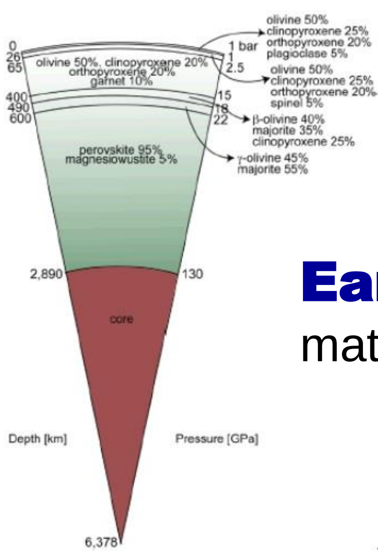
GEOLOGICAL PROCESSES
ASTEROID vs EARTH



Metal abundance on Earth

Space planets & asteroids
material distribution





Earth
material distribution

ASTEROIDS AND THEIR VALUE MATERIALS

Table 1. Metal contents and distributions in the diverse types of most valuable asteroids

Name	Type	Discovered year	Composition	MOID (AU)	Value ($)	Δv (km/s)
Ryugu	Cg	1999	Ni, Fe, Co, H_2O, N_2, H_2, NH_3	0.000638	82.76 billion	4.663
1989 ML	X	1989	Ni, Fe, Co	0.082029	13.94 billion	4.889
Nereus	Xe	1982	Ni, Fe, Co	0.003153	4.71 billion	4.987
Bennu	B	1999	Fe, H_2, NH_3, N_2	0.003223	669.96 million	5.096
Didymos	Xk	1996	Ni, Fe, Co	0.039777	62.25 billion	5.162
2011 UW158	Xc	2011	Ni, Fe, Co, Pt	0.002914	6.69 billion	5.189
Anteros	L	1943	$MgSiO_3$, Al, Fe, Fe_2O_4Si	0.062212	5.57 trillion	5.44
2001 CC21	L	2001	$MgSiO_3$, Al, Fe_2O_4Si	0.083067	147.04 billion	5.636
1992 TC	X	1992	Ni, Fe, Co	0.167212	84.01 billion	5.648
2001 SG10	X	2001	Ni, Fe, Co	0.017183	3.05 billion	5.88
2002 DO3	X	2002	Ni, Fe, Co	0.029415	334.44 million	5.896
2000 CE59	L	2000	$MgSiO_3$, Al, Fe_2O_4Si	0.008298	10.65 billion	6.015
1995 BC2	X	1995	Ni, Fe, Co	0.135685	78.87 billion	6.01
1991 DB	C	1991	Ni, Fe, Co, H_2O, N_2, H_2, NH_3	0.102803	168.20 billion	6.146
2000 RW37	C	2000	Ni, Fe, Co, H_2O, N_2, H_2, NH_3	0.008221	29.27 billion	6.225
1998 UT18	C	1998	Ni, Fe, Co, H_2O, N_2, H_2, NH_3	0.037188	644.70 billion	6.221
Seleucus	K	1982	Ni, Fe, Co, H_2O, N_2, H_2,	0.102357	33.52 trillion	6.289

Asterank *scientific and economic database of over 600’000 asteroids*

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WATER FOR ASTEROID MINING: NEED FOR DISRUPTIVE TECHNOLOGIES TO GIVE ECONOMIC CASE

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- South Australia's cobalt ~2900 t/a in Mount Gunson Copper Mine
- Largest mine on Earth: Glencore's Mutanda, Republic of Congo, 23,900 t cobalt in 2017
- 190 tons of water per ton of cobalt (190 : 1)
- 1 ton water from Earth to LEO: 3 million $ ⟷ 80 kdollar per t cobalt on Earth
- Ryugu (1999 JU_3): 4.5 x 10^6 t cobalt
- 80 kdollar per t cobalt, Earth <-> 300k per t water, Space 2025

METAL CONCENTRATION 10 mol/l (space) vs. 0.1 mol/l (Earth);

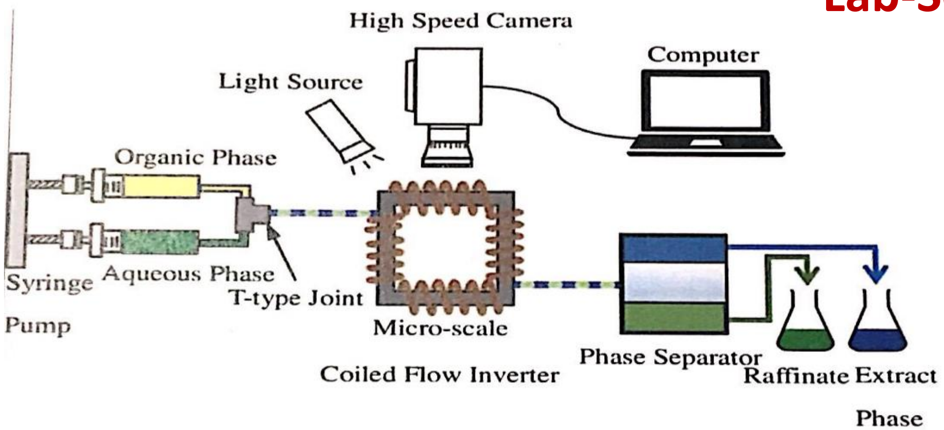
RELATIVE METAL LOAD i.e. Ni:Co = 10:1 in space vs. Ni:Co = 3:1 on Earth;

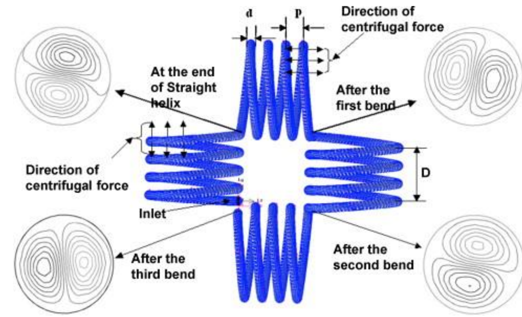
METAL MIXTURE COMPLEXITY i.e. Fe, Ni, Co, Pt, … ;

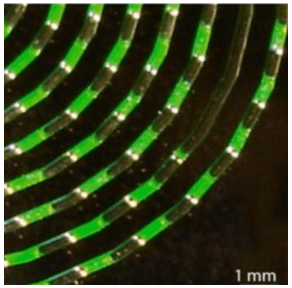
ALLOYS i.e. Kamacite in space, α-(Fe, Ni); Fe0+0.9Ni0.1

SEGMENTED FLOW IN A COILED FLOW INVERTER

Lab-Scale: Coiled-Flow Inverter (8 l/h)

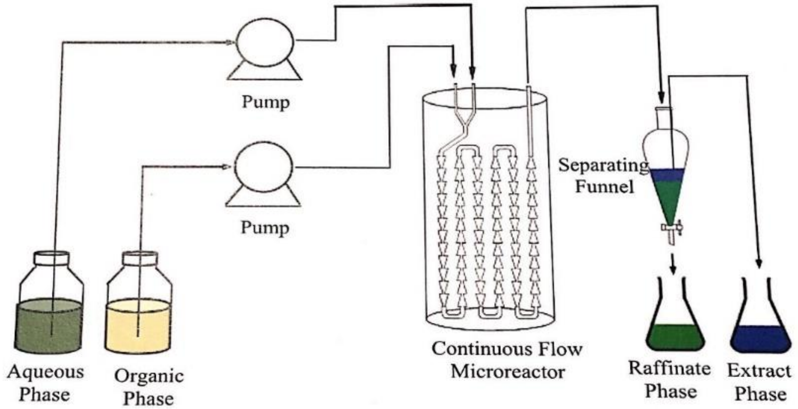






Production-Scale: Coiled-Flow Inverter (1700 l/h)

Pilot-Scale: Re-entrance Flow Reactor (360 l/h)



COBALT VS NICKEL ENRICHMENT BY CONTINUOUS-FLOW

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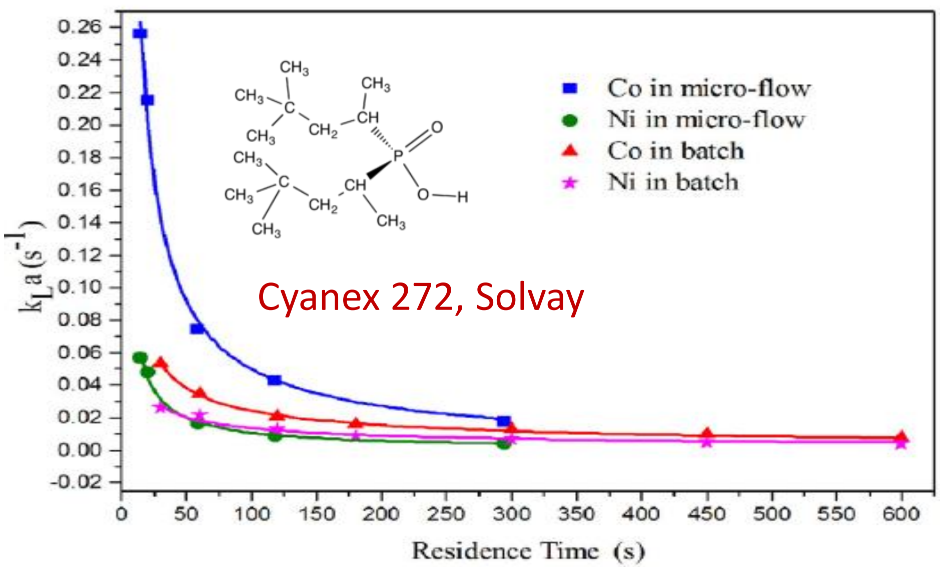
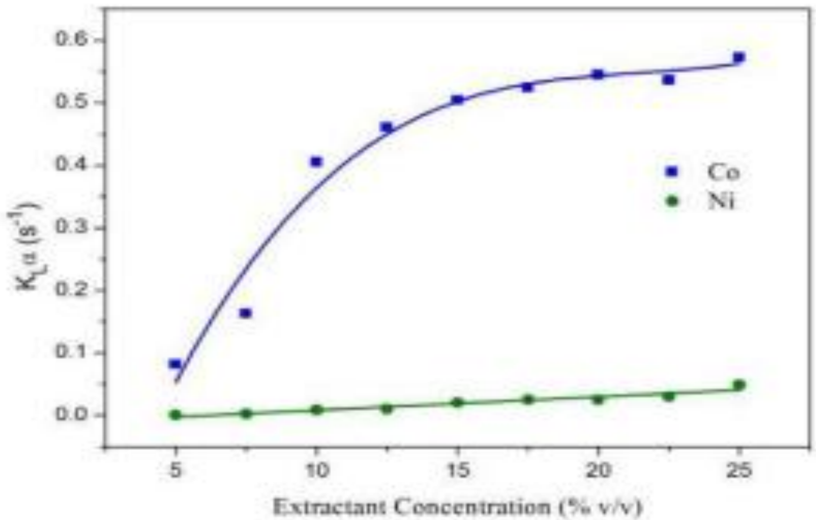


Volumetric mass transfer coefficient k_La in coiled micro-flow inverter



k_La in re-entrance flow reactor

- ❑ **Continuous-flow extraction 7 times more selective, and 10 times faster than batch**
- ❑ **Chance for substantial water savings and much higher productivity at small footprint**

Zhang, L., Hessel, V., Peng, J., Wang, Q. & Zhang, L., 2017. Chemical Engineering Journal, 307, pp.1-18.
Zhang, L., Hessel, V., Peng, J., 2018. Chemical Engineering Journal, 332, pp. 131-139.

DISRUPTIVE FLUID PROPERTIES
- mimicking ‘space fluids’

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Nickel nitrate
10 mol/l

‘wet liquid metal’

182 g metal salt

< 100 ml water

Almost 3 kg/l

4 x water viscosity

Pure nickel nitrate – melting point 56 C – solvent-free process?

FLOW PATTERNS OF WATER-KEROSENE WITH DIFFERENT MICRO-FLOW CONTACTORS

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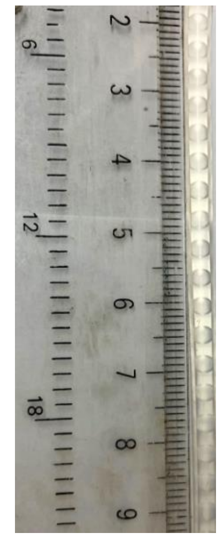
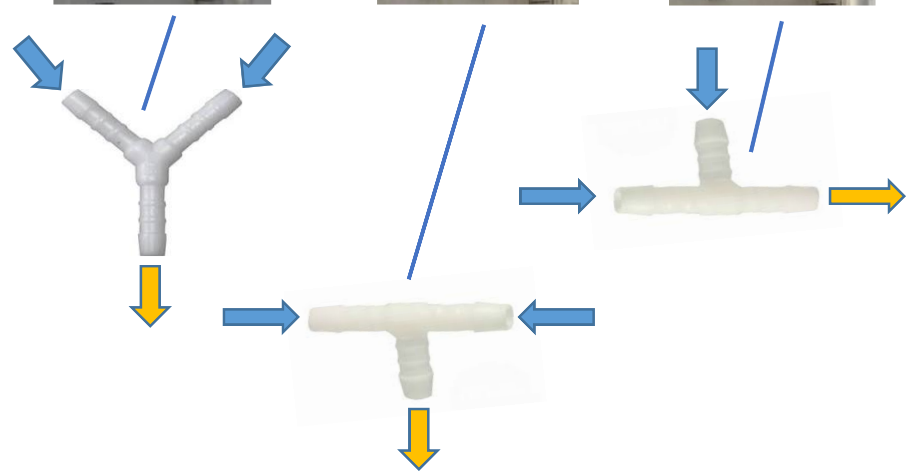
Y-junction
60 mL/h; 1:1

T-junction 180º
60 mL/h; 1:1

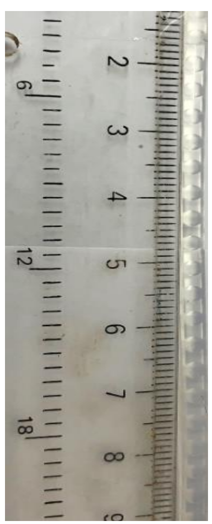


T-junction 90º
60 mL/h; 1:1

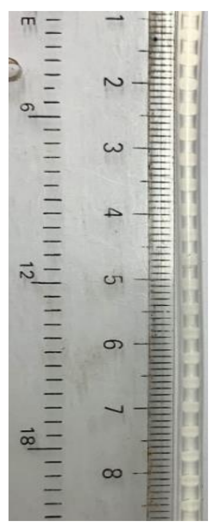


Y-junction
720 mL/h; 1:1

T-junction 180º
720 mL/h; 1:1



T-junction 90º
720 mL/h; 1:1



FLOW PATTERNS OF WATER-KEROSENE VS METAL LOAD AND FLOW RATE

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Y-junction 240 mL/h; 1:1 all 3 cases	**Y-junction** 480 mL/h; 1:1 Zero Ni,Co	**Y-junction** 480 mL/h; 1:1 Ni: 0.5 mol/l Co: 0.05 mol/l	**Y-junction** 480 mL/h; 1:1 Ni: 10 mol/l Co: 1 mol/l	**Y-junction** 720 mL/h; 1:1 Ni: 10 mol/l Co: 1 mol/l
In no case regular flow pattern **Irregular slugs**				

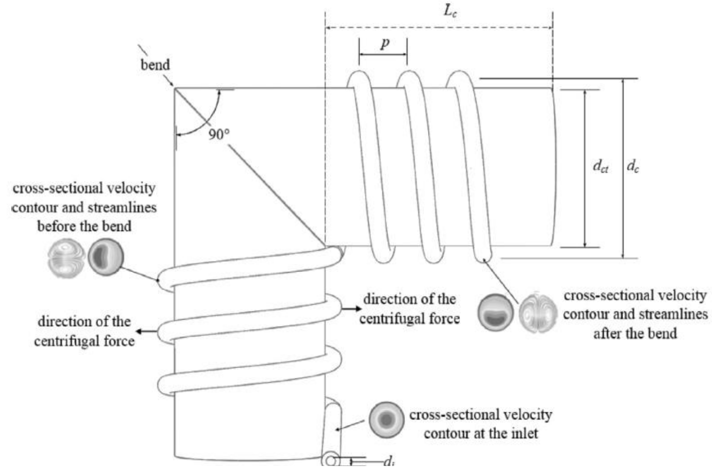
IONIC LIQUIDS

Ionic liquid	Metal ion	Mechanism	Ligand/solvent	Performance (E %)	Stripping agent	reference
[HMIM][BF_4]	Co(II)	IE[a]	NaCl	Co(II), D= 5.8	$NaPF_6$ (0.03 M): Co(II),100%	[34]
[HJMT][Cy272]/ Kerosene, Exxon D100 and Solvesso 200	Co(II), Ni(II)	IE	HCl (1 M)	Co(II),>99%; Ni(II),11%	EDTA (0.02 M): Co(II) ,95%; Ni(II), 83%	[35]
[BuGBOEt][Dca]	Cu(II), Ni(II), Pb(II), Cd(II)			Pb(II), 858%;Cd(II), 95%;Ni(II), 82%;Cu(II), 83%	EDTA (0.1 M): Ni(II), 100%; Cu(II), 100%	[36]
[BuGBOEt][Tf_2N]	Cu(II), Ni(II), Pb(II), Cd(II)			Pb(II), 38%; Cd(II), 41%; Ni(II), 20%; Cu(II), 22%	EDTA (0.1 M): Ni, 100%; Cu, 100%	[36]
[Dibutyl IM][Br]	Co(II), Ni(II)	AE[b]	Acidic thiocyanate HNCS	Co(II), >99%	NH_3 (1.0 M): Co(II), >93%	[37]
[N_{8888}][oleate]	Zn(II), Co(II) ,Ni(II)	IL metal complex	HCl	Co(II), D=20.4; Ni(II), D=13.5; Zn(II) D>200		[38]
$BuNC_2OC_4$ -Sac,	Cu(II), Ni(II), Co.(II), Pb(II), Cd(II)	cation exchange and IP[c]		Cu(II), 30%; Ni(II), 5%; Co.(II), 10%; Pb(II), 20%; Cd(II), 95%	EDTA (0.1 M)	[39]
$BuNC_2OC_4$-Clsal	Cu(II), Ni(II), Co.(II), Pb(II), Cd(II)	cation exchange and IP		Cu(II), 100%; Ni(II), 96%; Co.(II), 94%; Pb(II), 100%; Cd(II), 100%	EDTA (0.1 M): Ni(II), 100%; Co(II), 100%, Pb(II), 100%; Cd(II), 100%	[39]
$BuNC_2OC_4$-Dca	Cu(II), Ni(II), Co.(II), Pb(II), Cd(II)	cation exchange and IP		Cu(II), 98%; Ni(II) 98%; Co.(II), 95%; Cd(II), 95%	EDTA (0.1 M): Ni(II), 100%; Co(II), 100%; Pb(II), 100%; Cd(II), 100%	[39]
Cyphos IL 101	Co(II), Ni(II)	AE and split-anion	H_2SO_4 , $(NH_4)_2SO_4$	Co(II),>90%	Water: Co(II)>99%	[40]
[P_{44414}][Cl]	Co(II), Ni(II)	-	NaCl	Co(II), D=100; Ni(II), D=0.2	-	[41]
[A336][CA-12] [A336]$_2SO_4$	Co(II), Ni(II)	ion association	Toluene, Na_2SO_4	Co(II), D>95% ; Ni(II), D>65%	H_2SO_4: Co(II), 100%; Ni(II)>99%	[41]
[P_{66614}][Cl]	Cu(II), Co.(II),	-	HCl (9 M)	Co.(II), > 98%; Fe(III), >99%	(EDTA + Water): Fe(II)>80%	[42]

Ionic liquids are powerful in metal extraction: faster & more selective; can potentially be operated openly

DEAN NUMBER WATER

- Curvature & Miniaturisation



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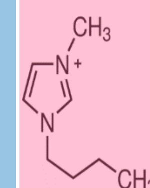
Flow rateQ(ml/min)	U(m/s)	*Re*	*Ca*	*We*	d_i(mm)	d_c/d_i	*Dn*
16	0.3392	371.6	0.0057	2.1381	1	5	166.19
18	0.3816	418.08	0.0064	2.7061	1	5	186.97
20	0.424	464.53	0.0071	3.3408	1	5	207.74
16	0.3392	371.6	0.0057	2.1381	1	10	117.52
18	0.3816	418.08	0.0064	2.7061	1	10	132.21
20	0.424	464.53	0.0071	3.3408	1	10	146.90
16	0.0331	294.47	0.0006	0.1655	3.2	20	25.968
18	0.0372	331.27	0.0006	0.2094	3.2	20	29.214
20	0.0414	368.08	0.0007	0.2585	3.2	20	32.460

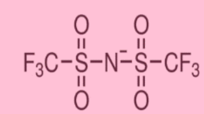
DEAN NUMBER
IONIC LIQUID

Flow rateQ(ml/min)	U(m/s)	*Re*	*Ca*	*We*	d_i(mm)	d_c/d_i	*Dn*
16	0.3392	371.6	0.0057	2.1381	1	10	117.52
18	0.3816	418.08	0.0064	2.7061	1	10	132.21
20	0.424	464.53	0.0071	3.3408	1	10	146.90
16	0.3392	9.71	1.336	12.979	1	10	3.07
18	0.3816	10.93	1.503	16.426	1	10	3.46
20	0.4240	12.14	1.670	20.279	1	10	3.84
16	0.3392	2.25	6.9290	15.623	1	10	0.713
18	0.3816	2.54	7.7951	19.773	1	10	0.802
20	0.4240	2.82	8.6612	24.411	1	10	0.891

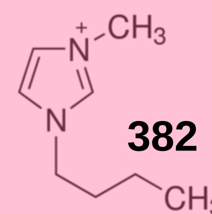
WATER

0.89 mPa·s





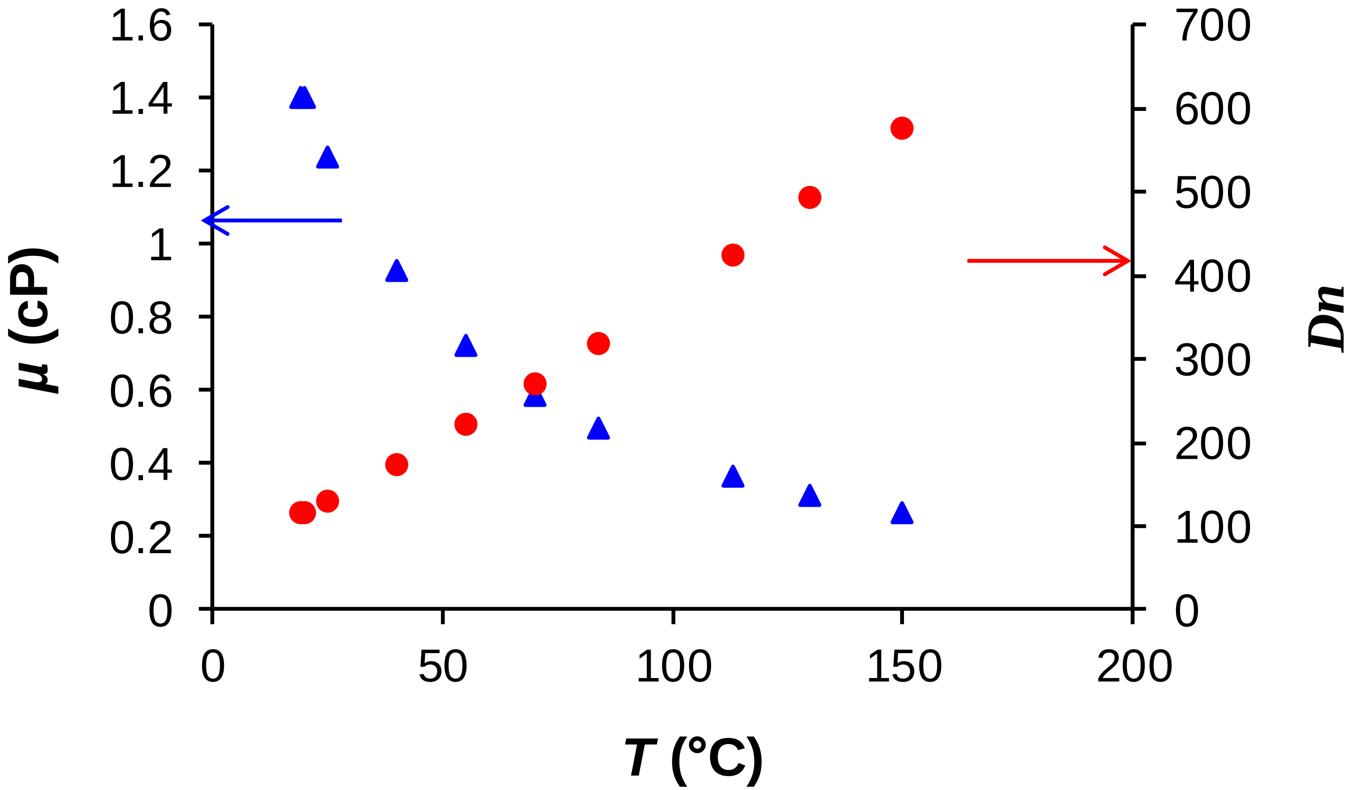
51.0 mPa·s



PF_6^-

382 mPa·s

DEAN NUMBER & VISCOSITY
NaCl (aq) - Brine



Salt solutions at extremely high concentrations (molar) will fluidically benefit from high-T through viscosity reduction

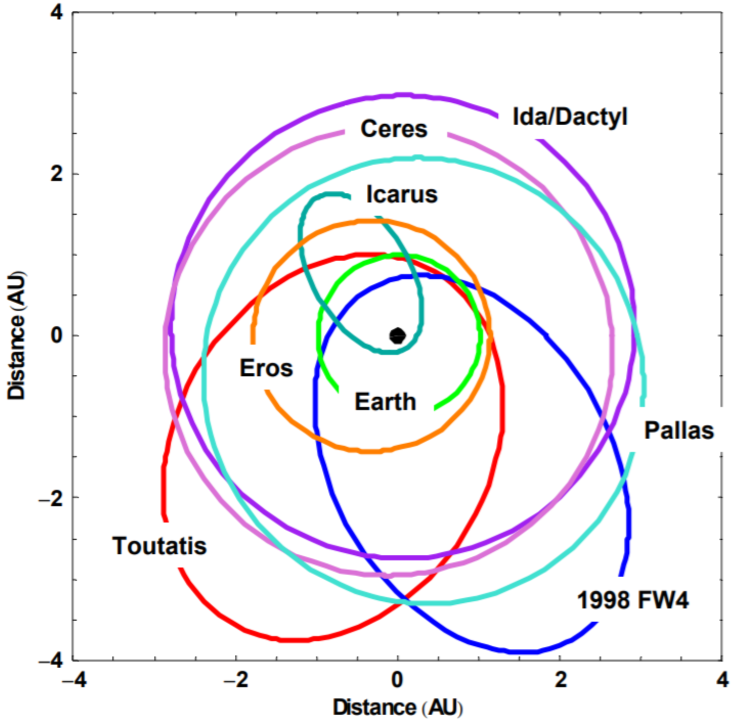
ORBITAL ECONOMICS
Easily Recoverable Asteroids

Rocket equation

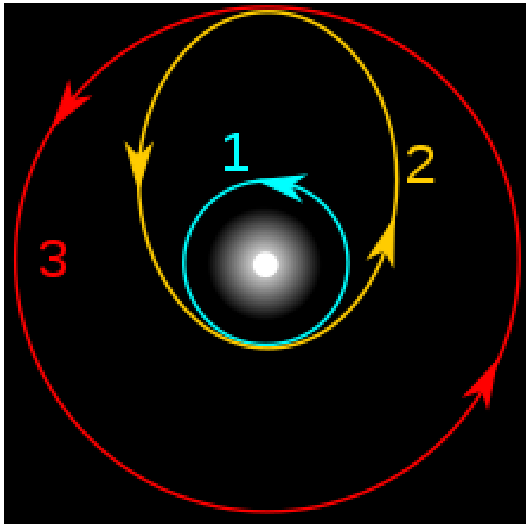
$$\frac{m_f}{m_i} = \exp\left(\frac{-\Delta v}{v_{ex}}\right)$$

$m_f \equiv$ final mass
$m_i \equiv$ initial mass
$\Delta v \equiv$ velocity increment
$v_{ex} \equiv$ exhaust velocity

- Selected asteroid trajectories



Hohmann transfer: delta-v



Mission	Δv
Earth surface to LEO	8.0 km/s
LEO to near-Earth Asteroid	5.5 km/s[note 1]
LEO to lunar surface	6.3 km/s
LEO to moons of Mars	8.0 km/s

ASTEROID COMMUNICATION

THE UNIVERSITY *of* ADELAIDE

Communication Challenges

- **ground support for the mission,**
- **trajectory corrections,**
- **remote control in case of emergencies,**
- **transmission of data for analysis**

Usada Deep Space Center

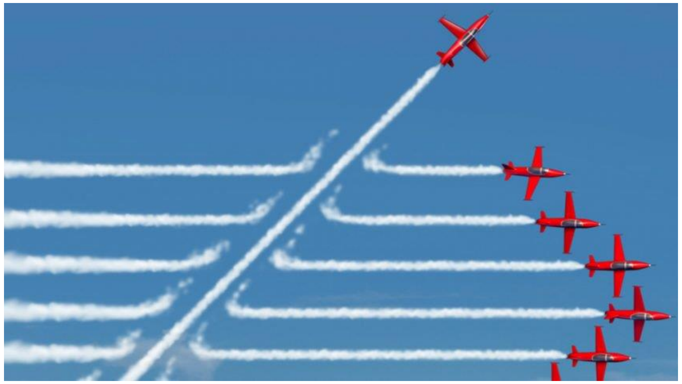
Technology High and low gain antennas, Deep Space Network (DSN), X-band communication, transponder, amplifier, …

Expenditure Typical communication module: 10 kg weight, 120 W power (10% of typical power consumption in an aircraft)

Limitations Low data rate, high latency, delay time in response, only 12 antennas in DSN

CONCLUSIONS

- ❑ Space mining is more than automation of remote processes
- ❑ Disruptive technologies are not considered in current ISRU approaches, yet are the key to economics



- ❑ Holistic picture needed – interdisciplinary
- ❑ The economics themselves have to be developed = business case
- ❑ Need for a business case – space mining trade
- ❑ Off-earth thinking for Earth?

SPACE HORROR – SPACE POLLUTION

AFCS 19

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Australian Flow Chemistry Symposium

2-3 December 2019

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8-11 December 2020

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