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Trends in RF and Microwave Heating

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Foundations of a career in industrial microwave engineering

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Early years

The day I joined the Microwave Applications Research Centre (MARC) — the commercial arm of the University of Wollongong — remains unforgettable. It was 25 July 1988, the day my first son Joel was born. Fittingly, Joel has now worked alongside me in microwave technology for more than eighteen years. At the time, I was a young engineer only two years into my career, stepping into a field that would shape the next several decades of my life.

Those early years were electrifying. For more than a decade, I genuinely looked forward to Mondays. I devoured every book and paper I could find on microwave science, often reading the best ones twice. My mentor, Professor Frank Paoloni — whose experience included high-temperature plasma research at Princeton University — was instrumental in my development. I spent countless hours in his office wrestling with concepts that pushed the boundaries of modern thermal processing.

Being an Australian engineer often meant feeling isolated from the large global community of microwave researchers. To bridge that gap, I attended every AMPERE and IMPI conference possible. These meetings were invaluable: an opportunity to learn from world leaders, exchange ideas, and enjoy a brief holiday while doing it.

Our early work at MARC centred on pyro-metallurgical extraction — an enormously challenging area led by one of Australia's most respected scientists, Professor Howard Warner. In hindsight, few fields are more complex to commercialise than high-temperature (above 1200 °C) extractive metallurgy. It has taken me nearly three decades to feel confident navigating its technical, thermal, and operational risks.

Over time, my enthusiasm for mastering the underlying physics and engineering made me an essential contributor to MARC's research portfolio. After roughly fifteen years, I presented a proposal to the University that ultimately led to the creation of Advanced Microwave Technologies Pty Ltd (AMT). Under that agreement, I became an Honorary Academic Fellow, acquired the assets and intellectual property of MARC, and in return committed to ongoing theoretical and practical support for university microwave projects, including supervision of students.

By the time AMT was formed in 2001, MARC had already completed commercial programs across Australia, New Zealand, South Africa, Italy and the Czech Republic. Yet there remained a clear global need for an organisation capable of bridging academic insight with commercially ambitious, entrepreneur-driven industrial scale-up. AMT was established precisely to fill that gap — and it continues to do so today.

Key Principles for Scaling High-Temperature Microwave Processes

1. Frequency Selection

Microwave energy absorption ($P_v = 2\pi f\varepsilon_0\varepsilon''E^2$) increases with frequency. However, commercial viability depends on source efficiency, waveguide dimensions, penetration depth, and capital cost per kW. The frequency of 915 MHz typically offers deeper penetration and lower cost, making it ideal for industrial scale-up.

2. Power Density & Field Uniformity

High temperatures amplify non-uniform field risks — hotspots, plasma formation, thermal runaway.

Stable industrial systems depend on uniform volumetric power distribution.

3. Temperature-Dependent Dielectric Behaviour
Material properties ε' and ε'' change significantly with temperature and phase transitions, sometimes abruptly. Predictive modelling must account for thermal runaway risks and structural transformations.

4. Thermal Management & Refractory Engineering
Above ~1000 °C, radiative losses dominate, refractories influence field patterns, and metals such as stainless steel become lossy. Proper refractory selection and thermal design are essential.

5. Modularity, Control Systems & Safety
Microwave systems at high temperature must operate within stable coupling windows. Modular reactor designs allow safe scaling: each module maintains controlled power density while enabling increased throughput.

Current High-Temperature Projects (Past Two Years)
1. Spodumene Calcination — 1000–1100 °C
2. Alumina (Al_2O_3) Calcination — 1000–1200 °C
3. Asbestos Thermal Inactivation — 800–1000 °C
4. Zinc Fuming from EAF Dust — 1000–1300 °C
5. Microwave Plasma Applicator Development — >1400 °C.

Closing Reflection
From a young engineer in 1988 to the founder of AMT, the journey has been shaped by curiosity, persistence, and a determination to master one of the most complex thermal technologies in modern industry. AMT continues to bridge research breakthroughs with commercial applications worldwide.

About the author

David McLean is a senior engineer and director of Advanced Microwave Technologies, based in Wollongong, Australia, with more than four decades of experience in high-power industrial microwave systems. He holds a Bachelor of Electrical Engineering from the University of Wollongong and has worked across research, consulting, and industrial deployment, including roles at the University of Wollongong's Microwave Applications Research Centre and Illawarra Technology Corporation. His career has focused on translating microwave science into robust, scalable industrial solutions across minerals processing, waste treatment, food manufacturing, textiles, and industrial chemistry. He is internationally recognised for developing and commercialising novel microwave processes, with major projects spanning PFAS soil remediation, asbestos treatment, microwave pyrolysis, rare-earth mineral processing, zero-emissions waste systems, and reversible animal stunning. McLean has authored numerous peer-reviewed papers presented at leading international conferences and is a named inventor on multiple patents covering environmental remediation, food processing, materials treatment, and electromagnetic applicator design. He is an active member of global microwave industry bodies, including AMPERE and the International Microwave Power Institute, and continues to work at the forefront of industrial microwave scale-up and applied innovation.

Processing ceramic composites using microwaves and RF at the University of Birmingham

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I have been invited to write a short article about the research being done in my research team that involves the use of microwave and radio frequency energy. Those who know me will know that this has to be associated with the processing of advanced ceramics and composites; materials with which I have been associated for over 45 years.

Historically, my team has investigated the potential for use the microwaves in a wide range of ceramic process routes – and for a very diverse range of ceramics. The processes include (but are not limited to) sintering, joining, slip casting, binder burn out and synthesis. To back this up we also devoted much time to exploring the so-called 'microwave effect' back in the 1990s and to dielectric measurements. Famously, all this work led to the publication of a deliberately controversial paper entitled *When Should Microwaves Be Used In the Processing of Ceramics* [1]. I remember presenting the paper at a conference at about the same time and had the misfortune to precede a speaker who went on to present their work on a topic that I had firmly put in the 'where microwaves should not be used category'; even more unfortunately, their results absolutely supported my hypothesis!

Since those early days we have focused on investigating those routes where I believed – and still believe – that there is a clear advantage to be had from using microwave, or RF, energy. The number one (but not the only) area has therefore been a process known as chemical vapour infiltration, CVI. In this process a gas is heated as it flows through a porous body to a temperature where it breaks down to yield a solid. As such, the process is closely related to the better-known chemical vapour deposition, CVD, which is used to produce a wide range of coatings from different gases. In CVI, in which the reactions are the same, the gas deposits a matrix inside the porous structure – the best known example is the production of commercial aircraft brakes. Methane is the gas and it flows through woven carbon fibre structures, known as preforms, that are heated to about 1000°C. The methane breaks down to yield carbon, creating carbon fibre / carbon matrix (or carbon / carbon, C / C) composites.

Although I have worked on these composites before – back in the 1990s I helped Dunlop Aviation to create a faster process for making aircraft brakes that I believe was commercialised – our work these days focuses on two main types of composites. The first are essentially carbon / carbon composites but which also contain specific ceramic powders, known as ultra-high temperature ceramics (UHTCs) [2].

Examples include quite specialised materials including zirconium diboride, ZrB_2, and hafnium diboride, HfB_2. The former composites have been demonstrated to survive temperatures of around 2500°C *combined simultaneously* with Mach 4 – 5 gas flows, whilst the latter can manage around 3000°C, again combined with hypersonic gas flows [3]. It has also been shown that our materials can survive multiple exposures to these conditions, so they exhibit reusability [4]. It won't be a surprise, therefore, to learn that these materials are being seriously considered for two main applications; hypersonics, e.g. leading edges for hypersonic craft, and the inner lining for rocket nozzles (though the latter are unlikely to need reusability!). So far, our materials have passed just about every test that has been thrown at them by potential end-users [5].

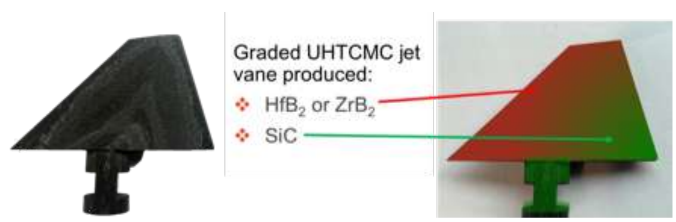
The second type of composites are made of silicon carbide, SiC, fibres infiltrated with a silicon carbide matrix; the so-called SiC / SiC composites [6]. These are now starting to be used fairly extensively in a range of aerospace applications since they can survive around 1700ºC and are much lighter than titanium- and nickel-based alloys, providing more efficient jet engines amongst many other applications.

So, what is the role of microwaves and RF? The biggest issue for the CVI process is that it is SLOW. It can take around 1000 hours to make an aircraft brake – albeit they are typically made in huge chambers that can hold up to around 1000 brakes. The problem is that the initial woven fibre preforms need heating very slowly indeed, typically at something like 1ºC min^{-1}. This is to minimise temperature gradients. Unfortunately, they still do get created and so deposition can occur preferentially in the surface layers and on the outside of the preform. This blocks the flow of the gas through the preform, slowing the process down further. The solution is to cool the system, remove all the parts, machine their surfaces to reopen the required channels, then reheat them back to the process temperature and start again. It can take 2 or even 3 of these steps before the parts are finished – in total, a period of 2 to 3 months.

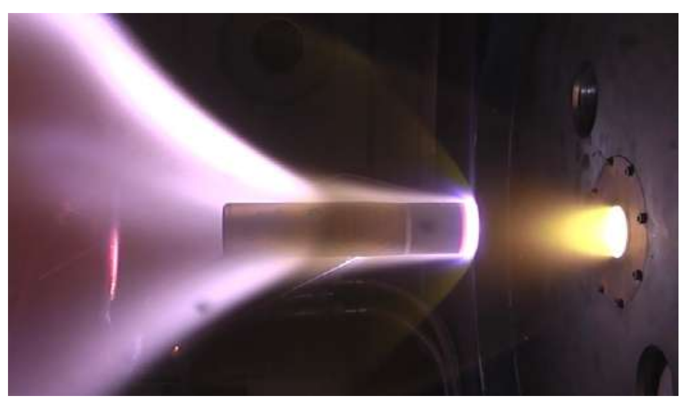
Many research teams have investigated approaches to speed the process up, including temperature gradients, pressure gradients and forced flow of the gases – including reversing the gas flow periodically. To the best of my knowledge, none have been commercialised. Our approach is to use microwaves when heating silicon carbide fibres and RF when heating carbon fibres; the two types of fibres couple particularly well with the appropriate frequency.

This means that now heating is from the 'inside-out'. What is known as an inverse temperature profile develops, i.e. the inside is hotter than the surface. Deposition therefore occurs first in or near the centre of the preform and then, as it builds up, the gases are increasingly forced through the surface layers allowing the whole preform to be infiltrated with the desired matrix [7]. For reasons that, irritatingly!, I don't know, the use of microwaves can enhance deposition times for SiC / SiC composites by about an order of magnitude, whilst RF can speed up the creation of C / UHTC composites by up to a factor of about 40. We can therefore make our hypersonic / rocket nozzles composites in as little as about 24 hours. Naturally, this is really rather beneficial for the economics of the process; whilst they are generally good when making thousands of aircraft brakes, they are less good when the component is only needed in the hundreds or less. Speeding up the process is the 'holy grail' for making components in relatively small batches.

The University of Pisa in Italy is doing some super work on scaling up the microwave CVI route to SiC / SiC composites, whilst we are focusing more on the C / UHTC composites. We can now make composites measuring up to around 30 cm in diameter and several centimetres thick – and can also produce 'graded' composites, in which the composition varies throughout the component. This allow us, for example, to put the most expensive (and dense) ceramic at the surface where it is needed and a cheaper (and less dense) ceramic further inside the component with a gradual change in composition between the two, avoiding stress build up from a sharp interface with different thermal expansions on either side.



Hypersonic jet vane and an example of the type of grading that is now possible.



The carbon fibre / UHTC composites being tested at 2500ºC in an arc-jet.

At this point I would like to introduce you to two of my research team who have done the most recent work on the C / UHTC composites; Drs Vinothini (Vinu) Venkatachalam and Rebecca (Becky) Steadman since I cannot pretend that I have done it all myself. Vinu is actually a former PhD student of mine from my Loughborough University days and, after several years in industry, she decided she couldn't live without me … – seriously, I was utterly delighted when she applied to join my group again a few years ago. Following on from a previous, and also super, postdoc, Dr Virtudes Rubio, she has worked on a range of contracts from Europe, the UK and the military. Without her the scaling up would not have happened. Becky, who is also a former PhD student but who moved straight into the role of postdoc at the end of her higher degree just a couple of years ago, has very much focused on the production of graded materials. Between them, they are a real force to be reckoned with! I have been so lucky with so many of my research team; talented individuals who are hard working and real team players – who could ask for more?!

So, where next? Much of my teams' current work is focused on ceramic composites, both the types described above as well as other types and those made by other routes. Key goals are to produce what I call a 'buffet table' of composites – with a wide range of tuneable properties that can be easily manipulated to suit whatever new application comes along – and to reduce the cost of the composites since this is a major factor holding back their exploitation. Amongst other things, we are working on oxide ceramic-based composites, also for aerospace applications, additive manufacturing of ceramic composites, joining of ceramics and composites to each other and to metals, and are currently reviewing the potential for ceramic composites in nuclear fusion. It is certainly keeping us busy!

For further reading

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About the author

Prof. Jon Binner is the Chair of Ceramic Science & Engineering in the School of Metallurgy and Materials, at the University of Birmingham. He has published over 260 research papers, as well as editing or contributing to 24 books, given around 90 keynote, plenary and invited talks at international conferences and holds 7 patents. He is a Fellow of Ampere, the European Ceramic Society (ECerS), the American Ceramic Society (ACerS) and the Institute of Materials, Minerals & Mining (IOM3). He was the President of ECerS from 2019-21, the President of the IOM3 from 2012-14 and has been the UK's representative on the International Ceramics Federation since 2011. He has supervised over 50 PhD students and even more postdocs and has won numerous prizes during his career. He is very proud of the fact that, despite working in an engineering subject, since the start of his career ~40% of his research team have been female and ~50% of them have been from ethnic minorities. He is constantly looking to improve the fraction that is female.

Ricky's Afterthought:

Data centres

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Why do we need data centres, what is the implication for energy consumption and what form of energy should be used?

With the exponential expansion of Artificial Intelligence (AI) pervading all diverse areas one requires massive data centres to store and disseminate the information and as a consequence the power requirement is huge.

Data centres are at the heart of digital technology. They are a physical facility where businesses store many servers, computer equipment and storage data enabling cloud computing, AI and the internet itself to function.

Servers

A server is a specialized computer or software system designed to provide services, data, or resources to other computers, known as clients, over a network.

These services can range from delivering web pages and emails to storing and managing files or running applications. These machines run on a client-server model, where clients request specific services or resources, and the server fulfils these requests. In addition data centres also include many rooters and switches and other hardware equipment which enable the flow of data between servers and external networks with increasing speed which necessitates more power. In short, data centres role is to process, store, and communicate the data behind the enormous amount of information that needs to be processed daily whether it be streaming video, email, social media, online collaboration, or scientific computing.

These servers require massive amounts of electricity to function which puts a strain on the ability to provide continuous uninterrupted power.

Back up generation

Data centres operate continuously so backup systems such as diesel generators or battery storage must be in place in case of an outage from the grid. Because they function continuously they generate enormous amount of heat which must be dissipated so cooling systems are used which themselves require an increasing amount of energy to function.

Type of electricity generation

The transition from fossil fuels to electricity is at the heart of what AMPERE members have been advocating for over 40 years.

For example, use of electricity for drying of textile packages is carried out by Radio Frequency (RF) particularly after the removal of as much moisture as possible by mechanical means (mangling) or putting the product through centrifuges. Ideally, the RF power should be derived from electricity generated from nuclear or renewables such as wind or solar especially as these produce no greenhouse gases. But when considering the massive amount of power required for data centres questions arise as to whether nuclear, solar or wind generated electricity would suffice. These data centres require continuous power therefore powering these by renewables may pose a problem in that wind generation depends on atmospheric conditions and solar is not always available unless the data centre is located in a desert-like environment such as the one in Reno, Nevada.

Further, as renewable energy takes much longer to bring online than building data centres, oil and gas would still have to play a major role in bridging the gap in energy supply.

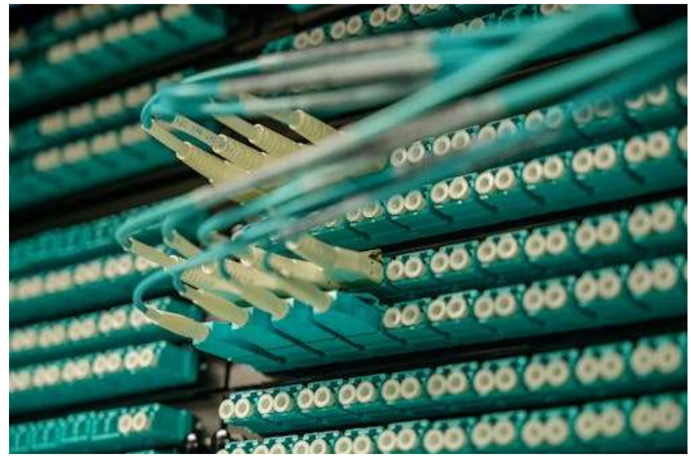
Some have advocated that as we need all the available resources for electricity generation for powering data centres, gas fired power stations alongside nuclear should continue to be used because their carbon footprint is less than that from oil or coal fired stations. Some systems use combined heat and power (CHP) systems to produce both electricity and heat from the same source. Cogeneration, as it is termed, may play a large part in powering power-hungry data centres.

Fuel cells can also be used as a power source which converts hydrogen (preferably itself generated through electrolysis powered by renewables) to produce electricity which can power a data centre (See Issue 107 July 9 2021).

Typical data centre courtesy of Pexels.

Cooling

Some AI data centres are deploying liquid cooling solutions to improve thermal management as computer workloads increase. Such an innovative method is direct-to-chip cooling which dissipates heat directly from the chip, using liquid's high thermal transfer properties allowing data centres to support higher rack densities while maximizing energy efficiency. That in itself can cause problems because the water consumption used in some data centres is extremely high, often hundreds of millions of gallons per annum which could provoke the fury of local residents once they realise that their water shortages could be blamed on nearby data centres.



An array of cables and sockets in a typical rack courtesy of Pexels.

However, air-assisted liquid cooling offers a strategic advantage for businesses aiming to harness AI and maintain a competitive edge. Combining efficient room and direct liquid cooling methods can help organizations lower energy costs, boost performance, and meet AI data centre demands. Another way to reduce the amount of water used is to deploy a closed system whereby cold water is circulated around the chips producing very high temperatures in the water which is in turn cooled by fan power behind the racks. This of course requires even more electrical power.

Large data centres

China and the USA are spearheading the data centre revolution. One of the largest is China Telecom, a large campus in Mongolia, where it is cold and allows air cooling which reduces costs, holding 50000 servers and aiming at 1million savers. In the USA the Citadel in Nevada is powered entirely by renewable energy, having a capacity of 130 MW or 55kW per rack. E-bay, Microsoft, Google, Amazon all make use of this facility for cloud, AI and e-commerce data transmission. Oracle Corporation, which has built its reputation for database management software, is heavily committed to cloud computing, and its co-founder billionaire Larry Ellison has promised to build many more data centres around the world having already 160, 6 alone in the UK. The company is spear heading its cloud-based infrastructure to serve the public sector and businesses alike.

Mark Zuckerberg remarked recently that he was going to allocate hundreds of $1b towards building and powering data centres presumably to satisfy Meta's operations and not rely on systems that serve many companies. No doubt Google, Amazon Microsoft and e-Bay have similar aims.

One of the largest and more sustainable in Europe is in Portugal run by data centre company Start Campus' called Sines. The IT capacity is about 1.2 GW powered off the grid. Currently France's Paris-Saclay facility run by Data4 aims to increase the existing data centres from 13 to 30 to be completed in 2029 with a total power capacity of 375 MW. Powered by the very powerful Villejust electricity substation it has two underground voltage lines of 90kV each. It is interconnected to over 70 telecom operators and has access to more than 150 cloud platforms. Germany has some 490 data centres while France and Italy 320 and 209 respectively. Estimates of data centres in Canada, Australia, India and Japan are all in the region 250-300.

The UK scene

Currently there are over 400 data centres in the UK and predictions are that the number in the next 10 years is set to increase tenfold. Water reservoirs are being constructed so that there is sufficient water for cooling. The electricity demand is also set to dramatically increase which may almost certainly put up the cost for local consumers, although many suggest that any increase in electricity costs should be borne by the massive companies such as Microsoft and Meta owning these data centres. Apparently the UK is only behind the USA and Germany in the number of data centres already under construction and projected into the future. Most of these are to be built near London and surrounding counties although sites in Wales and Scotland will also have data centres.

One such system is the CWL1 Vantage data centre located near Cardiff, Wales, where two data centres, and a third under construction, are powered by renewable energy. It has a capacity of 148 MW, with a direct-private 400kV super grid connection. Many investment companies are also in need of large data centres such as the Blackstone Group wishing to build a £10bn unit in Blyth near Newcastle starting in 2031 and to be completed in 3 years. It involves massive buildings occupying some 540,000 m^2. Although this is huge one must remember that old power stations are being demolished and in their place giant data centres are springing up. If truth be told it is fair to say that it would be very difficult to predict how many data centres currently exist in the UK but one estimate suggests that 13% of data centres are in London and its surroundings.

A word of caution

A note of caution must be aired on the coexistence of the huge drive of AI in many areas, which suggests exponential acceleration of energy usage, with climate ambition towards net zero. A report from the University of Cambridge suggests that this can only be achieved if the strategies for digital and climate are aligned. I suggest that similar dilemmas exist in many countries worldwide.

Postscript

In my Afterthought article in Issue 116 on AI, I mentioned the impact that Nvidia has made worldwide, co-founded by Jensen Huang currently valued at $5tn and is the leading manufacturer of high end Graphics Processing Units. Huang and his family were in Cambridge last November to be awarded The Hawking Fellowship, an honour bestowed in memory of Professor Stephen Hawking to someone who has made a significant impact on science and particularly AI. After the ceremony he and his family were hosted at the Master's Lodge at St John's College. During his visit to the UK he also met King Charles who awarded him with the 2025 Queen Elizabeth Prize for Engineering during a ceremony at St James's Palace.

2026 PhD studentship application, University of Lyon, France

Thermal and microwave-assisted catalysis for the valorisation of CO_2 and biomass model molecules

Laboratoire IRCELYON (UMR 5256) CNRS – UCBL

https://www.ircelyon.univ-lyon1.fr/en/welcome-2/

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Dr. Marilena Radoiu https://orcid.org/0000-0002-4449-7130

Background and objectives:

CO_2 capture and utilization (CCU) are means to combat global warming. Converting CO_2 to CH_4 is a practical way to recycle CO_2 and store energy in off-peak conditions when H_2 can be produced more cheaply. Properties of adsorbents-catalysts used for the sequential trapping and methanation of CO_2 (**Figure 1**), possibly assisted by microwaves (MW), will be studied. The valorization of molecules representative of biomass, such as furfural, will also be investigated through selective hydrogenation or oxidation, either thermally or though microwave heating.

Our group has been working on these topics for years and equipment is up and running [1-8]. The student will receive training in catalyst preparation, testing, *in situ* and *operando* spectroscopic investigations (**Figure 2**) and microwave technologies. This project will be a collaboration with the private company Microwave Technology Consulting (https://www.microwavetechs.com/), through Marilena Radoiu, recipient of the Irène Joliot-Curie 2023 prize (https://www.enseignementsup-recherche.gouv.fr/fr/le-prix-irene-joliot-curie-recompense-cinq-chercheuses-d-exception-93492), with privileged access to state-of-the-art microwave equipment (**Figure 2**, right). A video that nicely illustrate typical microwave-assisted reactions that would be investigated, fitting perfectly with the Festive season is available at https://sdrive.cnrs.fr/s/LeRyN23kyLcdRGX: doesn't this plasma look like Bethlehem star (until the quartz melted down...)?

Starting date: October 2026
Applicants with Engineering or Master degrees to be completed **in 2026 will be prioritized Send: (i) CV + (ii) Mark records + (iii) Motivation letter at** fcm@ircelyon.univ-lyon1.fr

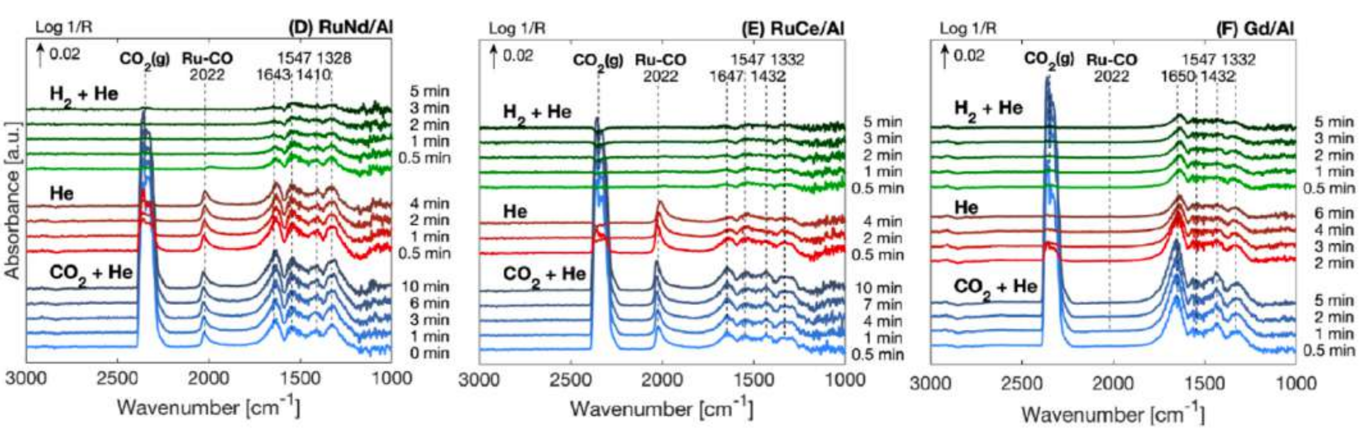

Fig. 1. Examples of operando IR spectra obtained during a collaboration with McGill University in Montreal, Canada. This technique allows monitoring species adsorbed at the surface of the sorbent and catalysts during reaction [1].

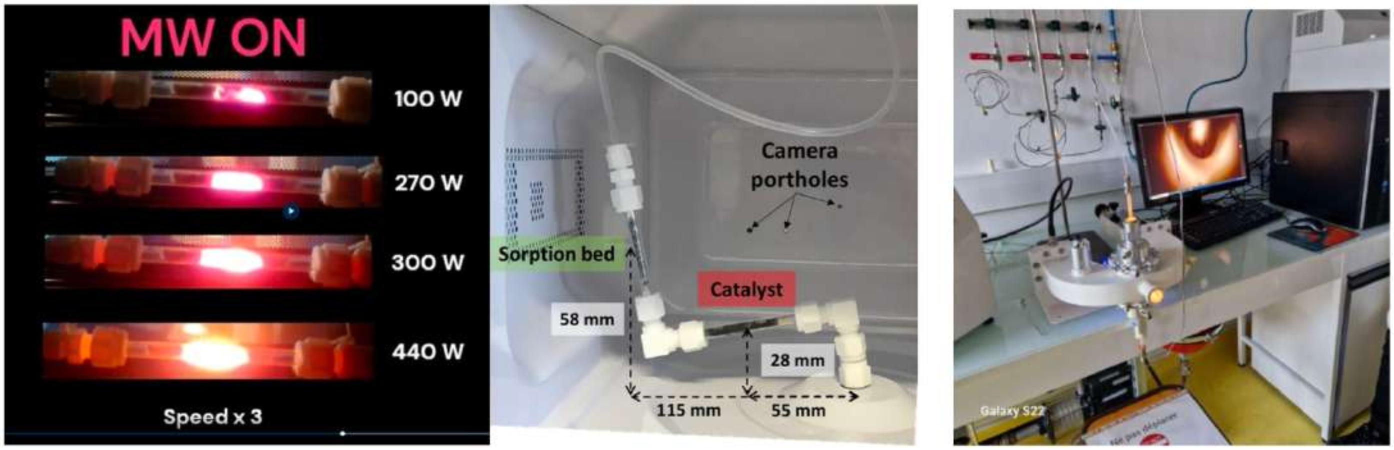

Fig. 2. (Left) Reactors under MW irradiation, video: https://sdrive.cnrs.fr/s/5gHqBEbqXtFQfoH. Photos of reactors located in (Middle) a domestic MW oven [2,3] and (Right) a research grade MW equipment (https://www.microwavetechs.com/).

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About AMPERE Newsletter

AMPERE Newsletter is published by AMPERE, a European non-profit association devoted to the promotion of microwave and RF heating techniques for research and industrial applications (http://www.ampereeurope.org).

New structure of the AMPERE Newsletter

At a management meeting during AMPERE23 it was decided that in view of the introduction of the new scientific Journal entitled "European Journal of Microwave Energy" supported by CUP, no technical papers will be published in future Issues of the Newsletter. Instead, AMPERE welcomes submissions for short bios on individuals, articles, research proposals, projects, briefs as well as news.

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