IFRF

INTERNATIONAL FLAME RESEARCH FOUNDATION

70th Anniversary 1948 2018

The First Seventy Years 1948–2018

Expanding Knowledge – Advancing Together

Contents

IFRF is:

- A not-for-profit research foundation providing the global reference point for clean, efficient and safe industrial combustion.
- Committed to promoting co-operation throughout the international combustion community, and to advancing research into applied combustion.
- Underpinned by a 136-strong network of Members (industrial companies, academic institutions and individuals) and eight National Committees: American Flame (AFRC), British Flame (BFRC), Finnish Flame (FFRC), French Flame (CF), German Flame (DVV), Italian Flame (CI), Netherlands Flame (NVV) and Swedish Flame (SFRC); an Associate Member Group co-ordinates services in other regions.
- Funded through membership fees, collaborative research programmes, and contract research and technical services provided for Members and non-Members.

Celebrating the Past, Embracing the Future

For 70 years, IFRF has pursued its mission with energy, enterprise and success.

As a centre of excellence and recognised leader in its field, it has generated, gathered and distributed knowledge, insights and information vital to making industrial combustion cleaner, safer and more efficient. While adapting to the changing scientific, technological, industrial, economic and environmental landscape, IFRF has consistently proved its value as an asset to the world's combustion community.

This publication tells that remarkable story. Reaching such a significant milestone – the 70th anniversary of IFRF's creation – provides an appropriate opportunity to look back and celebrate past achievements, while reflecting on the organisation's continuing relevance and looking ahead with confidence to the next chapter in its evolution.

But at its heart, this is an even wider story. It belongs to thousands of individuals and hundreds of organisations who have made a critical contribution along the way: Members, researchers, partners, collaborators, supporters, sponsors, administrators and more besides – from the pioneers who, in the uncertain yet idealistic post-War world of 1948, first set everything in motion, to everyone now involved and invested in IFRF as we embrace the future from our new base at the University of Sheffield in the UK.

Sharing, co-operating, networking: these have been the hallmarks of the IFRF philosophy – from research programmes that our Members have helped to direct and deliver, to education and training initiatives that have disseminated knowledge and shaped new generations of engineers and researchers, to consultancy, technical and information services extending the benefits of our work far and wide.

Today, our underlying aims and ambitions are the same as they have always been: to drive research forward, to tackle existing and emerging combustion challenges, and to unlock new opportunities for the combustion community. The need for IFRF is as great as ever – and it remains a need that can best be met by advancing together.

Our story is your story. It is, then, our great pleasure to share it with you.

Philip Sharman
IFRF Director

Through the Decades

From its role in building a new blueprint for international co-operation in the aftermath of the Second World War, to its non-stop drive to identify and shed light on key issues in industrial combustion and heat transfer, IFRF has survived and thrived in an ever-changing, ever-challenging world.

1940s...

As post-War Europe picks up the pieces, the need for renewal and modernisation is clear – especially in an iron and steel industry tasked with rebuilding a continent. Cutting costs and boosting efficiency is vital but research funding is limited, so KNHS (the Royal Dutch Blast Furnaces and Steel Company, 'Hoogovens'), IRSID (France's Iron and Steel Research Institute) and BISRA (the British Iron and Steel Research Association) discuss the scope for collaboration. In November 1948, they agree to proceed on an informal basis. A joint programme of experiments gets under way at KNHS's IJmuiden site in the Netherlands.

1950s...

Drawn from the three partner organisations, a resident research team is established at IJmuiden. A major new oil- and gas-fired furnace (Furnace No.1) is installed, followed by a coal-fired furnace as the range of research expands to include coal-fired combustion and non-steelmaking applications. Core European funding is secured and provides a more stable financial foundation for the venture, whose membership base broadens as more countries begin to come on board. The deed is signed that formally creates IFRF.

1960s...

IFRF continues to forge a growing global reputation. The emphasis of research evolves as combustion aerodynamics becomes a key focus, and an aerodynamics laboratory is installed. The scope of work extends to natural gas combustion following discovery of gas fields in the northern Netherlands. More countries join the organisation and the first-ever IFRF Conference takes place. Technical Panels increasingly add an extra dimension to the pool of knowledge that IFRF can access and to the effective dissemination of its research findings.

1970s...

As the need to cut pollution climbs the global agenda, IFRF targets damaging emissions caused by power generation and industrial combustion. To tackle emissions of oxides of nitrogen (NO_X), IFRF develops in-furnace NO_X reduction technologies and mathematical models of NO_X formation. A spin-off from this work – contract R&D (e.g. the testing of low-NO_X burners) – creates a new revenue stream that complements the development of technical services for Members. Major new international customers harness IFRF expertise.

1980s...

As work on NO_X reduction continues, the need to tackle oxides of sulphur (SO_X) opens another front in the battle to cut emissions and, using its new Isothermal Plug Flow Reactor (IPFR), IFRF engages in leading-edge research on sulphur dioxide (SO_2) capture. A series of 'firsts' sees IFRF's first participation in major European Commission (EC) and other international programmes, its first involvement in establishing and leading industrial research consortia, and delivery of its first-ever training course and inaugural Topic Oriented Technical Meeting (TOTeM).

1990s...

Extensive upgrading results in a new $5MW_{th}$ Furnace No.1 and $60kW_{th}$ IPFR, enhanced computing facilities and installation of cutting-edge laser diagnostic tools. IFRF delivers innovative low-NO_X burner technology, new insights into the scaling of combustion systems, specialised software to aid burner and boiler design, and important work on biomass combustion. The IFRF Coal Database (later expanded to include a broad range of solid fuels and rebranded as the IFRF Solid Fuel Database) is established. In 1998, restructuring sees the organisation divide into IFRF Information Exchange and IFRF Research Station BV.

2000s...

Key areas of activity include mathematical modelling, burner scaling, NO_X reduction and carbon dioxide (CO_2) reduction. In 2006, IFRF moves to a new home: Enel's research facility at Livorno, Italy. Core facilities there include the new FOSPER (FOrnace SPERimentale) furnace. Solid-fuel characterisation continues and the IFRF Solid Fuel Database begins its evolution into an online resource, strengthened by improved understanding of novel combustion techniques and co-combustion of fossil fuels with biomass. A long-established IFRF specialism – development and manufacture of in-flame and in-furnace measurement and sampling probes – gains fresh momentum.

2010s...

Alongside input to major European programmes, IFRF contributes to the development of innovative ultra-low-NO_X burner technology, explores the formation of inorganic aerosols, produces probes for oxy-firing and novel combustion processes, and widens its work on characterising biomass fuels. Enel's move away from 'traditional' combustion technologies necessitates another relocation exercise and the UK's University of Sheffield becomes IFRF's third host organisation. In 2017, a new phase begins in IFRF's long, productive and distinguished history – just ahead of its 70^{th} anniversary in 2018.

Seven Key Achievements

Seven decades of leading-edge science and technology have generated breakthroughs and advances of huge value not just to the international combustion community but also to the economy, the environment and wider society. Here is just a selection of IFRF's most significant achievements from 'the first 70 years':

Pioneering Understanding: **Flame Science**

Back in 1948, fundamental understanding of combustion processes was very limited. But trailblazing work at IFRF's IJmuiden research station was to change everything, delivering a body of knowledge that helped to underpin the progress later achieved by combustion engineers and researchers worldwide. A key focus was a topic crucial to furnace and boiler efficiency: flame emissivity (flames' effectiveness at emitting heat).

Between 1949 and 1959, a series of in-furnace trials on oil and gas flames delivered a succession of important discoveries. For instance:

- **The impact of fuel type on flame radiation was demonstrated; so too, for oxygen-enriched flames, was the effect on flame emissivity of changing the distance between the burner and the point of oxygen injection.**
- **Steam or air gave momentum to the fuel jet, allowing it to entrain combustion air and also recycle combustion products to ignite fuel entering the furnace; this provided a basis for ensuring stable ignition and controlling flame length, for example.**
- **Experiments revealed the importance of the recirculation region that formed in the furnace and identified factors affecting rates of soot-particle combustion in oil flames.**

Between 1956 and 1960, IFRF began a parallel series of trials on pulverised coal, including full 3-D mapping of a pulverised-coal flame. The trials enabled interpretation of the fluid dynamics at work within both flame and furnace, and investigation of key phenomena such as the combustion of volatiles.

These pioneering programmes that marked IFRF's early years achieved insights that were to prove vital to propelling IFRF's own work forward – and to informing the future direction of global combustion research.

Game-Changing Technology: **NO_X Reburning**

In the 1970s, the need to tackle NO_X emissions – key acid-rain precursors and contributors to ground-level ozone – became part of clean air agendas and wider environmental initiatives that increasingly gained global traction. For the combustion community, the challenge was to reduce NO_X formed during the combustion process as a result of oxidation of nitrogen chemically bound to coal and the reaction of nitrogen in combustion air with excess oxygen in the furnace or boiler.

IFRF was at the forefront of efforts to understand the problem and find solutions capable of mitigating it:

- **After an initial desk study, a fundamental investigation quantified the impact of a range of combustion-process parameters on NO_X production.**
- **This data helped to frame optimum operating conditions for implementing NO_X reburning technology (the incorporation of a separate 'reburn zone' in the furnace/boiler where fuel-rich conditions would enable conversion of NO_X into harmless nitrogen).**

This influential work on reburning pinpointed the vital role played in NO_X reduction by temperature, secondary stoichiometry and residence time, as well as the more minor role of factors such as coal type and particle size distribution. The findings provided the basis for semi-industrial-scale experiments on Furnace No.1 that used as the reburn fuel both gas (for 'gas-over-coal' reburning) and coal (for 'coal-over-coal' reburning).

This platform of research was crucial to accelerating the development of NO_X reburning technology and facilitating its emergence as a viable option for the international combustion community.

Innovative Design: Low **NO_X Burners**

In the drive to develop effective responses to the challenge of NOx emissions, IFRF delivered a succession of important advances in low-NO_X burner technology:

- **Externally Air-Staged Low-NO_X Burner**
  In 1972, IFRF developed the first prototype of this novel burner design, fired using pulverised coal. To ensure a high level of emissions control, a series of trials helped to frame design and operational guidelines covering a range of coal types. Incorporating a coal injector, a swirling combustion air stream and 32 air injectors, the prototype evolved into the commercial Staged Mixing Burner later developed by Steinmüller GmbH and tested at the IJmuiden research station. During the 1980s, IFRF carried out a number of experiments to optimise the performance of this class of low-NO_X burner.
- **Aerodynamically Air-Staged Low-NO_X Burner**
  In the mid-1980s, IFRF trials led to development of a new type of burner that achieved air-staging by harnessing fluid mechanics, rather than relying on external ports for the introduction of the combustion air. The design comprised (i) a central injector for the coal and (ii) a swirling air stream; this simplicity was central to its appeal. Exploiting the chemical environment within the internal recirculation zone was key to the burner's ability to offer potentially greater NOx reduction than the Externally Air-Staged Low-NO_X Burner – potential that was exploited successfully by commercial manufacturers.
- **Internally Fuel-Staged Low-NO_X Burner**
  In the 1990s, IFRF developed a new approach to NO_X emissions control that built on the concept of reburning. Its first design of an Internally Fuel-Staged Low-NO_X Burner was based on the reburn fuel's penetration of the primary flame's internal recirculation zone; this subjected the reburn fuel to very high temperatures and very high heating rates, maximising production of the radicals that reduced NO_X production in the primary flame. A wide-ranging IFRF study confirmed the substantial potential of this innovative design as a NO_X reduction option.
- **Ultra-Low-NO_X Hydrogen-Fuelled Burner**
  In 2012, IFRF became a partner in a ground-breaking project that continued to extend the frontiers in the field of NO_X control. Funded by Italy's Regione Veneto and its Ministry of the Environment, this initiative developed and tested prototypes of an innovative burner design fuelled by hydrogen – with the aim of keeping NO_X emissions below 100mg per Nm^3 by applying reduced inert in-flame injection. IFRF's role included carrying out aerodynamic tests to characterise burners and furnace liners, and taking measurements using Laser Doppler Velocimetry (LDV – see below).

Trailblazing Techniques: **Laser Diagnostics**

An enduring aspect of IFRF's work has been its tireless development of new ways of measuring combustion flames more accurately and comprehensively. In the 1980s, efforts focused on exploiting opportunities and possibilities presented by laser technology. Specifically, the primary aim was to pioneer the application of laser diagnostics on a bigger scale, taking techniques beyond the laboratory and into the realm of semi-industrial and industrial flames. Major successes were secured in:

- **Laser Doppler Velocimetry (LDV)**
  Also known as Laser Doppler Anemometry (LDA), this technique uses the Doppler shift in a laser beam to measure fluid velocity non-invasively. Problems had traditionally been encountered when trying to apply LDV at larger than laboratory scale, but the arrival in the mid-1980s of laser velocimeters incorporating optical fibre links offered a potential solution. Harnessing this approach, IFRF developed and took to market a water-cooled LDV probe that was the first of its kind. Its capabilities included measuring both velocity and turbulence within industrial-scale flames quickly and easily – a genuine game-changer in the field of flame diagnostics.
- **Laser Sheet Visualisation (LSV)**
  This technique uses laser light to show a 'slice' of a complex fluid flow pattern. In the 1990s, IFRF adapted an LSV technique – Mie scattering – to the needs of industrial research. Mie scattering involves feeding marker particles into the flow stream and then illuminating the area to be visualised using pulses of laser light; the light scattered by the flow can then be filmed, with the pictures processed using specialised software to deliver the required quality. Suited to both scientific and engineering research, the technique has proved especially effective at revealing interactions between flows, jets and sprays inside burners, and at shedding light on particle mixing.

Such breakthroughs were not only significant in their own right and in assisting the development of low-NO_X burners; when exploited in tandem with 'traditional' flame-probing techniques, they also enabled important advances in understanding combustion processes.

Breaking the Mould: **Mathematical Modelling**

In the field of combustion research and the design of new, improved combustion technology, arguably no development has had a greater impact than the ability to simulate combustion processes computationally with increasing accuracy and sophistication. Beginning in the 1980s, IFRF built up an enviable reputation as a pioneer in this area.

By developing, refining, validating and applying leading-edge mathematical modelling techniques, this work added a new dimension to knowledge and understanding, and laid the foundations for industry-standard tools such as ANSYS Fluent computational fluid dynamics (CFD) software.

- **Early initiatives focused on the modelling of pulverised-coal flames, which involved modifying the basic Fluent code and then generating predictions for a range of in-flame measurements.**
- **Modelling work then extended into areas such as NO_X prediction, while also embracing 'off-specification' fuels such as coal-water slurries, pulverised wood, wood char and petroleum coke.**
- **The 1990s saw IFRF enhance its ability to simulate boilers, flames and furnaces on an unprecedented scale. New software packages – using coal characterisation and in-flame data generated by IFRF – generated insightful simulations of full-scale utility boilers and enhanced capabilities in computing in-furnace radiative exchange, for example.**

Underpinned by the ready availability of in-flame, in-furnace and fuel characterisation data critical to model validation, IFRF emerged as an acknowledged global authority that would continue to drive forward leading-edge combustion modelling into the 21st century.

New Tools for Industry: **Analytical Probes**

From its earliest days, IFRF recognised that the ability to develop robust, reliable in-flame and in-furnace measurement and sampling techniques would be central to its success. Work in this area was driven by a whole host of requirements – from accurate analysis of combustion processes, to informing furnace design and validating mathematical models.

As a result, the design and manufacture of analytical probes became a core IFRF activity, with a remarkable array of innovative probes developed for industrial applications and many of these establishing themselves as industry-standard instruments.

Early IFRF breakthroughs in industrial-flame measurement were collated in the book 'Measurement in Flames', published in 1972; this soon became recognised as a classic in its field. But it merely proved to be a springboard for further relentless effort and advancement over the following decades – with Furnace No.1 at IJmuiden and Livorno's FOSPER facility especially proving invaluable in the design and development of novel types of probe.

The inventory of IFRF-designed analytical probes includes:

- **A water-cooled suction pyrometer for flame-temperature measurement.**
- **A phase Doppler particle analyser for spray characterisation.**
- **Gas samplers, ellipsoidal radiometers, slag deposition probes and other flame-sampling devices for determining flame chemistry.**
- **A suction probe for in-flame Fourier Transform Infrared (FTIR) analysis, aiding the study of minor species.**
- **A quartz-tipped probe enabling utilisation of optical diagnostic combustion (ODC) technology in oxy-/recycled-flue-gas combustion regimes.**

Accommodating, anticipating and adapting to real-world requirements, IFRF's fundamentally practical approach to meeting challenges in this area has resulted in probes that have proved their value around the world and across the decades.

Information Dissemination: **The IFRF Solid Fuel Database**

When the IFRF Solid Fuel Database (SFDB) was made available online in 2010, it marked another key milestone in the ongoing development of an invaluable information resource – a resource that, for over 20 years, has proved hugely beneficial to, among others, designers and operators of industrial solid-fuel-fired combustors and gasifiers.

Its roots are to be found in the coal characterisation experiments launched at IFRF in the 1980s to underpin a range of burner development and mathematical modelling projects. The IPFR at the IJmuiden research station played a central role in these experiments.

The IFRF Coal Database (as it was originally known) incorporated data on coal devolatilisation, char combustion and nitrogen release for an extensive range of coal samples. It then expanded steadily through the years. In the 2000s, this already huge data repository grew to include not only bituminous, anthracitic, lignitic and sub-bituminous coals but also biomass, sludges, wastes and blends. Concerted efforts were also made to collect, process and add data from IFRF Members, as well as information obtained from other databases and through literature reviews. A significant advantage of the SFDB over other available online fuel databases is the inclusion of details of the experimental rigs and operating conditions used in generating the data – very useful to both designers and modellers.

The database that finally went online in 2010 offered Members robust, wide-ranging data on over 200 different solid fuels. Since then, it has continued to grow and improve – a unique, easy-to-access, easy-to-use resource and an undoubted asset to the international combustion community.

In the Picture: Past, Present, Future

IFRF locations

IJmuiden the Netherlands
(1948–2005)

Livorno Italy
(2006–2016)

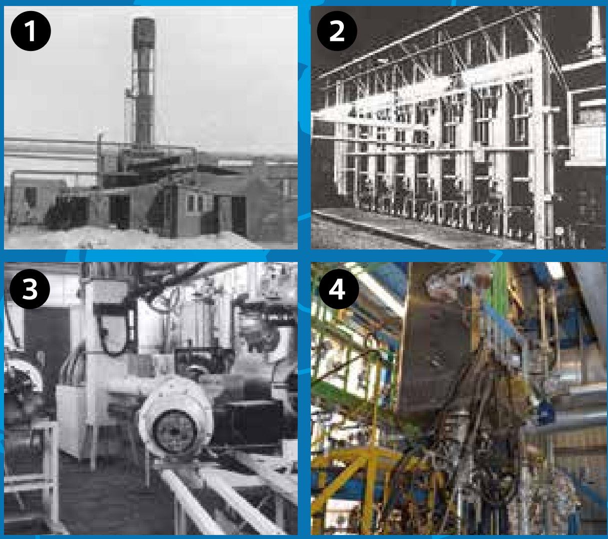
Sheffield the UK
(2017–present)

Sheffield, the UK (2017–present day)

1 IFRF's current base: the Sheffield Bioincubator
2 PACT's post-combustion carbon capture plant
3 IFRF's future home: the PACT-2 development
(artist's impression)

The Netherlands
IJmuiden
Italy
Livorno

IJmuiden, the Netherlands (1948–2005)



1 KNHS experimental furnace, c.1950
2 Furnace No.1, c.1955
3 Aerodynamics laboratory, 1965
4 IPFR, originally commissioned in 1983

Livorno, Italy (2006–2016)

1 IFRF research facility
2 FOSPER facility
3 Inserting an IFRF suction pyrometer into FOSPER, 2006

Chapter One: **The IJmuiden Era**

If any document can claim to be IFRF's 'founding charter', it is a note produced on 22nd November 1948 by BISRA's Dr Meredith Thring and entitled 'Proposals for the Establishment of an International Research Project on Luminous Radiation'. This was the initial catalyst leading to the three-country collaboration (see p.4) that launched its first series of experiments early in 1949 using a new KNHS industrial-scale experimental furnace on the IJmuiden site.

The initial objectives were to improve the performance of open-hearth furnaces and to boost flame emissivity – issues of critical importance to the iron- and steel-making industry. Recognising the need to study combustion and heat transfer in a holistic way, a combination of performance and combustion-mechanism trials explored luminous radiation and its role in furnace efficiency and in oil-flame and gas-flame emissivity. As this work evolved over the next few years, a body of knowledge began to build up that would provide a foundation for advances in burner and flame engineering for decades into the future.

The new organisation rapidly developed formal structures and began widening its reach to include more countries, with National Committees established in the USA (1952) and Belgium (1953). It also sought the additional sources of financial support vital to its long-term future and its ability to develop the new, world-class experimental facilities that its research would require. With core funding successfully secured from the European Coal and Steel Community (ECSC) – itself only formally established in 1951 – the fledgling IFRF now had the security and confidence to invest in the new oil- and gas-fuelled Furnace No.1, which was joined a little later by a pulverised-coal-fired furnace as the scope of work continued to expand.

Technical Edge

Furnace No.1

Officially 'lit' in October 1953, this brand new furnace was a statement of intent that IFRF would be a major player in pioneering combustion research. The facility would also act as the centrepiece of the IJmuiden research station and, crucially, enable a broadening of research themes to include a growing number of industrial applications. Incorporating a chamber measuring 2m x 2m x 6.25m and designed to work with a wall temperature of up to 1600°C, the furnace was equipped with multiple slots/ports enabling access for analytical probes. In 1991, it was eventually replaced by a new Furnace No.1 equipped with a vertical scrubber – another flagship IFRF facility until its eventual decommissioning in the mid-2000s.

The pressing need to improve understanding of in-furnace fluid mechanics soon triggered initiation of an influential new series of studies into the aerodynamic parameters governing recirculation inside furnaces. Similarly driven by urgent requirements, the development of specialised instruments for taking a range of in-flame and in-furnace measurements also established itself as a core activity in these formative years.

Snapshot

1955

On 12th November, a deed is signed creating the International Flame Research Foundation as a non-profit-making organisation and finally giving IFRF a formal, legal footing........ The same day sees inauguration of the new 1.5m x 1.5m x 10.5m pulverised-coal furnace designed to operate at temperatures up to 1500°C, following a decision three years earlier to extend research to include coal combustion........ During the course of the year, pioneering performance trials examine the effect on oil and gas flames of using preheated combustion air.

As IFRF moved into the 1960s, combustion aerodynamics evolved into a pivotal theme within the overall research programme. This new emphasis began by focusing on non-swirling jet flames, especially with regard to their entrainment and the way they interacted with the furnace. Subsequently, 'swirl' was introduced to explore how this could stabilise flames and improve the in-furnace mixing of fuel and air. Other work based on furnace experiments and isothermal models led to the observation of new flow patterns, with comparisons made between isothermal and combusting flows, and methods were developed for producing flames with specific fluid-flow characteristics.

As ever, developments reflected the research interests of IFRF's steadily widening membership, and new National Committees were formed in Germany (1962), Italy (1965) and Sweden (1967). Progress was also made possible by construction of additional cutting-edge facilities on the IJmuiden site – including installation of a new aerodynamics laboratory in 1965. Increasing emphasis on research into natural gas combustion, meanwhile, led to a growing portfolio of experimental work in this field; much of this was undertaken on behalf of, or in collaboration with, the Shell Research Station at Egham in the UK.

Snapshot

1969

In May, IFRF hosts its first-ever Conference, attended by around 120 delegates and including presentation of 18 technical papers........ Natural gas combustion trials continue, now with a focus on natural gas flames with swirl........ Coal trials continue with investigations into the combustion and devolatilisation behaviour of non-swirling pulverised-coal flames........ Produced by Professor Hoyt Hottel (USA), 'A Proposed New Statement of Objectives of the IFRF' proves influential in shaping research directions (e.g. by highlighting the key role for computer programming in furnace design).

The sharpened environmental focus that characterised the 1970s would have a fundamental impact both on the thrust of IFRF's research and on its continuing development as an organisation. Above all, with the development of in-furnace NO_X reduction technologies and the use of mathematical modelling to explore NO_X formation and pollution reduction techniques, IFRF's work assumed an increasingly 'near-market' character.

In addition to a growing portfolio of work for industry – including 0.5-33MW burner scaling trials for the UK's Central Electricity Generating Board, and trials on the combustion of residual coal and coke in gas-turbine exhaust gases in conjunction with German company Vereinigte Elektrizitätswerke Westfalen – the US Environmental Protection Agency emerged as a major new customer. Numerous low-NO_X burner trials carried out on Members' behalf added a further dimension to IFRF's work, dovetailing with the design and development of innovative low-NO_X technology. The formation of a National Committee in Japan (1977) also provided confirmation of the ever-extending scope, reach and relevance of IFRF's activities.

Chapter One: **The IJmuiden Era** (continued)

The 1980s saw environmental issues remain at the apex of IFRF's research agenda. Continuing activity in the field of NO_X emissions – especially in burner design and reburning technology – was supplemented by the response to an urgent new priority: finding effective ways of combating SO_X emissions, as the catastrophic effects of acid rain on forests, buildings and aquatic environments became increasingly apparent around the world.

A key enabler of IFRF's work in this new sphere, the newly built IPFR, explored the use of calcium sorbent injection options for the direct capture of SO_2 produced by combustion processes, as part of a collaboration with German and French companies. This state-of-the-art rig was to further underpin IFRF's reputation for delivering world-leading research through investment in cutting-edge experimental facilities – a reputation also reinforced by significant extension to IFRF's computational capabilities.

Technical Edge

Isothermal Plug Flow Reactor (IPFR)

Built in 1982 and commissioned the following year, this 80mm x 2m facility incorporated a primary fuel-rich zone and a secondary burnout zone; both zone residence time and stoichiometry could be varied. The IPFR's first task was to study the combustion performance of four different coals in order to identify optimum zone characteristics, and its major role in the field of sulphur capture was to be complemented by its support for work on power utilities' fuel-blending practices.

In 1994, a new 4.5m 60kW$_{th}$ drop-tube IPFR replaced the existing facility. The new reactor proved of enormous value – particularly in the field of coal characterisation, being used to test the combustion characteristics of an enormous range of coals ranking from anthracite to lignite, as well as alternative fuels including biomass, sewage sludges and a variety of waste materials and plastics. The facility was dismantled and shipped to Livorno when IFRF relocated there, prior to recommissioning in 2009.

This decade, which had begun with the establishment of a Finnish National Committee (1980), was soon to see IFRF's participation in major international research programmes – above all, the International Energy Agency's (IEA's) Coal Combustion Sciences Programme and the EC's non-nuclear energy research and innovation programme (JOULE) and clean coal technology programme (APAS); this signalled that a new phase in the IFRF story had begun. So too did involvement in research consortia such as the Natural Gas NO_X Group, which focused on glass-melting furnaces.

Snapshot

1989

IFRF's first 'Topic Oriented Technical Meeting' (TOTeM), held in Amsterdam, focuses on NO_X, nitrous oxide and soot/polyaromatic hydrocarbons........ Air pollution furnace trials address the effect of mixing on coal fuel-staging, and also investigate combustion of fuel blends in an Aerodynamically Air-Staged Burner........ Coal characterisation experiments explore the combustion performance of bituminous coals........ A new mathematical modelling project examines near-burner-zone properties of swirling flames from pulverised coal.

As the 20th century headed towards its conclusion, IFRF built further momentum on a host of fronts. Crucially, this was made possible by investment in a programme of comprehensive facility upgrading, including a new Furnace No.1 and a new IPFR, as well as installation of a phase Doppler particle analyser, progressive strengthening of on-site computational facilities and installation of an array of laser-based tools, including LDV and LSV.

Alongside further numerical simulation and software development work, burner tests, work on in-furnace NO_X control, and provision of technical services, the 1990s saw new research priorities emerge. A primary example was the scaling of combustion systems, including the major Scaling 400 study – involving British Gas and four US organisations, this explored the scaling of laboratory-scale and semi-industrial-scale natural gas and pulverised-coal flames from $30kW_{th}$ to $12MW_{th}$, with a focus on their near-field aerodynamics. Three new European Commission-funded consortia were also launched: CEMFLAME, exploring fuel use in cement kilns; OXYFLAM, focusing on oxy-combustion of natural gas; and the EUROFLAM training consortium.

The 1990s also witnessed further advances on in-furnace NO_X control, including development of the Internally Fuel-Staged Burner and optimisation of reburn jet penetration and mixing. Other areas of focus included tangentially-fired boilers and the combustion/pyrolysis of biomass and waste materials. Technical service contracts included work on direct reduction of iron ore, while work under JOULE and APAS now addressed the combustion of pulverised coal with oxygen and recycled flue gases, the co-firing of pulverised coal with shredded straw and sewage sludge, and atmospheric combustion of pulverised coal and coal-based blends for power generation.

Snapshot

1994

The new IPFR is installed and commissioned........ Pilot-scale tests continue on the direct reduction of iron ore in a cyclone converter furnace........ $1.3MW_{th}$ burner tests are undertaken as part of the Scaling 400 study........ Air pollution experiments focus on the NO_X reburning effects of coal properties........ Advanced power generation experiments explore the combustion of pulverised coal with recycled flue gas and oxygen........ Modelling work focuses on NO_X predictions in gaseous and pulverised-coal flames.

Into the new millennium, core activities continued, existing priorities were pursued and three new consortia began work: MECBURN (looking at advanced burner design for clean, efficient gas-fired commercial/industrial boilers), BioFlam (focusing on CO_2 reduction through use of short cycle, carbon-containing fuels) and PowerFlam (addressing the co-firing of pulverised coal with biomass and wastes). Other projects included HEC-EEC (High Efficiency Combustion-Excess Enthalpy Combustion), co-funded by the Dutch Government, and CAFENOX (Cost Abatement for Efficient NO_X Reduction in Pulverised Fuel Coal-Fired Power Plants), co-funded by the European Commission.

The new century was also to bring a major new challenge and a real watershed in IFRF's history. A planned merger between the owners of the IJmuiden site, Hoogovens (formerly KNHS), and British Steel inevitably meant new plans for the site – and the need for IFRF to find a new host organisation as the activities of the IJmuiden research station gradually wound down.

IFRF already had strong links with Enel, the Italian multinational energy company, which was both a member of the Italian National Committee and a partner in the EUROFLAM consortium. Enel's offer to host IFRF at its research facility in Livorno was therefore accepted enthusiastically. In 2006, IFRF successfully relocated to a new home where it would benefit from an outstanding suite of experimental facilities and strong links with the nearby University of Pisa.

Chapter Two: **Ten Years at Livorno**

By September 2006, IFRF had completed its move to Italy and was ready to embark on a new era in its history.

At its new headquarters, it had ready access to an impressive range of equipment. As well as Enel's own array of semi-industrial-scale combustion test facilities, this included the IPFR, which was shipped to Livorno for rebuilding, upgrading and recommissioning, and a newly constructed IFRF facility known as FOSPER.

With the close involvement of Members, IFRF swiftly initiated a new suite of research activities focusing, for example, on combustion modelling, benchmarking and validation, as well as on solid fuel characterisation (work that fed directly into the IFRF Solid Fuel Database and ensured it remained a unique, ever-expanding resource of immense practical value to users). The move to Italy also provided the opportunity to convert IFRF's archive of over 3000 documents into electronic format, complemented by an automated online search engine and creating an outstanding new information service for Members.

Technical Edge

FOSPER (FOrnace SPERimentale)

A 5MW$_{th}$ replica of IJmuiden's Furnace No.1, FOSPER served as one of IFRF's premier test facilities during the Livorno years. The furnace was used, for example, to test a variety of burner configurations and fuels, with measurements including velocity profiles, temperature, gas composition and solids distribution (both in-flame and along the furnace). It also played a vital role in the design/testing of analytical probes and instruments for IFRF's own use and for industrial applications. After being upgraded to oxygen operation, enabling it to undertake oxy-gas and oxy-coal campaigns, it established itself as one of the world's few experimental rigs capable of allowing access to oxy/recycled-flue-gas/coal and oxy/recycled-flue-gas/gas flames at 2-3MW pilot scale, while also delivering practical experience in the firing of solid fuels in oxy/recycled-flue-gas atmospheres.

New momentum was given to IFRF's activities in the field of training, including re-establishment of the School of Industrial Combustion, while a significant spin-off from IFRF, the collaborative European Flame Research Initiative (EFRI), set out to share information about test rigs and flame measurement capabilities. Concerted efforts were also made to maintain and boost IFRF's capabilities in probe manufacture and the development of new instrumentation adapted to new combustion concepts. A valuable by-product of probe-related work was the introduction of a specialist service, available to both Members and non-Members, for undertaking on-site tests of combustion equipment.

Snapshot

2009

The IPFR is recommissioned........ FOSPER is upgraded to oxygen operation........ IFRF's Members' journal is relaunched as 'Industrial Combustion'........ The first-ever IFRF Conference is held on US soil........ Three online forums are established to facilitate Members' research and the work of EFRI........ The Validation & Verification and Uncertainties Quantification (V&V-UQ) approach begins to be circulated through the IFRF community.

From 2010, oxy-fuel combustion emerged as a main focus of research as IFRF continued to open up research horizons in response to the changing energy landscape. Oxy-combustion tests were run for a number of organisations, and specific studies not only assessed oxy-gas and oxy-coal but also broke new ground with, for example, experiments that fired solid fuels in oxy/recycled-flue-gas atmospheres. A report was published on the retro-fitting of oxy-fuel technology in semi-industrial plant, and probes were developed for oxy-firing and other oxy-combustion and novel combustion technologies.

Another major development in the new decade saw IFRF secure partner status in two important European Commission 7th Framework Programme initiatives, and play a prominent role in a third:

- **RELCOM** (Reliable and Efficient Combustion of Oxygen/Coal/Recycled-Flue-Gas Mixtures):
  As well as taking on a dissemination role, IFRF led research into scale-up criteria for oxy-coal burners; involvement also enabled IFRF to further develop its research into oxy-combustion.
- **BRISK** (Biofuels Research Infrastructure for Sharing Knowledge):
  This resource/facility-sharing initiative in the field of thermochemical biomass conversion generated data that was fed into the IFRF Solid Fuel Database (as was RELCOM data).
- **DEBCO** (Demonstration of Large-scale Biomass Co-firing and Supply Chain Integration):
  IFRF assumed a dissemination role in this initiative, which focused on increasing the share of biomass in coal/biomass co-firing at fossil fuel power plant.

In addition to the development of an ultra-low-NO_X hydrogen-fuelled burner, other technical advances and important new insights were secured on topics such as the formation of inorganic aerosols and, using Enel's Turbina Accesso Ottico (TAO) 400kW_{th} optical test rig, hydrogen combustion in gas turbine burner cans.

While fuel characterisation work extended to incorporate biomass-based fuels, the Biopower in Tuscany project saw IFRF perform in-flame measurements of temperature and chemical species distribution in the combustion chamber of a biomass system fed with a range of biomass fuel types. A further European programme called OnCorD (Online Corrosion Diagnostics) involved thorough investigation of corrosion mitigation in pulverised-coal and circulating fluidised bed (CFB) power plants fuelled with biomass in combination with coal, aiming to enhance understanding of corrosion in power plant furnaces.

Such widening horizons and diversifying interests were reflected in the upweighting of IFRF's 'Monday Night Mail' e-newsletter to include a twice-monthly international news round-up, and the opening up of IFRF membership to individuals such as professionals, students and retirees. The Livorno years were also characterised by multiple industrial collaborations and the securing of numerous contracts for the provision of technical services, involving work on rigs at Livorno and on-premise testing campaigns at clients' sites. Those working with and benefiting from IFRF expertise included Andritz Oy, Endesa, SSV, CIUDEN and ENEA.

In 2016, IFRF's hosting agreement with Enel came to a close as the Italian organisation's strategic focus turned towards renewable energy and power grids. Once more, a new host organisation had to be identified – one that could deliver stability for IFRF as well as a basis for maximising its future potential.

Chapter Three: **A Secure Future at Sheffield**

In January 2017, the establishment of not-for-profit organisation IFRF Ltd signified that a brand new phase in IFRF's history was under way.

Following a selection procedure that had started at the end of 2015, the University of Sheffield became IFRF's new host organisation. Archives, practices, processes and a range of equipment were transferred from Livorno efficiently and effectively, enabling the third and latest chapter in our story to begin.

The University's connections with IFRF have a very long and distinguished pedigree, reaching right back to the very earliest days of our organisation. But those strong ties to the past – and the endurance of many core IFRF features, capabilities and priorities – are now reinforced by a new mission integral to our move to Sheffield: delivery of a fresh, flexible, cost-effective new approach to IFRF operations. A powerful combination of continuity and change is creating a novel, unique and above all relevant offering that will enable the organisation to look to the years ahead with renewed confidence and vitality:

Continuity

The primary focus of IFRF is now on networking functions as we seek to strengthen communication, co-operation, collaboration and information dissemination across national, organisational and disciplinary boundaries, while delivering the suite of tried-and-tested services that have proved of enduring value to our Members down the years and decades. These services include:

- **A searchable, comprehensive online archive of IFRF reports and IFRF conference and workshop presentations.**
- **Our 'Monday Night Mail' e-newsletter, our 'Industrial Combustion' peer-reviewed online journal and our online 'Combustion Handbook'.**
- **A technical events diary.**
- **Career/training opportunities.**
- **The IFRF Solid Fuel Database.**
- **The European Facilities Database.**
- **TOTeMs, 'Flame Day' national meetings and specialist workshops.**

Change

Rather than invest in establishing, maintaining and regularly refurbishing an expensive in-house suite of research facilities, IFRF has implemented an innovative arrangement by appointing its first-ever 'preferred research partner': the PACT pilot-scale facilities, which IFRF can access and utilise as and when required. These facilities enable IFRF not simply to span the divide between laboratory-scale R&D and industrial pilot-scale testing, but also to achieve this goal with unprecedented cost-effectiveness. Looking ahead, IFRF aims to develop further research partnerships which will enable us to access and leverage an even more extensive range of experimental facilities at a range of scales. In another planned development, 'PACT-2' (a proposed purpose-built site for PACT owned by the University of Sheffield) will provide IFRF with a wider range of pilot-scale experimental facilities and a new location for our headquarters.

Technical Edge

PACT

Located at the Universities of Sheffield, Cranfield, Nottingham and Edinburgh, and Imperial College London, the not-for-profit PACT collaboration focuses on research in fields such as advanced fossil fuel energy, biomass, energy from waste and carbon capture and storage. Its facilities include integrated and pilot-scale test rigs, online laboratory-based analytical facilities and leading-edge modelling and simulation capabilities. Plans are in place for a PACT-2 initiative that will substantially extend and diversify PACT facilities. The following inventory is currently available for IFRF's use under our present hosting agreement with the University of Sheffield:

- **250kW$_{th}$ air/oxy-fuel pulverised-fuel (biomass and/or coal) combustion plant.**
- **150kW$_{th}$ air/oxy-fuel pulverised-fuel combustion plant.**
- **300kW$_{th}$ CFB combustor/gasifier.**
- **750kW$_{th}$ gas turbine burner with deposition probes.**
- **300kW$_{th}$ grate combustor combined heat and power (CHP) energy system for biomass and waste.**
- **Two 330kW$_{th}$ (inlet) CHP gas turbines.**
- **50kW$_{th}$ chemical looping facility.**
- **1 tonne/day plant for post-combustion capture of CO_2.**
- **Gas-mixing facility for modulation of real flue gases or generation of synthetic flue or industrial process gases.**
- **CO_2 transport flow rig.**
- **State-of-the-art laboratory facilities for fuel and solvent analysis (including spectrometry and spectroscopy).**
- **Online analytical facilities.**
- **Unique inductively-coupled plasma optical emission spectrometry (ICP-OES) capability for simultaneous analysis of up to 50 metal species in flue/process gases.**
- **Multi-point FTIR gas analysis.**
- **Conventional combustion gas analysers.**
- **Chemical solvent analysers.**
- **Fast real-time particle size analyser.**
- **Transportable mini-lab for on-site, long-term CO_2-capture media testing under real operating conditions.**
- **Mobile DMS500 for submicron particle (aerosol) measurements from stacks.**
- **Modular 800°C 100bar flow reactor.**
- **Milling equipment with powders analysis.**

PACT sponsors (all UK-based):

- **The Department for Business, Energy and Industrial Strategy (BEIS).**
- **The Engineering and Physical Sciences Research Council (EPSRC).**
- **The UK Carbon Capture and Storage Research Centre (UKCCSRC).**

Building on a solid platform secured in the past while maintaining a firm focus on the future, IFRF is set fair to continue its mission into the coming decades in its very best pioneering yet practical tradition.

By continuing to extend our reach, relevance and influence, we are committed to continually strengthening our capacity to deliver scientific, technological, economic and environmental value for Members, partners, collaborators, industry, the economy and society.

The next 70 years are just beginning!

Getting in Touch

For more information about IFRF's aims, work and services, please contact:

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