

HYDROGEN FUEL CELLS: OPTIMIZATION THROUGH NDT USING NEUTRON RADIOGRAPHY



Frikkie de Beer

Chief Scientists: Radiography & Tomography
South African Nuclear Energy Corporation SOC Ltd



**THE CONERSTONE OF ENGINEERING: NDT NATIONAL CONFERENCE
& EXHIBITION: 7-8 Feb 2018**



Naspers hires
ex-HBO exec as
ShowMax CFO



Consumer
confidence takes
a battering

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Tuesday, July 05, 2016

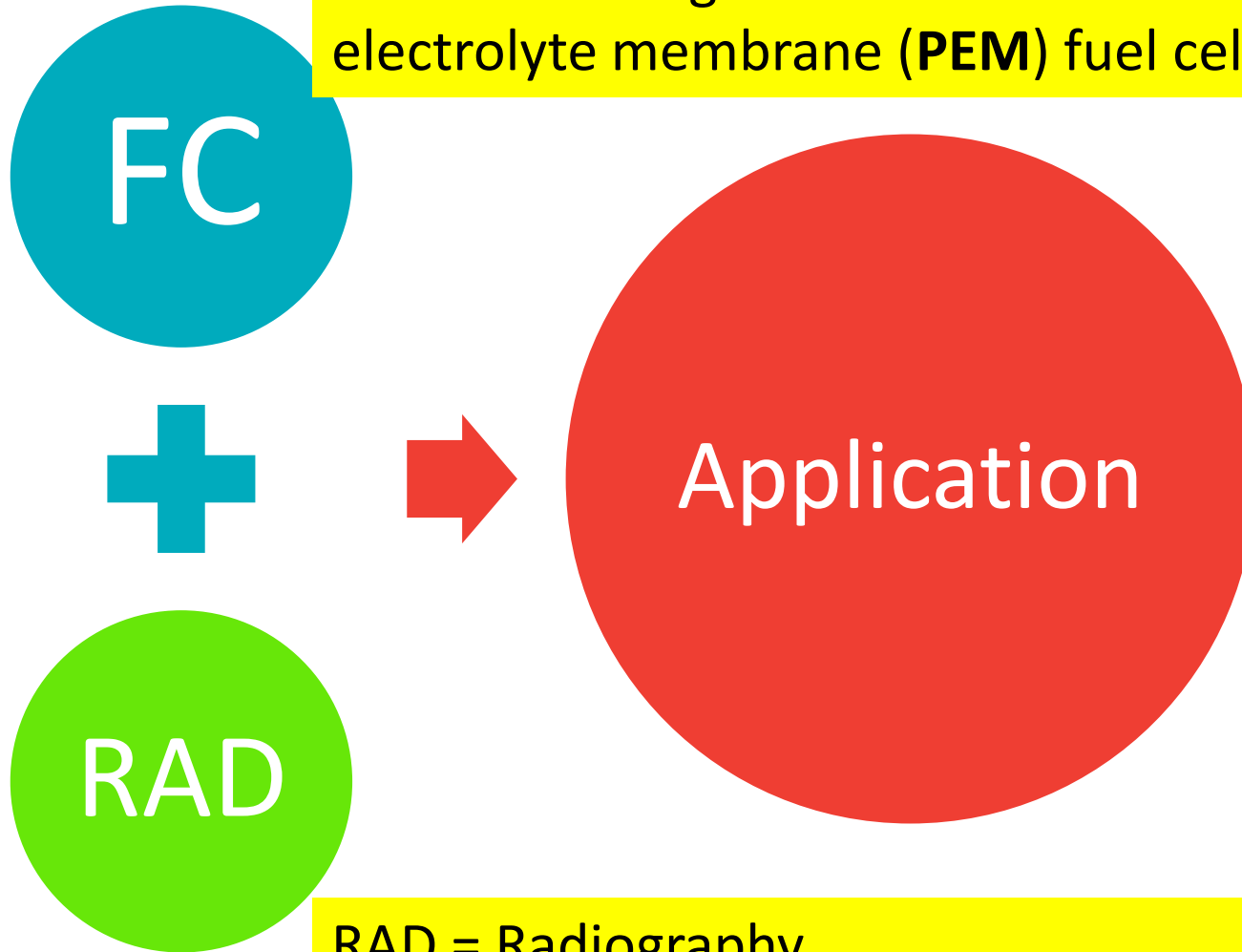
SA sets sights on becoming hydrogen fuel cell hub

South Africa is making a number of bold moves that could see the country leapfrog into being a leading hydrogen fuel cell technology industrial hub, said minister of science & technology Naledi Pandor.



Science & technology minister Naledi Pandor

Proton Exchange Membrane fuel cells or polymer electrolyte membrane (**PEM**) fuel cells (PEMFC)



RAD = Radiography

NRad = Neutron radiography

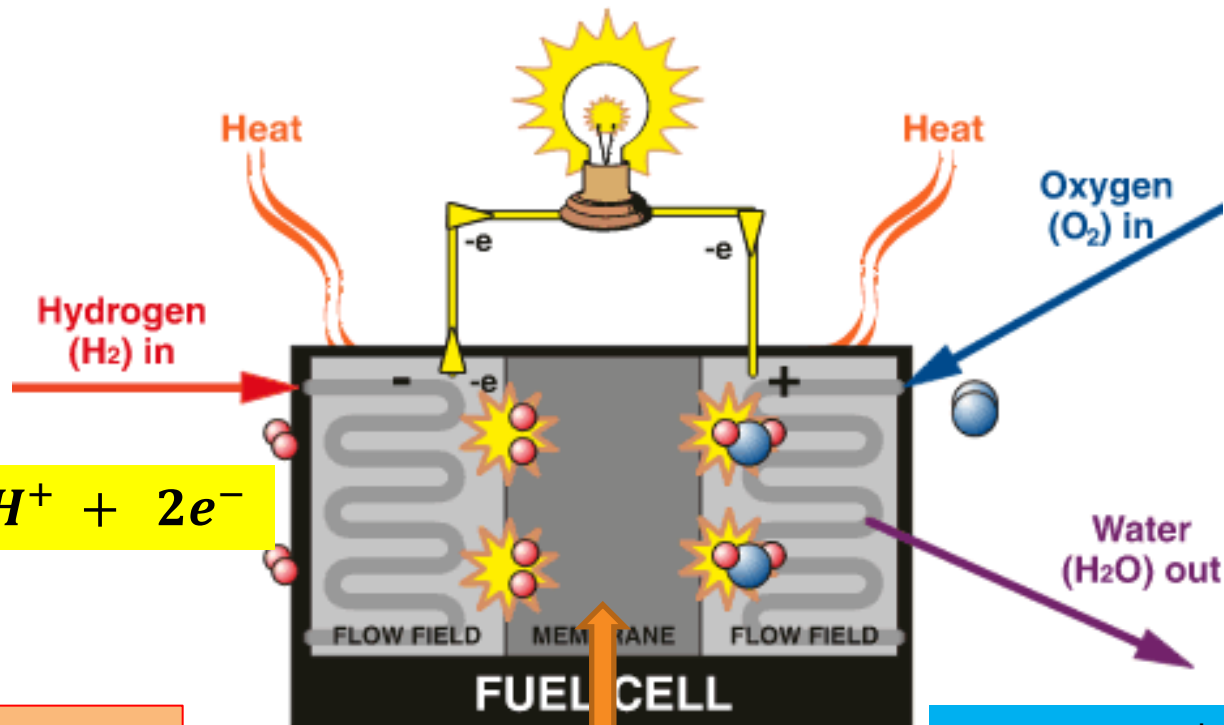
What is a fuel cell (FC)

- An electrochemical device that
- continuously converts the chemical energy of
- **fuel** (hydrogen) and **oxidant** (oxygen)
- directly to electrical energy and heat,
- without combustion.
- Overall reaction:



SCHEMATIC: FUEL CELL TECHNOLOGY

ELECTRICITY PRODUCTION



ANODE

Theory: 1.2V
Prac: 0.7 – 0.9V
Power: 1W/cm²



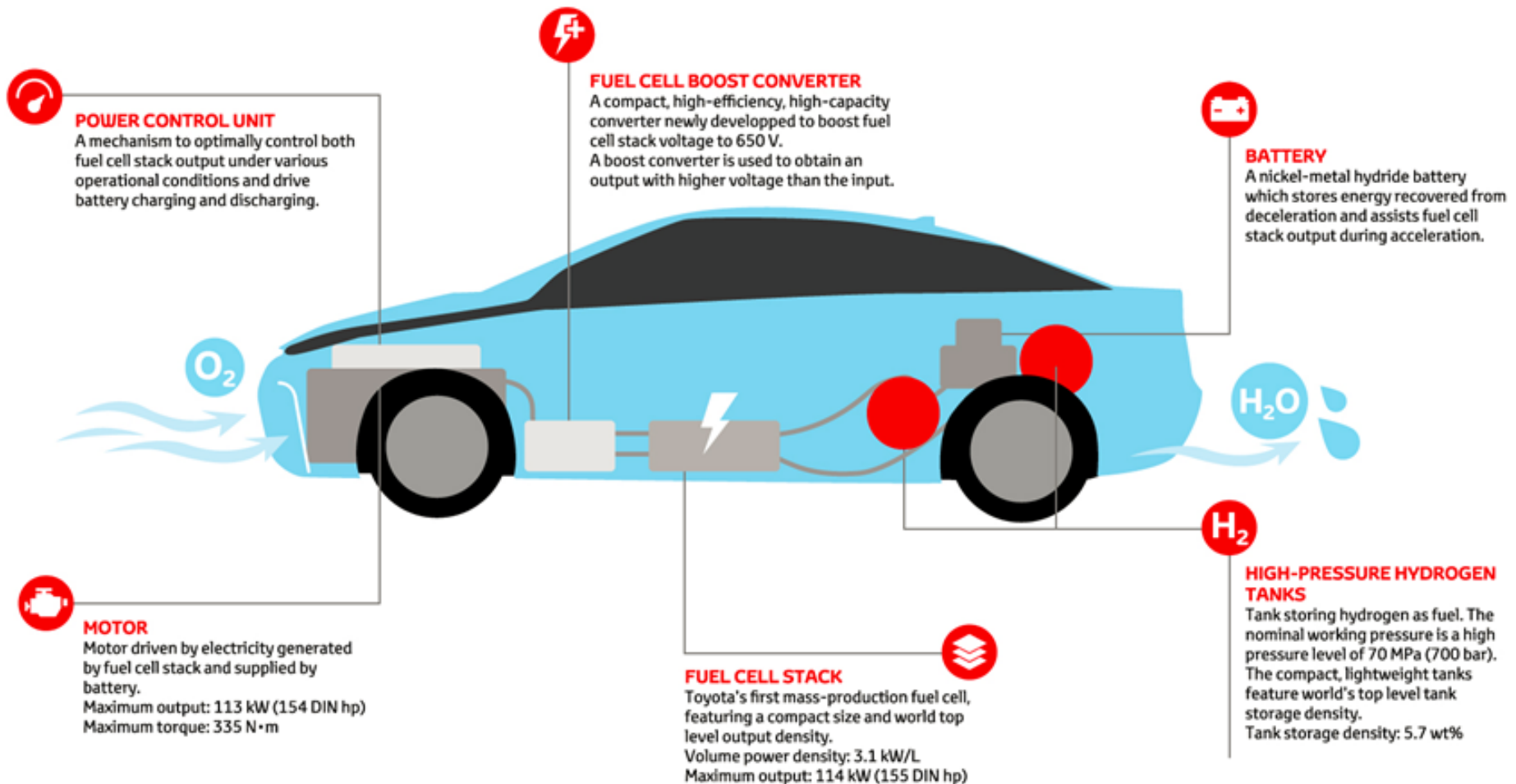
CATHODE

Polymer Electrolyte Membrane (PEM)
Allow H-protons to pass but not electrons

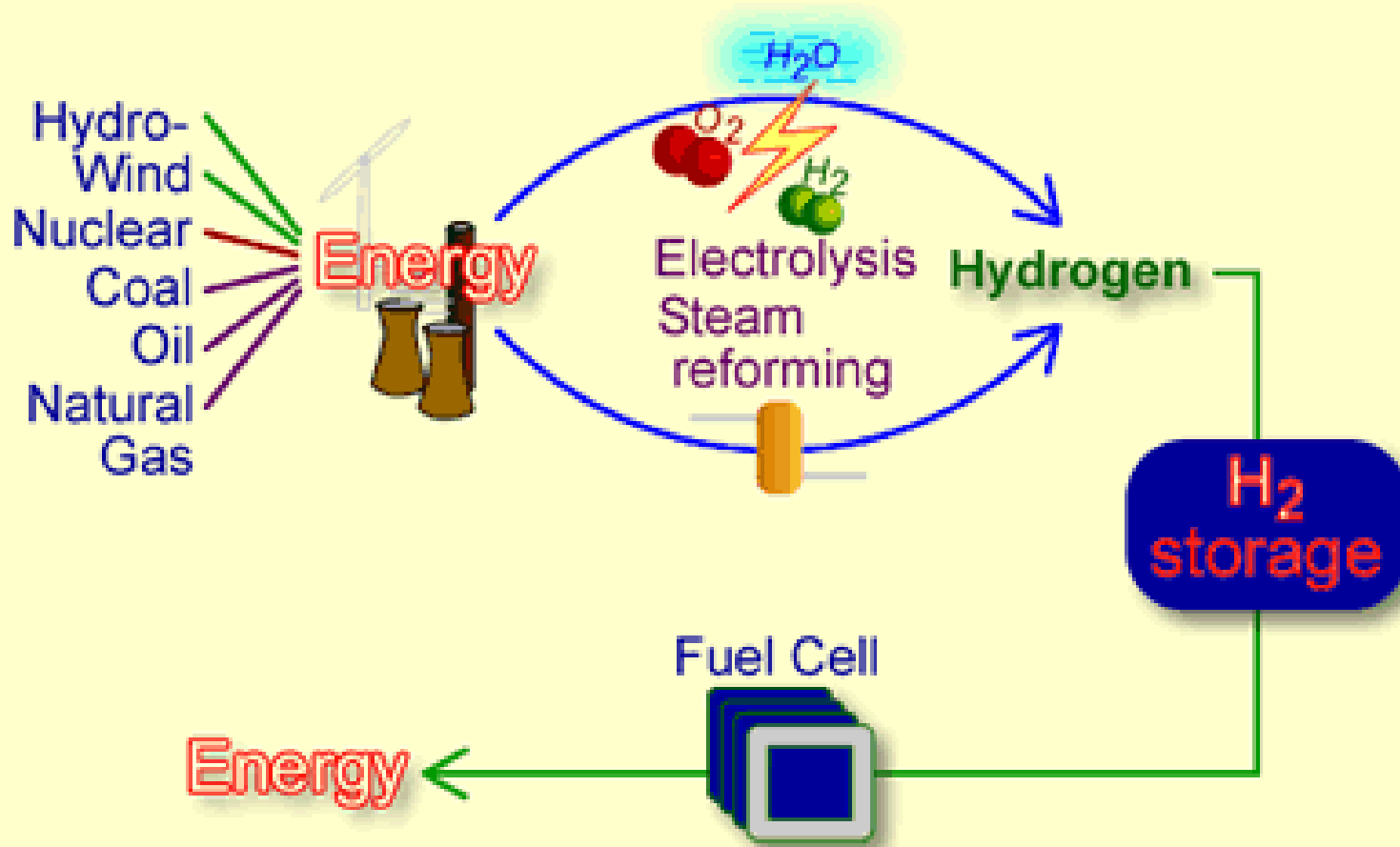
No Combustion = No Pollution

APPLICATIONS FOR FC TECHNOLOGY

Fuel cell technology explained



APPLICATIONS FOR FC TECHNOLOGY

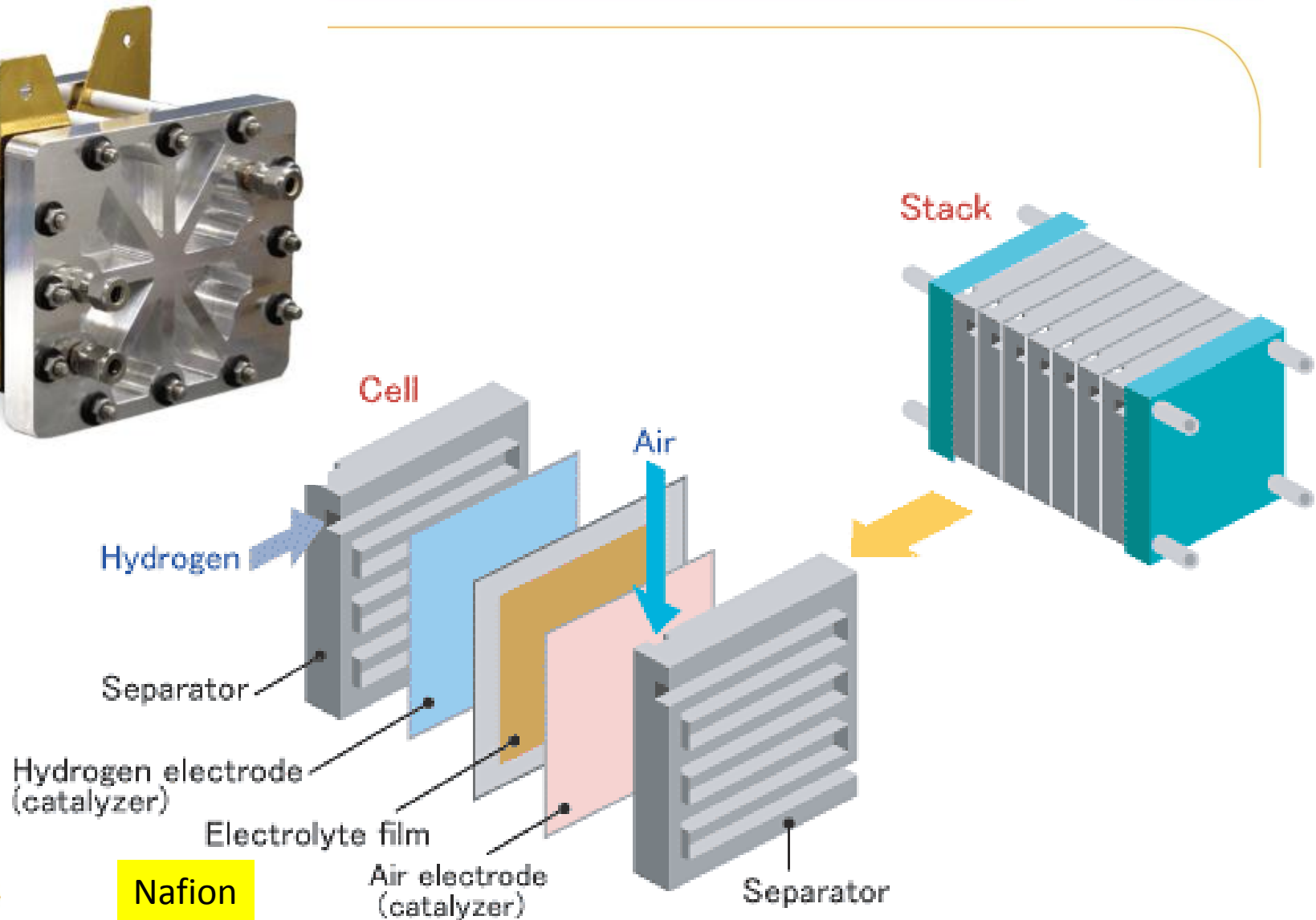


Hydrogen acts as a store of energy

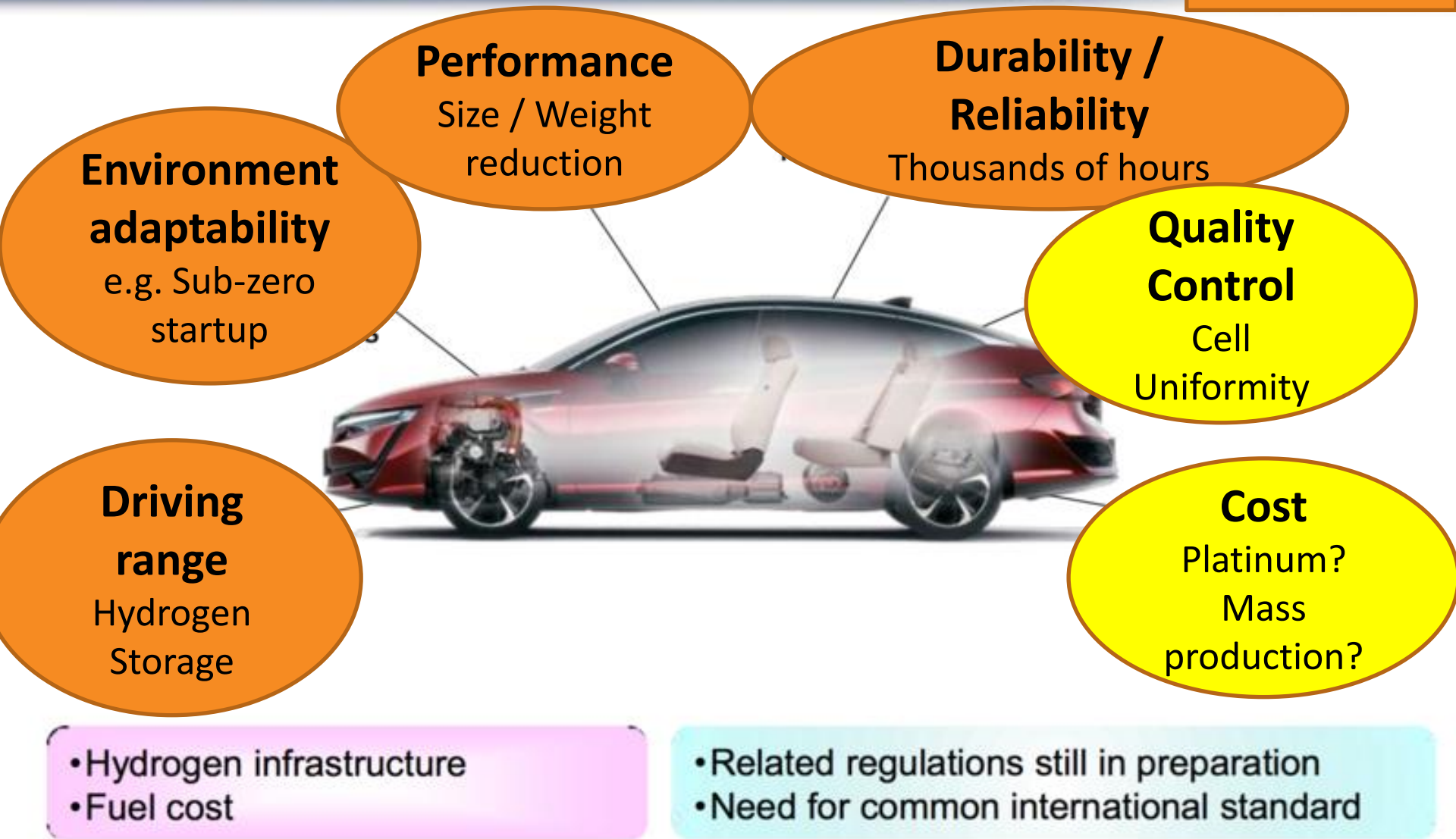
Current FC technologies

Fuel Cell Type	Operating Temperature	System Output	Efficiency	Applications
Alkaline (AFC)	90–100°C	10kW–100kW	60–70% electric	• Military • Space
Phosphoric Acid (PAFC)	150–200°C	50kW–1MW	36–42% electric 80–85% overall with CHP	• Distributed generation
Polymer Electrolyte Membrane or Proton Exchange Membrane (PEM)	50–100°C	<250kW	50–60% electric	• Back-up power • Portable power • Small distributed generation • Transportation
Molten Carbonate (MCFC)	600–700°C	<1MW	60% electric 85% overall with CHP	• Electric utility • Large distributed generation
Solid Oxide (SOFC)	650–1000°C	5kW–3MW	60% electric 85% overall with CHP	• Auxiliary power • Electric utility • Large distributed generation

Fuel Cell internal structures.



Fuel Cell electric Vehicle: Issues Lying Ahead



Range, Environment adaptability and Performance are received vision from past developments. Durability, Reliability, Quality control and Cost reduction have a characteristics affected one other.

Improving the efficiency, reliability, and cost effectiveness of a PEMFC system.

- Non-destructive analysis.
- **In situ** visualisation of the internal cell processes an operating fuel cell.
 - **Transportation of water** throughout the cell.

THUS: Efficient water management has become increasingly important in the effort to optimize fuel cell energy production.

NEED A TOOL: Radiation as probe

Beer–Lambert law

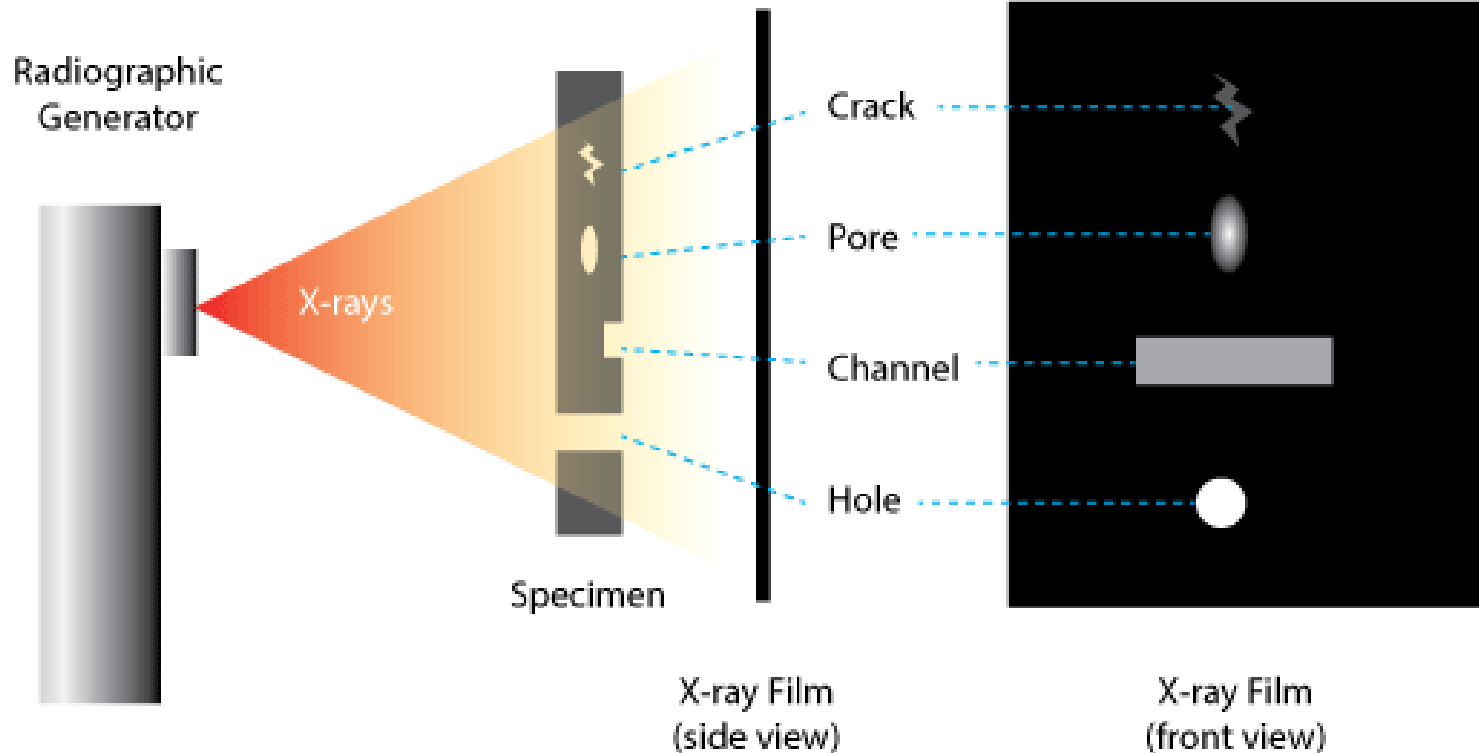
$$I(E) = I_0(E)e^{-[\sum(\rho_i\mu_i(E)x_i)]}$$

$$\mu_i(E) = \mu_{abs}(E) + \mu_{scat}(E)$$

PROPERTIES OF RADIATION	INSTRUMENT / TECHNIQUE	RESOLUTION
Particle	2D Radiography	nm - μm - mm (Physical properties)

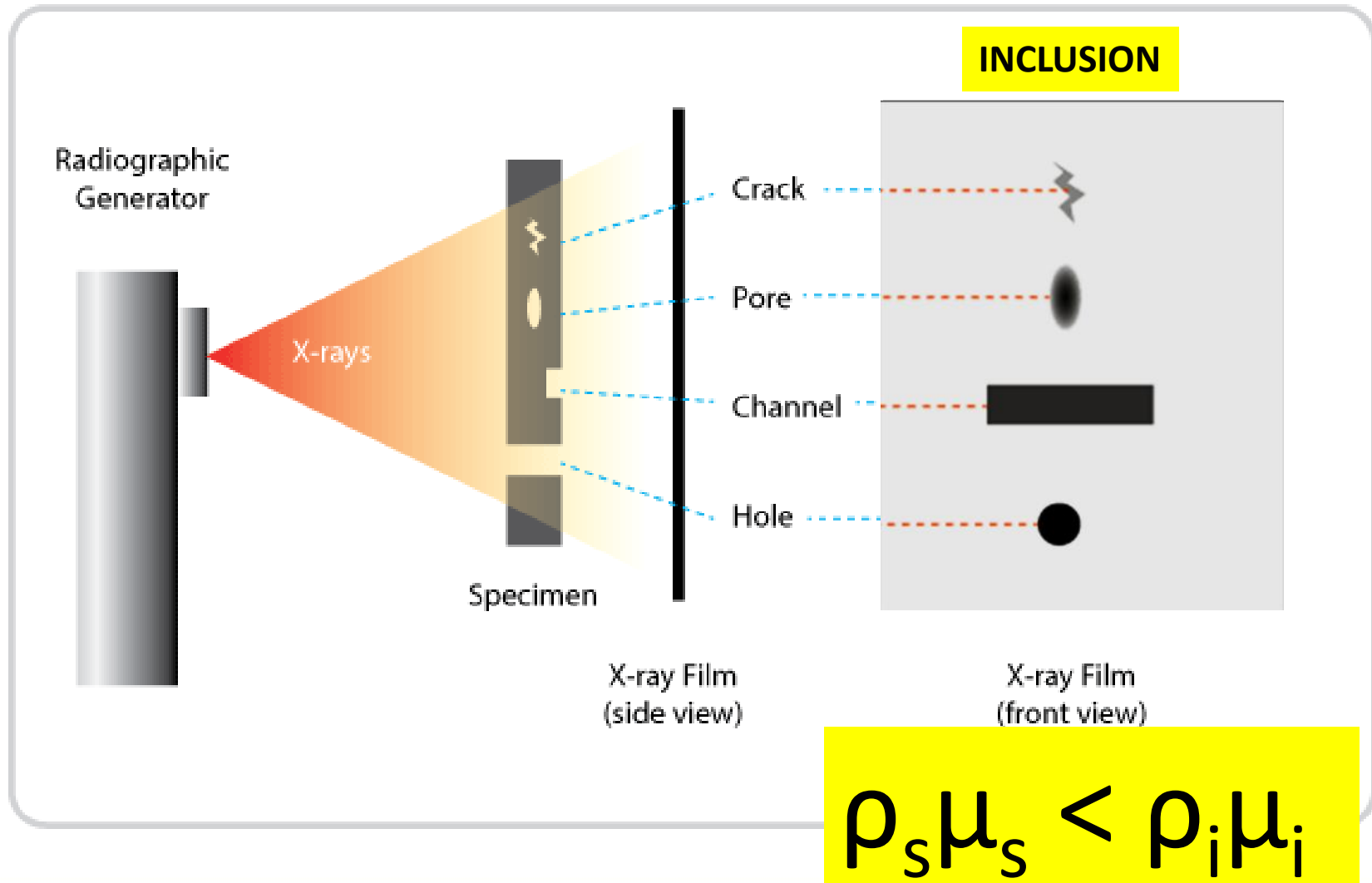
INTRODUCTION - PROCESS

VOIDS (LACK of MATERIAL)



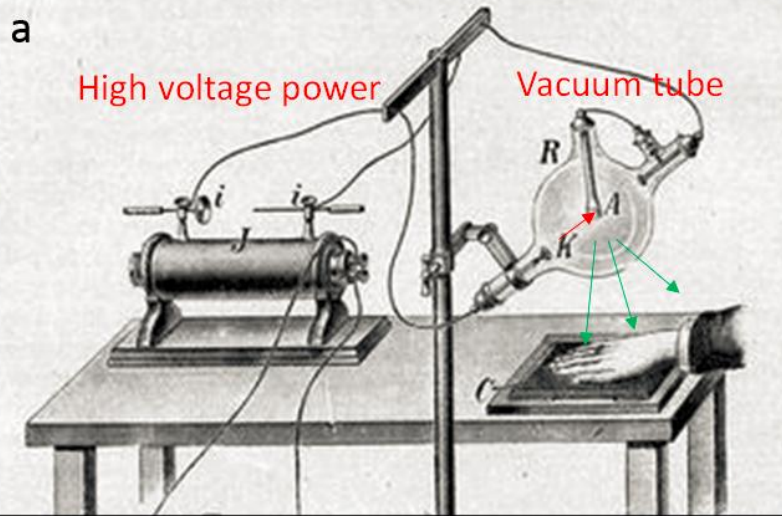
$$\rho_s \mu_s > \rho_v \mu_v$$

INTRODUCTION - PROCESS



Introduction – Use of Radiation

X-rays discovery: 1895: Roentgen



THE SPRINGFIELD SUNDAY UNION AND REPUBLICAN, SPRINGFIELD, MASS.: NOVEMBER 21, 1926

Dr. William D. Coolidge and his NEW MAGIC RAY

WHAT
will it do for
Humanity?

Producing
as Many
ELECTRONS
Every
SECOND
as a
TON of
RADIIUM

By Robert Merrill

Since roentgen's discovery, medical science has been busy with the use of X-rays. It is now known that X-rays are produced by the action of high voltage on a vacuum tube. The new type of vacuum tube, perfected by Dr. Coolidge, which projects the magic cathode ray, the need for radium is entirely determined, but it is known to produce marvelous changes in living tissues.

Dr. Coolidge, assistant director of the Research Laboratory of the General Electric Company, Schenectady, recently startled scientists by his cathode tube.

He then with other scientists like the roentgen, which was used for changes in medicine and in industry. In all of which Dr. Coolidge and his associates have made the tube is now a scientific masterpiece, and its commercial possibilities are being studied.

AN interesting conversation in a laboratory in the General Electric Company, Schenectady, New York, the roentgen tube has been subjected to the rays and all the best have been offered by Dr. Coolidge. A collection of diamonds was brought to the laboratory in the hope that they might be changed from their natural state to a more brilliant one. Dr. Coolidge has been working in collaboration with a medical scientist, who is now using the rays of high voltage to cure the disease of cancer.

Dr. Coolidge has made many discoveries in the field of X-rays. He is now working on the problem of producing X-rays from a vacuum tube. The new type of vacuum tube, perfected by Dr. Coolidge, which projects the magic cathode ray, the need for radium is entirely determined, but it is known to produce marvelous changes in living tissues.

Introduction – Use of Radiation

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Factory Experts**
from Chicago

will conduct
at this store a



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your feet and how
shoes fit. Guaranteed
successful.

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the Street from
RUTLAND'S

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Troubles ?



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Remedies give quick
relief.

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LA PLAZA
THEATER

X-RAY SHOES
516 CENTRAL AVENUE

DR. SCHOLL'S FOOT COMFORT SERVICE HEADQUARTERS

X-RAY FITTING TEST



RIGHT
WAY



LEFT

RIGHT

☐
☐
☐

GOOD
FAIR
POOR

☐
☐
☐


WRONG
WAY

Hair Removed Permanently

Patient receiving treatment on the cheek. No pain or sensation of any kind. The **INFALLIBLE** method successfully used for 16 years by Dr. Albert C. Geyser, late Professor of Electrical Therapeutics at Cornell University and endorsed by many leading physicians. No Needle, No Wax, No Chemical. Painless and Harmless—Guaranteed to be Permanent.

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played here during this
special demonstration,

Winter Garden, Fla.

INTRODUCTION: X-RAYS

Attenuation coefficients with X-ray [cm²g⁻¹]

1a	2a	3b	4b	5b	6b	7b	8				1b	2b	3a	4a	5a	6a	7a	0	
H 0.02																			He 0.02
Li 0.06	Be 0.22											B 0.28	C 0.27	N 0.11	O 0.16	F 0.14	Ne 0.17		
Na 0.13	Mg 0.24											Al 0.38	Si 0.33	P 0.25	S 0.30	Cl 0.23	Ar 0.20		
K 0.14	Ca 0.26	Sc 0.48	Ti 0.73	V 1.04	Cr 1.29	Mn 1.32	Fe 1.57	Co 1.78	Ni 1.96	Cu 1.97	Zn 1.64	Ga 1.42	Ge 1.33	As 1.50	Se 1.23	Br 0.90	Kr 0.73		
Rb 0.47	Sr 0.86	Y 1.61	Zr 2.47	Nb 3.43	Mo 4.29	Tc 5.06	Ru 5.71	Rh 6.08	Pd 6.13	Ag 5.67	Cd 4.84	In 4.31	Sn 3.98	Sb 4.28	Te 4.06	I 3.45	Xe 2.53		
Cs 1.42	Ba 2.73	La 5.04	Hf 19.70	Ta 25.47	W 30.49	Re 34.47	Os 37.92	Ir 39.01	Pt 38.61	Au 35.94	Hg 25.88	Tl 23.23	Pb 22.81	Bi 20.28	Po 20.22	At	Rn 9.77		
Fr	Ra 11.80	Ac 24.47	Rf	Ha															
Lanthanides	Ce 5.79	Pr 6.23	Nd 6.46	Pm 7.33	Sm 7.68	Eu 5.66	Gd 8.69	Tb 9.46	Dy 10.17	Ho 10.91	Er 11.70	Tm 12.49	Yb 9.32	Lu 14.07					
*Actinides	Th 28.95	Pa 39.65	U 49.08	Np	Pu	Am	Cm	Bk	Vf	X-ray		Md	No	Lr x-ray					

Legend

Attenuation coefficient [cm²g⁻¹] = sp.gr. * μ_δ

sp.gr.: Handbook of Chemistry and Physics, 56th Edition 1975-1976.

μ_δ: J. H. Hubbell* and S. M. Seltzer Ionizing Radiation Division, Physics Laboratory National Institute of Standards and Technology Gaithersburg, MD 20899,
<http://physics.nist.gov/PhysRefData/XrayMassCoef/tab3.html>.

INTRODUCTION: NEUTRONS

Attenuation coefficients with neutrons [cm²g⁻¹]

1a	2a	3b	4b	5b	6b	7b	8				1b	2b	3a	4a	5a	6a	7a	0	
H 3.44																		He 0.02	
Li 3.30	Be 0.79											B 101.60	C 0.56	N 0.43	O 0.17	F 0.20	Ne 0.10		
Na 0.09	Mg 0.15											Al 0.10	Si 0.11	P 0.12	S 0.06	Cl 1.33	Ar 0.03		
K 0.06	Ca 0.08	Sc 2.60	Ti 0.60	V 0.72	Cr 0.54	Mn 1.21	Fe 1.19	Co 3.92	Ni 2.05	Cu 1.07	Zn 0.35	Ga 0.49	Ge 0.47	As 0.67	Se 0.73	Br 0.24	Kr 0.61		
Rb 0.08	Sr 0.14	Y 0.27	Zr 0.29	Nb 0.40	Mo 0.52	Tc 1.76	Ru 0.58	Rh 10.88	Pd 0.78	Ag 4.04	Cd 115.11	In 7.58	Sn 0.21	Sb 0.30	Te 0.25	I 0.23	Xe 0.43		
Cs 0.29	Ba 0.07	La 0.52	Hf 4.99	Ta 1.49	W 1.47	Re 6.85	Os 2.24	Ir 30.46	Pt 1.46	Au 6.23	Hg 16.21	Tl 0.47	Pb 0.38	Bi 0.27	Po	At	Rn		
Fr	Ra 0.34	Ac	Rf	Ha															
*Lanthanides	Ce 0.14	Pr 0.41	Nd 1.87	Pm 5.72	Sm 171.47	Eu 94.58	Gd 1479.04	Tb 0.93	Dy 32.42	Ho 2.25	Er 5.48	Tm 3.53	Yb 1.40	Lu 2.75					
**Actinides	Th 0.59	Pa 8.46	U 0.82	Np 9.80	Pu 50.20	Am 2.86	Cm	Bk	Cf	thermal neutrons									

thermal neutrons

Legend

σ -total * sp.gr. * 0.6023

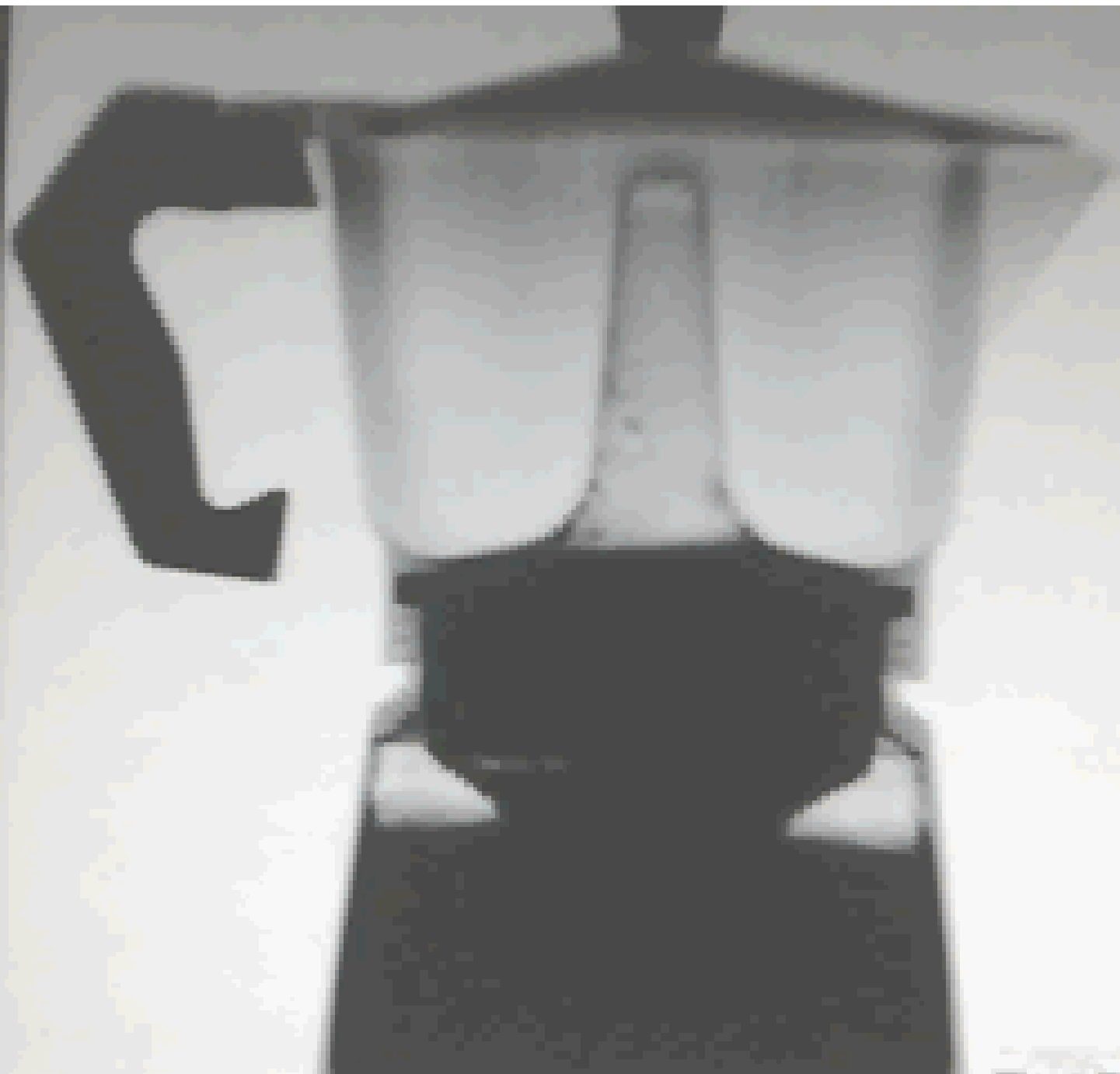
Attenuation coefficient [cm²g⁻¹] = $\frac{\sigma\text{-total} * \text{sp.gr.} * 0.6023}{\text{at.wt.}}$

σ -total: JEF Report 14, TABLE OF SIMPLE INTEGRAL NEUTRON CROSS SECTION DATA FROM JEF-2.2, ENDF/B-VI, JENDL-3.2, BROND-2 AND CENDL-2, AEN NEA, 1994.

and Special Feature: Neutron scattering lengths and cross sections, Varley F. Sears, AECL Research, Chalk River Laboratories Chalk River, Ontario, Canada KOJ 1JO, Neutron News, Vol. 3, 1992, <http://www.ncnr.nist.gov/resources/n-lengths/list.html>.

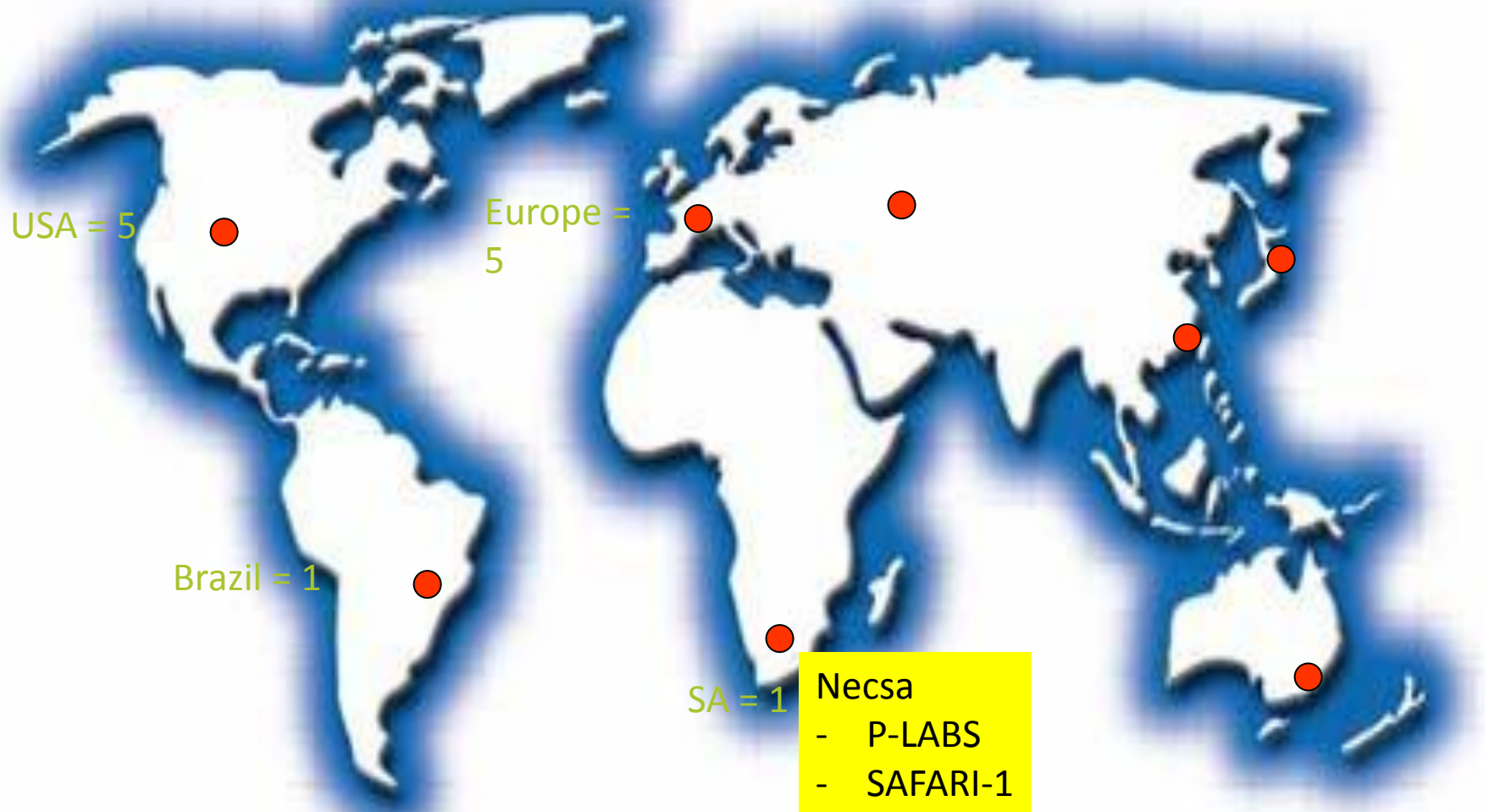
sp.gr.: Handbook of Chemistry and Physics, 56th Edition 1975-1976.

at.wt.: Handbook of Chemistry and Physics, 56th Edition 1975-1976.

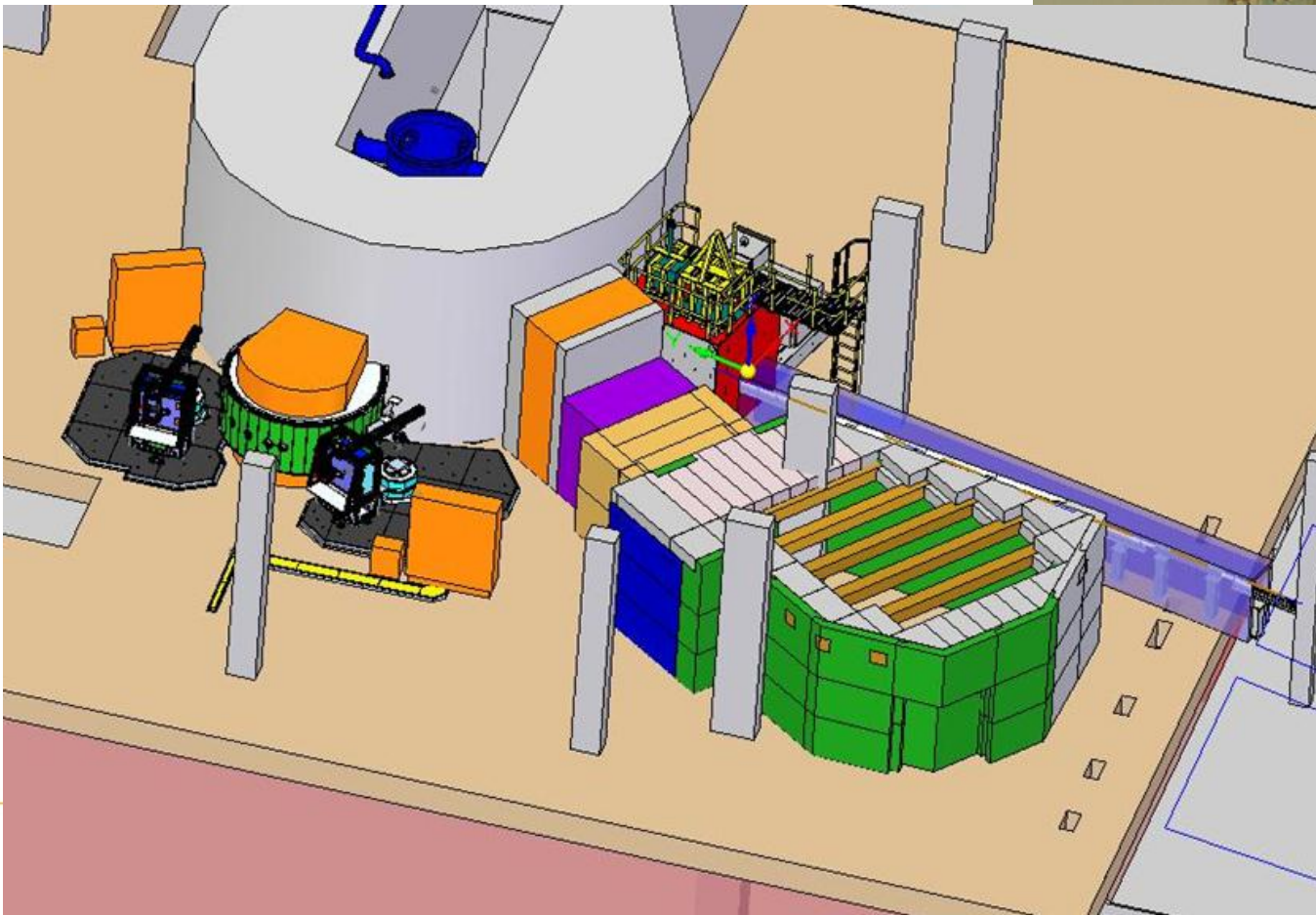
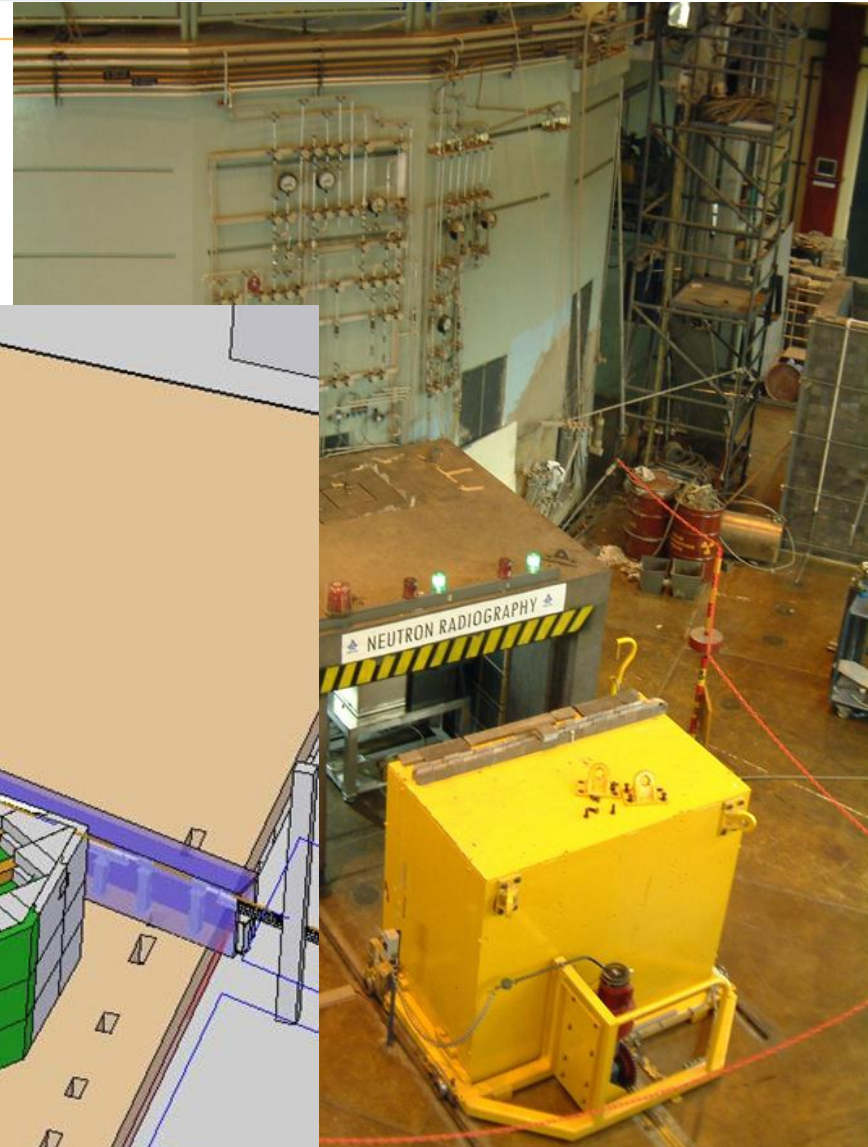


- **TOOLS?**
- **RESEARCH EQUIPMENT**

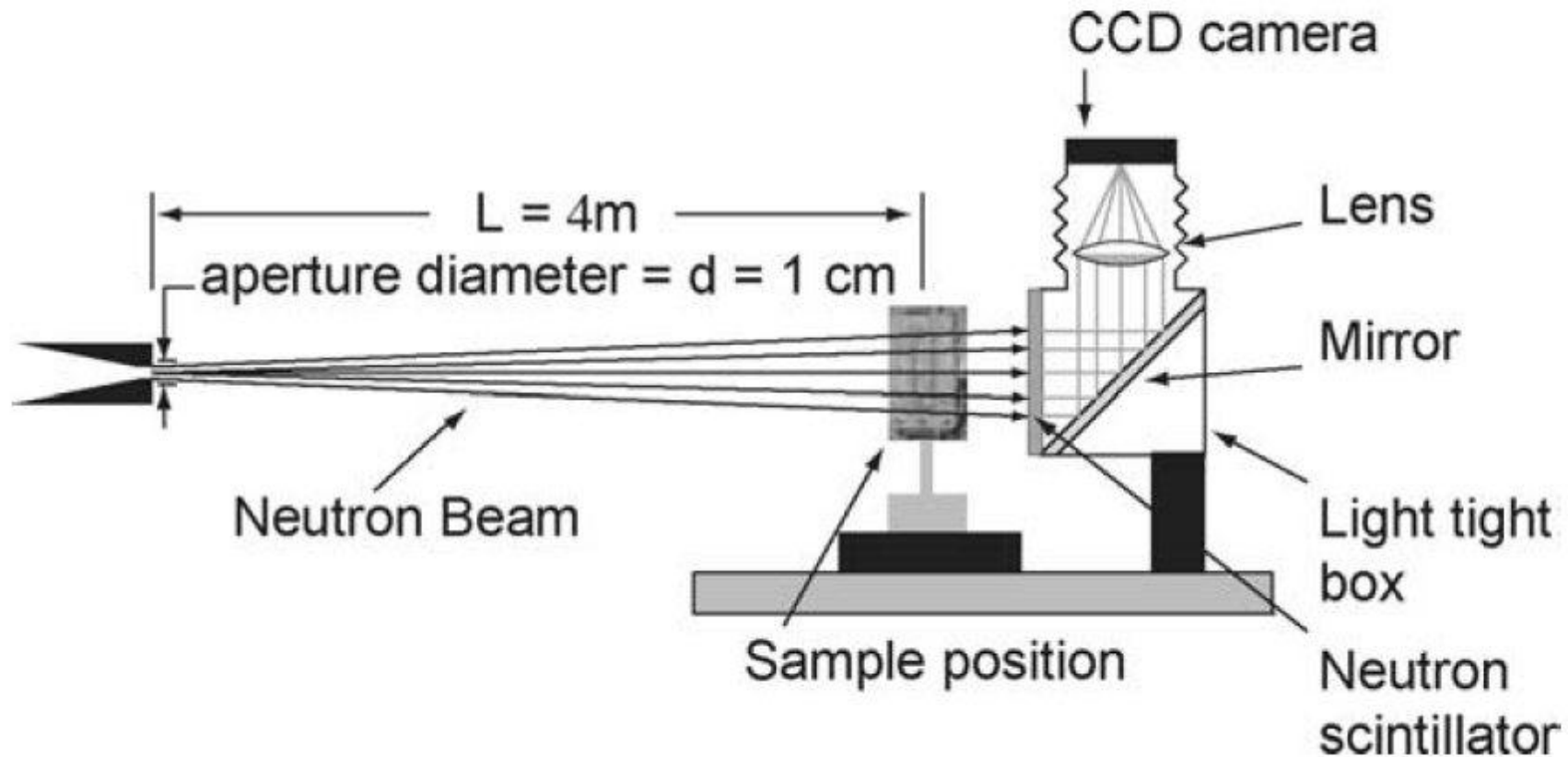
RESEARCH TOOLS: NRAD facilities



SOUTH AFRICAN NEUTRON RADIOGRAPHY (SANRAD) FACILITY



FUEL CELL OPTIMISATION & NRad

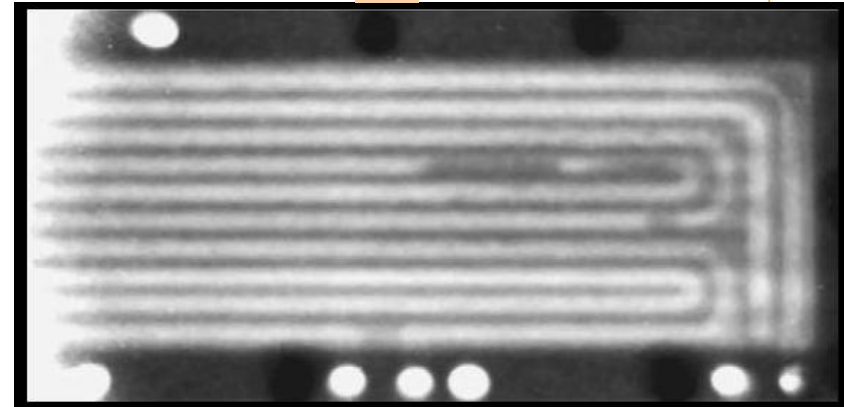
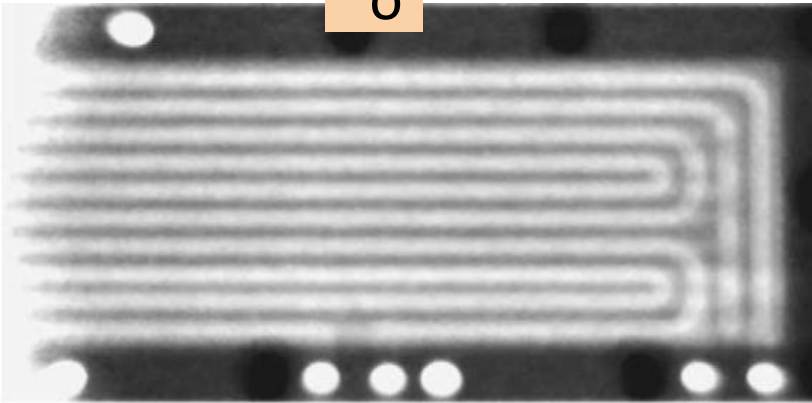


Working PEM Fuel Cell & NRad

I_0

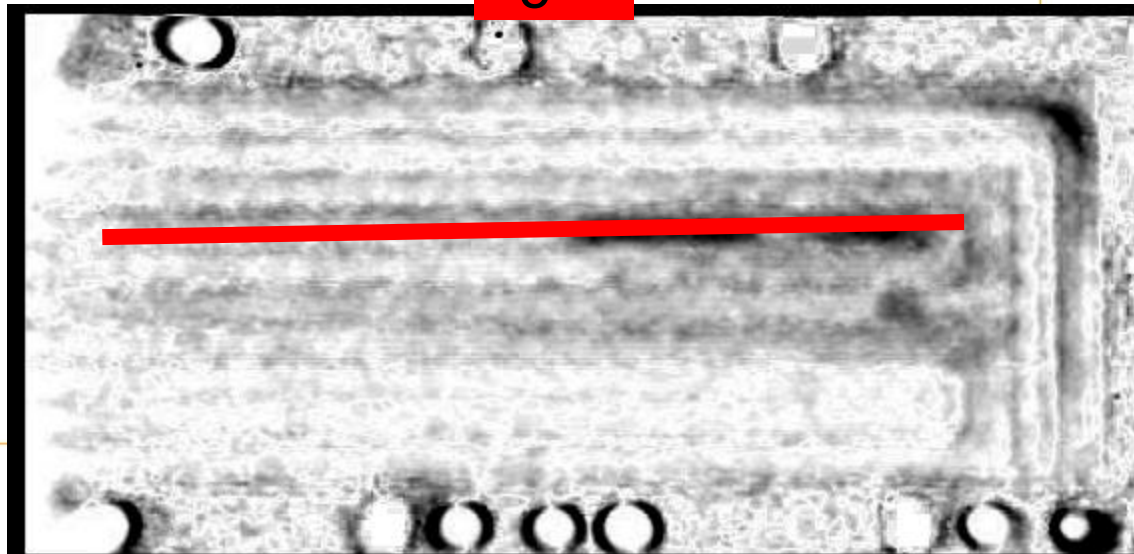
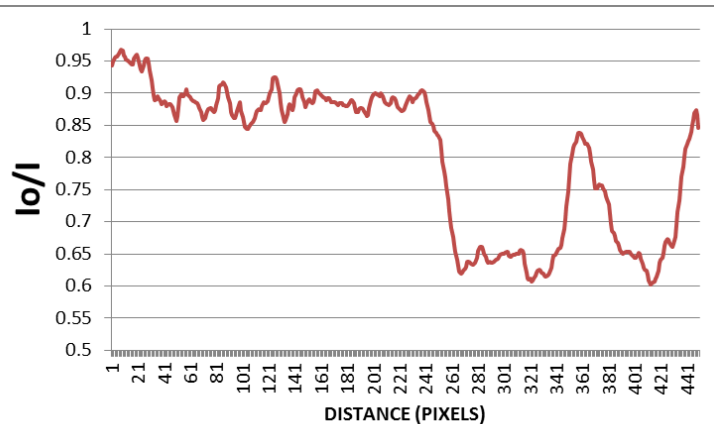
PEM FUEL CELL WORKING

I

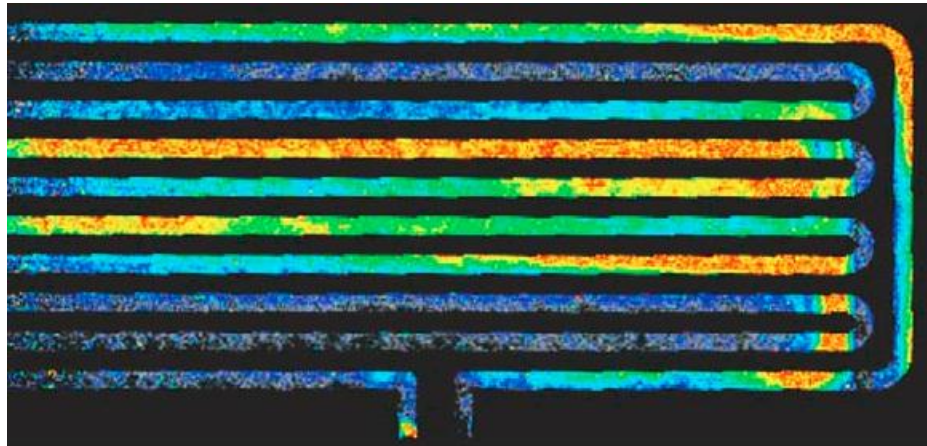


I_0/I

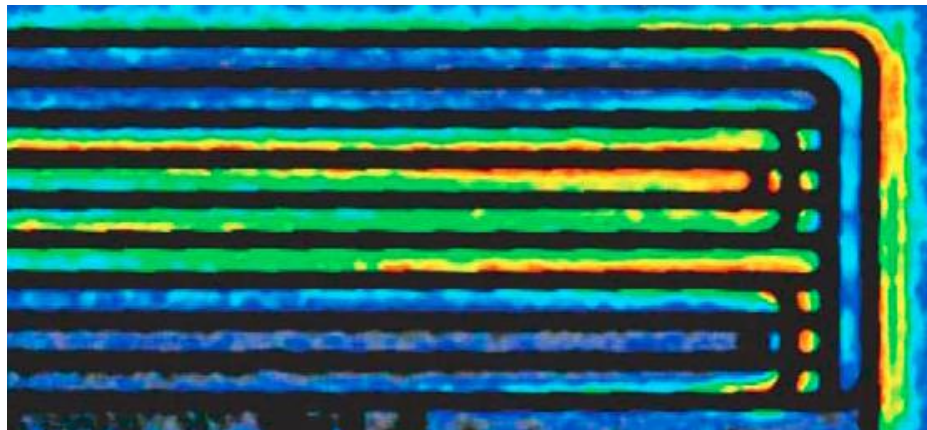
$$\ln \frac{I_0}{I} = \mu \rho x$$



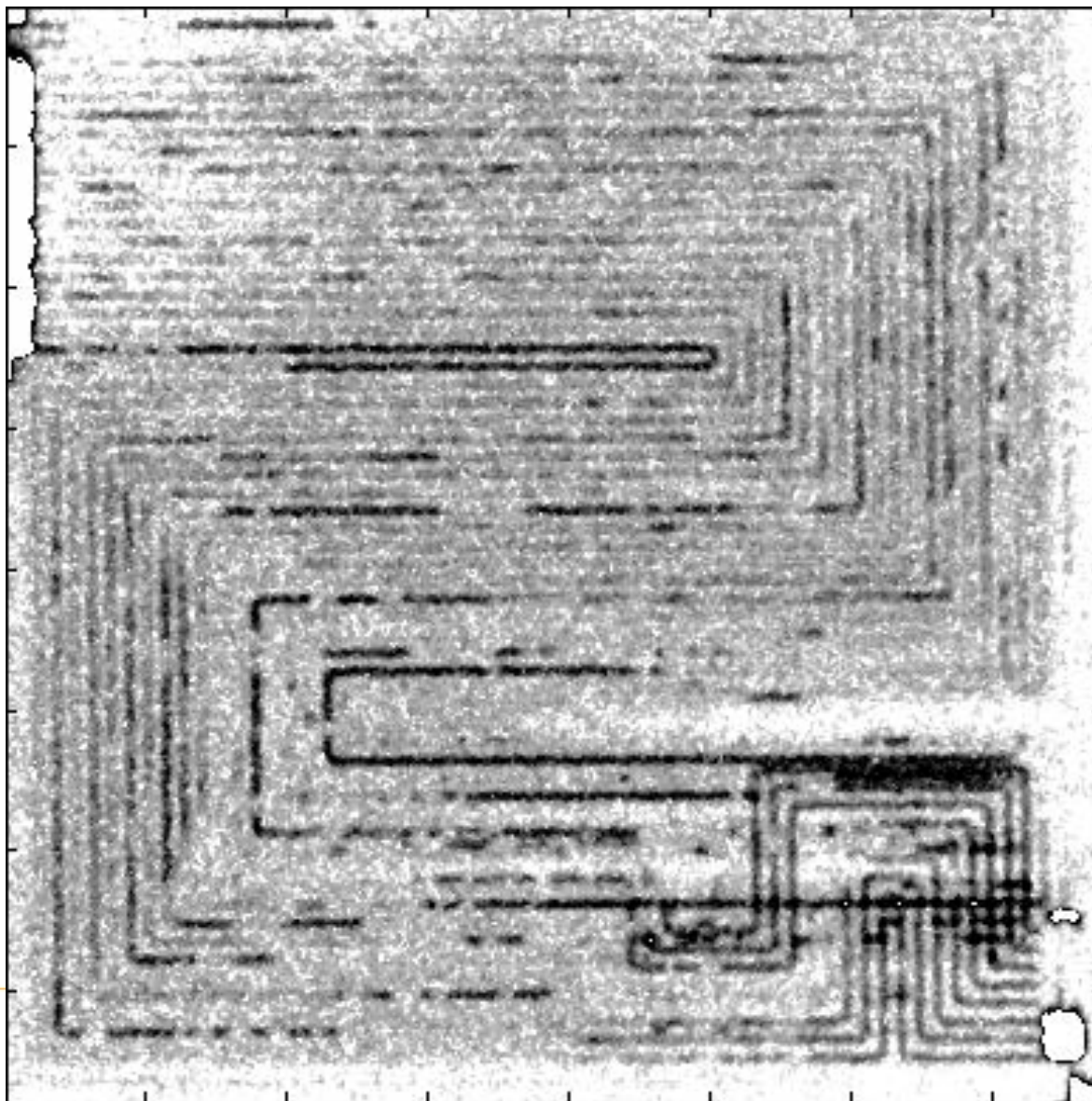
Working PEM Fuel Cell & NRad



1.0 mm H₂O



0.0 mm H₂O



IN-SITU
DETECTION OF
WATER
PRODUCTION
IN A FUEL CELL

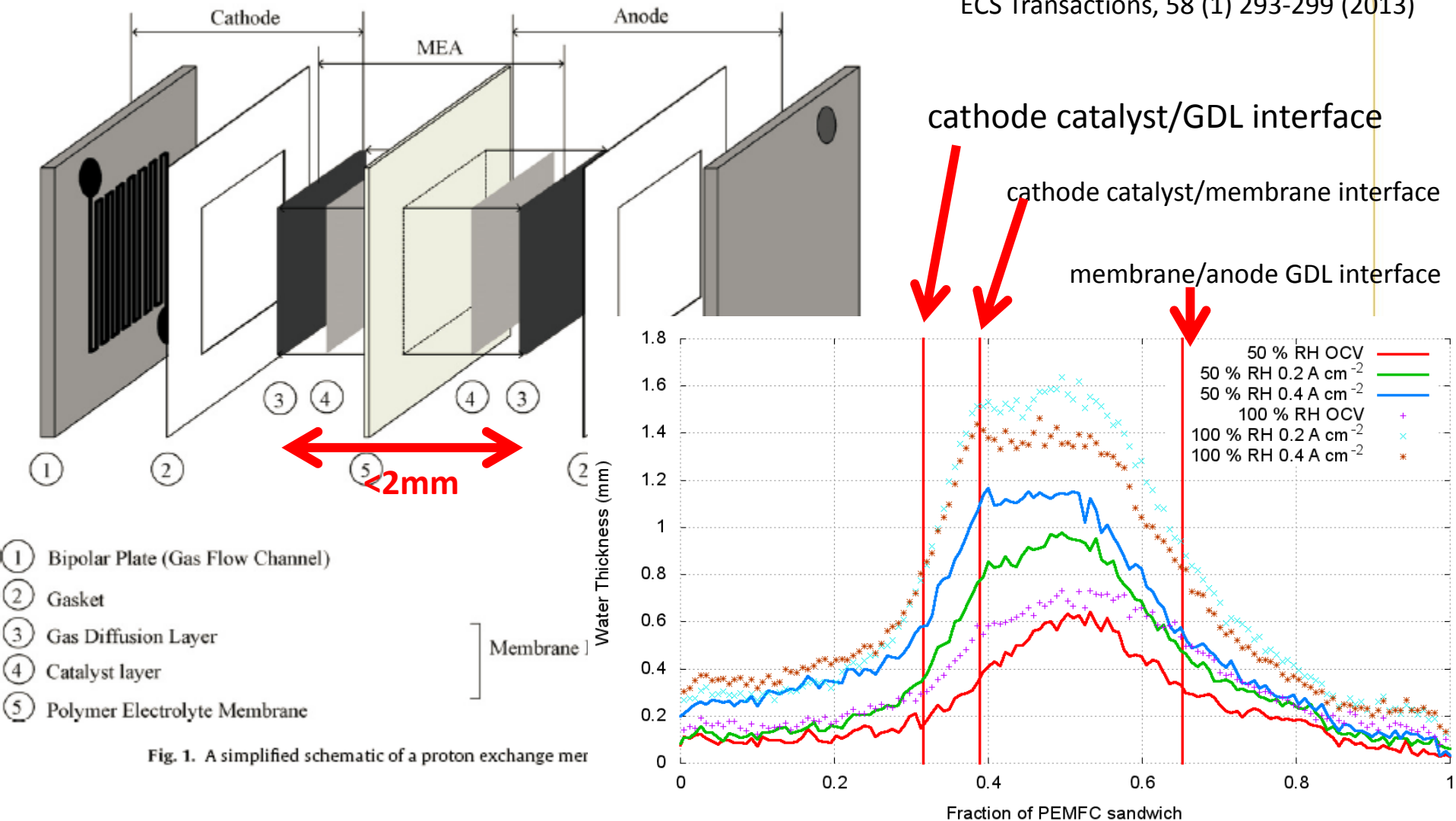
(Black = Water)

Working PEM Fuel Cell & NRad

H.-Y. Tang et al. / Journal of Power Sources 195 (2010) 6774–6781

Hussey, et.al.

ECS Transactions, 58 (1) 293-299 (2013)



Neutron Production Institution

Title: Neutron radiography of electrolysis using a fuel cell concept.

Necsa:

HySA / NWU:



Hydrogen Production

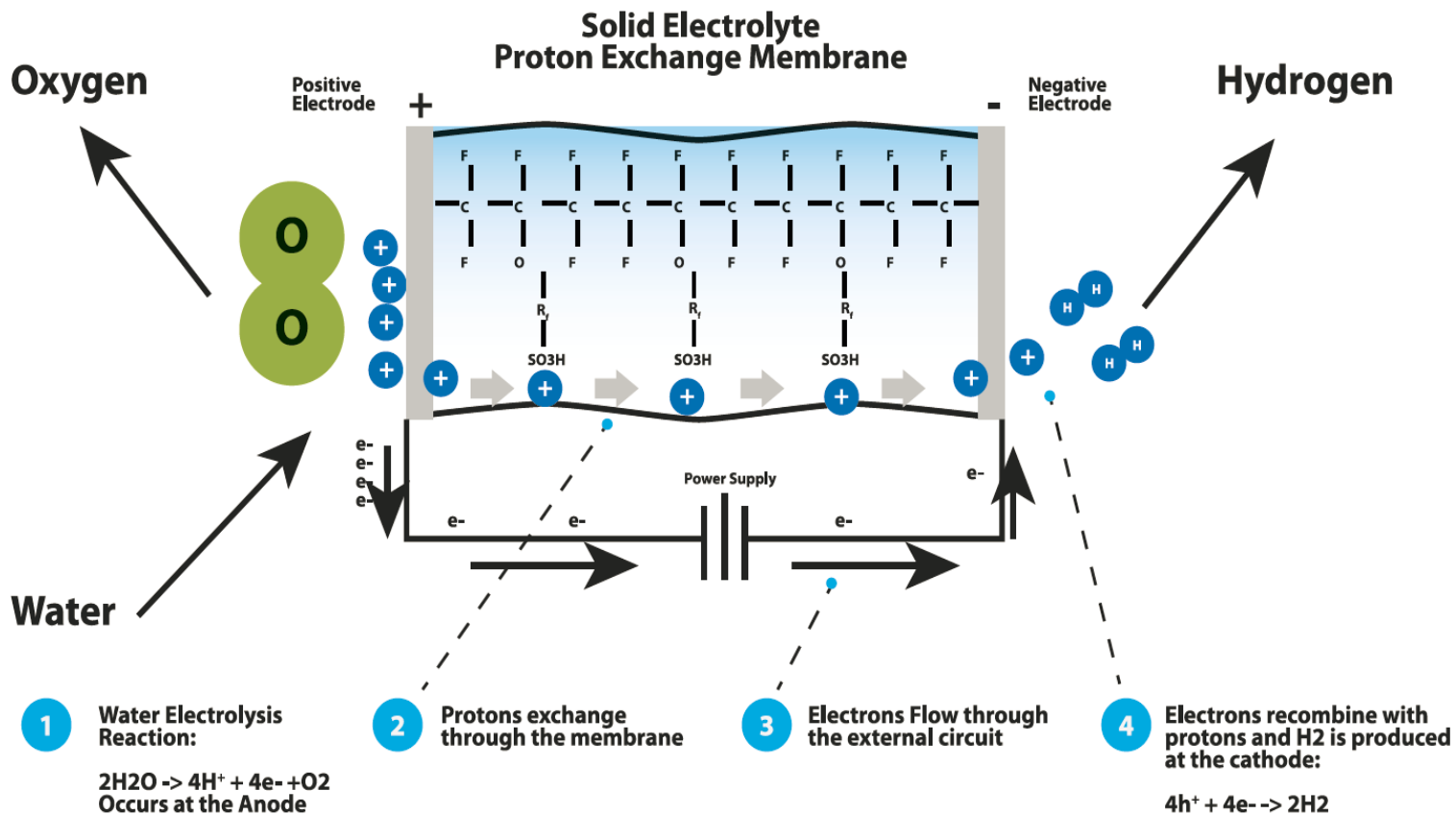
Electrolytic Process:

Use of electric current to split water into
Hydrogen & Oxygen

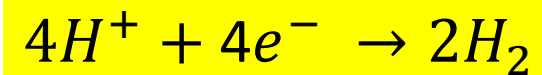
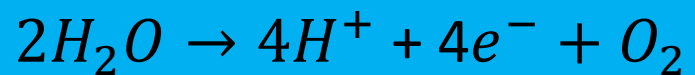
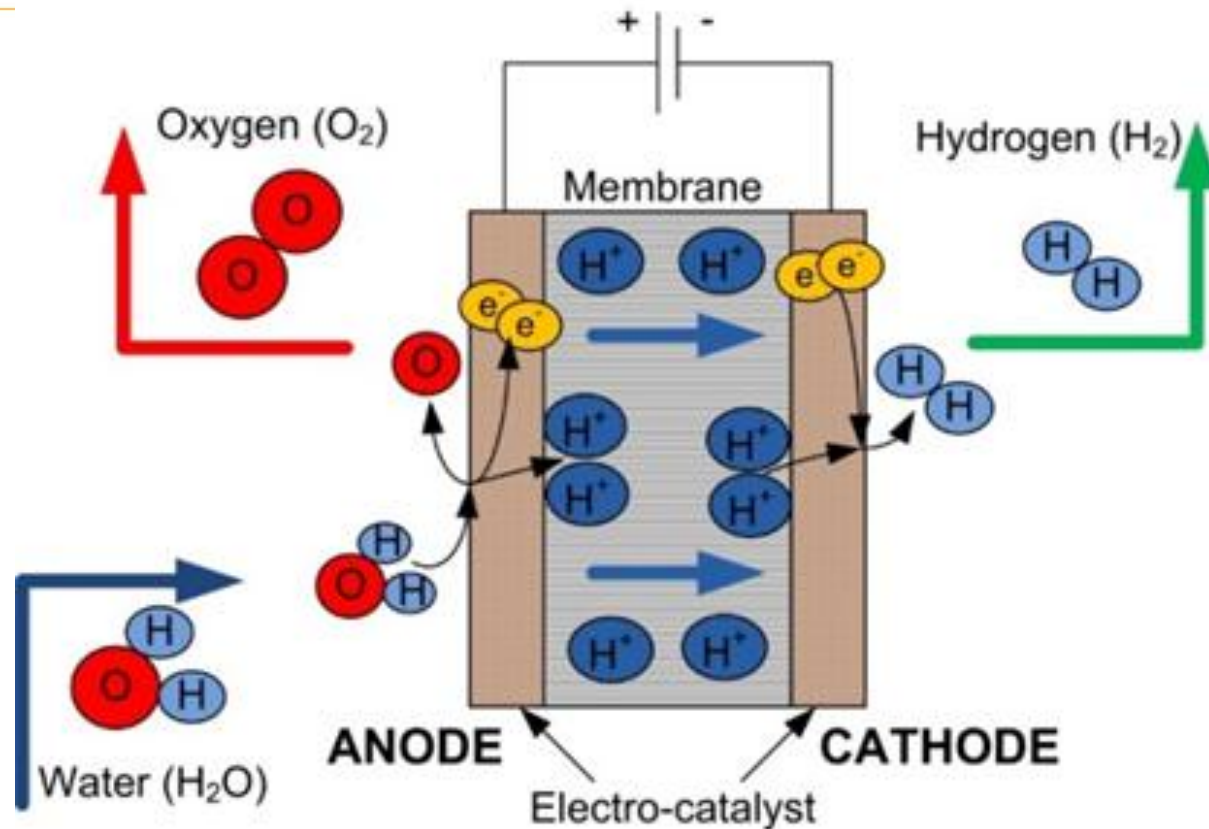
Electricity required: Generated by renewal
technologies:

Wind; Solar; Geothermal; hydroelectric

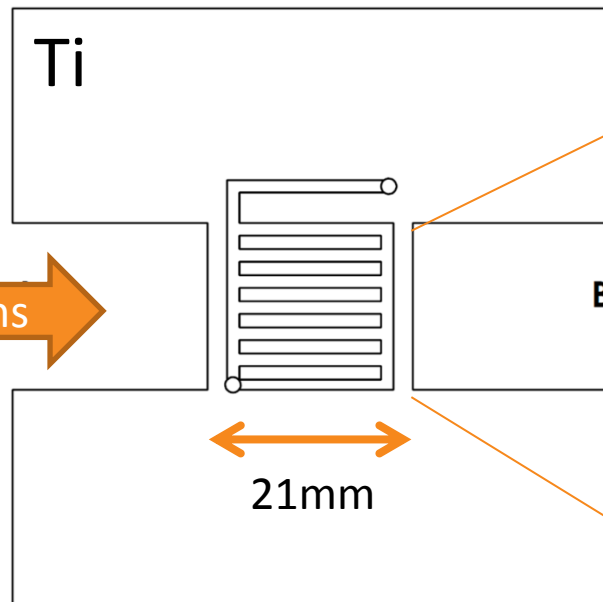
ELECTROLYSIS: HYDROGEN PRODUCTION



Schematic: Electrolysis



NEUTRON RADIOGRAPH



CATHODE ANODE

2mm x 2mm x 21mm

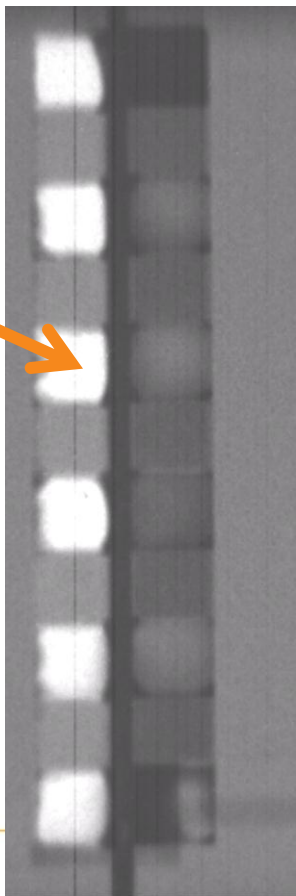
Resolution obtained: =
10 μ m/pixel

Quasi-dynamic electrolysis

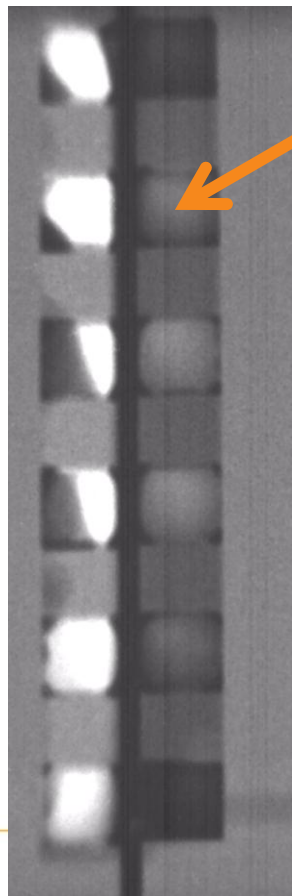
Current Density: _____ 1A
Water flow: _____ 37ml/min
Temp: _____ 27°C 80°C
Camera Frame rate: 2 sec/frame

VERTICAL ORIENTATION

Should
be only
 H_2



Should be only
 H_2O and O_2



Quasi-dynamic electrolysis

Current Density:

1A

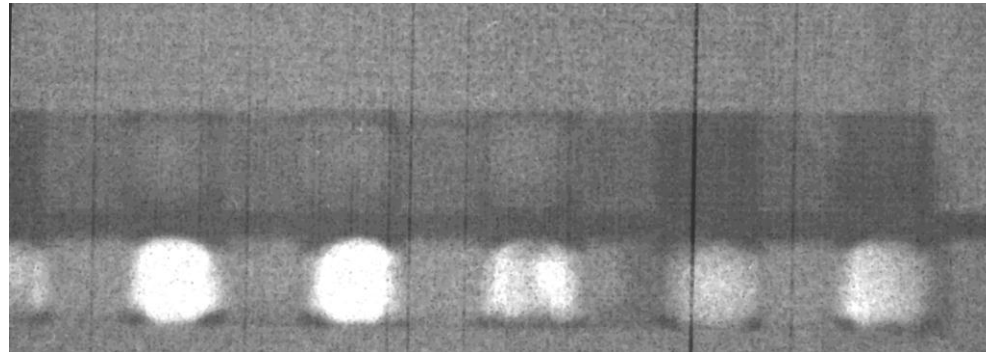
Water flow:

37ml/min

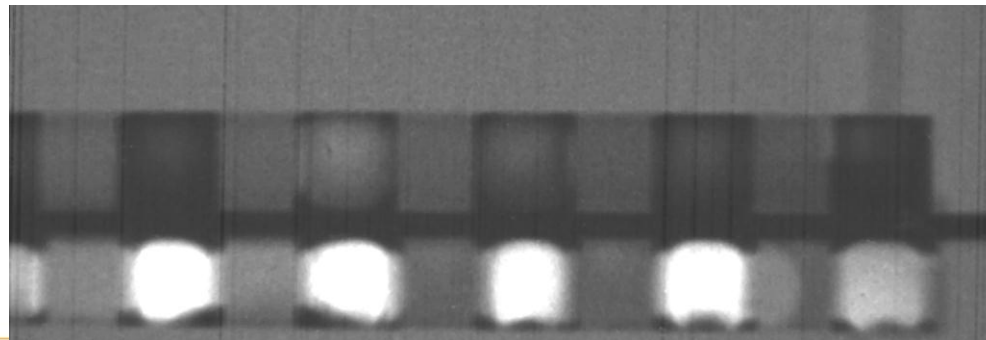
Temp: CCD Frame
 Rate

HORIZONTAL ORIENTATION

27°C 0.8 spf



80°C 2 spf



- **Electrolysis**
 - Derive Quantitative results
 - Formulate proper investigation
- **Fuel Cell**
 - Learned from International
 - Approach role players in SA
- **Utilisation Local SA Nrad facility @ Necsa**
- **Non-destructively : In situ : Real time**
- **Use neutron as microscope – high resolution**

Acknowledgements

- SAIP2016
- DST-NRF
- HySA - NWU
- Necsa

APPLY & THANK YOU

