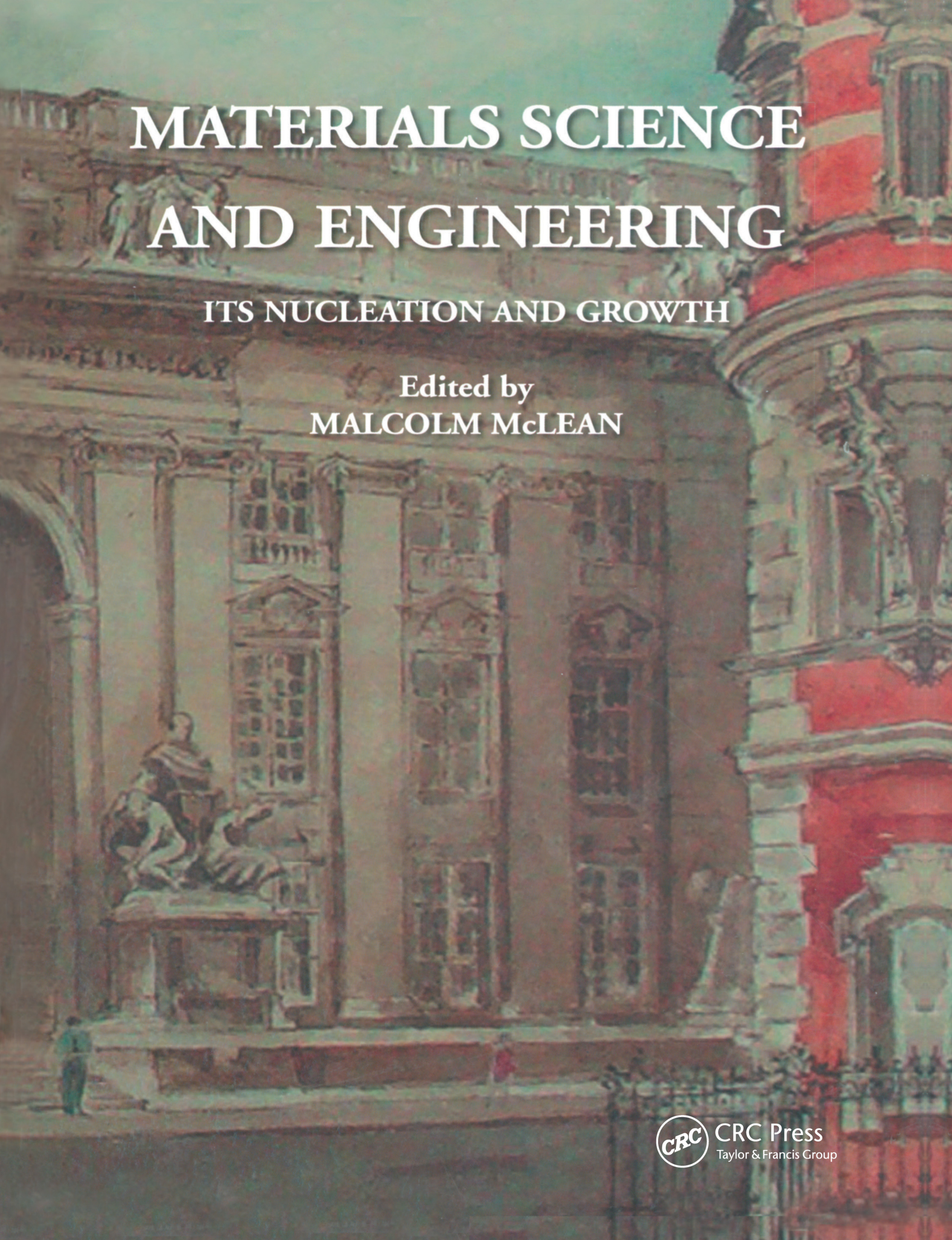
MATERIALS SCIENCE AND ENGINEERING

ITS NUCLEATION AND GROWTH

Edited by
MALCOLM McLEAN



CRC Press
Taylor & Francis Group

Materials Science and Engineering
It's Nucleation and Growth

Materials Science and Engineering
It's Nucleation and Growth

Proceedings of a conference held at
Imperial College of Science, Technology
and Medicine, London, UK
14–15 May 2001

Edited by
Malcolm McLean

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

ISBN-13: 978-1-902653-59-4 (hbk)

Publisher's Note

The publisher has gone to great lengths to ensure the quality of this reprint but points out that some imperfections in the original copies may be apparent.

Typeset in the UK by Keyset Composition, Colchester

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

DOI: 10.1201/9781003580201

Contents

Mechanism for Development

Mature and Incremental Developments Diffusional Growth

Novel Revolutionary Developments Displacive Transformations

Modelling

Introduction and Background

MALCOLM McLEAN
Department of Materials, Imperial College of Science, Technology and Medicine, Prince Consort Road, London SW7 2BP, UK

This book is a record of the conference, entitled 'Materials Science and Engineering: Its Nucleation and Growth' held at Imperial College on 14 and 15 May 2001 as one of the events held to mark the 150th Anniversary of the founding of the Royal School of Mines (RSM). The present Department of Materials at Imperial College has been in continuous existence, under various names, since the establishment in 1851 of the Department of Metallurgy in the Government School of Mines and Science Applied to the Arts, the initial title of the RSM. The Department is the oldest of the discipline in the UK, and we believe remains one of the most active in both teaching and research in metallurgy and materials science and engineering.

The impetus for the formation of the RSM and its constituent Department of Metallurgy came from the rapid technological developments that occurred during the late 18th and early 19th centuries. An entrepreneurial spirit had taken advantage of the available scientific knowledge and had exploited it to tremendous industrial advantage. However, in the early 19th century there was growing concern that continuing industrial advances were being limited by a lack of systematic scientific understanding. The development of the steam engine is an excellent example. James Watt, through his contacts with Joseph Black at the University of Glasgow, understood the evolving concepts of latent heat and modified the Newcomen steam engine by the inclusion of a condenser to greatly improve its efficiency. As the Boulton–Watt steam engines were progressively developed commercially, Watt was well aware of the thermodynamic benefits that would result from increasing the steam temperature (or using *strong steam*). However, he also understood that steel-making technology was not then available to allow this development. There were similar barriers to progress in limitations in basic understanding of chemistry.

Intense lobbying of Government led to the establishment of a Museum of Economic Geology in 1841 and to the Royal College of Chemistry in 1845. Further pressure, led by Sir Henry de la Beche, culminated in the establishment of the Government School of Mines and Science Applied to the Arts in new premises in Jermyn Street (close to Piccadilly Circus) in 1851 under his direction. *Crafts* would, more accurately describe in modern English usage the term *Arts* that was used at that time. John Percy, a physician, was appointed

Lecturer (later Professor) of Metallurgy, a position that he held for some 28 years, and he led the Department towards an improved knowledge of mineral resources and the winning of metals from them. During his tenure, the name of the institution changed: to the Metropolitan School of Science Applied to Mining and the Arts (1853) and the Royal School of Mines (1863). The Royal School of Mines was an independent institution until 1907 when it combined with the Royal College of Science and the City and Guilds College to form the Imperial College of Science and Technology. It remains one of the constituent schools of the current expanded Imperial College of Science, Technology and Medicine. The Department, which has been in continuous existence since 1851, has changed its name less frequently than RSM; it became a Department of Metallurgy and Materials Science in 1970 and adopted its present name, Department of Materials, in 1986.

1851 was, coincidentally, the year of The Great Exhibition, which brought to public notice the growing importance of science and technology. This was a great financial, as well as critical, success and Prince Albert was largely responsible for the profits being devoted to educational and cultural development. A trust administered by the Royal Commissioners of the Exhibition of 1851, which still exists, was responsible for establishing on an 86 acre site in South Kensington the educational establishments (including Imperial College), museums and concert hall that continue to dominate this area.

Of course nothing goes smoothly, particularly when academics are involved. John Percy was vehemently opposed to widening the interests of RSM to more general scientific subjects; others, such as T. H. Huxley, advocated its development into a broad-based technical college incorporating chemistry and biology. It was this proposal, coupled with a planned move from Jermyn Street to South Kensington in 1879 that caused John Percy to resign. His successor as Head of Department was Sir William Chandler Roberts-Austen, whose scientific contributions are the subjects of one of the articles in this volume. He, and his successor, William Gowland in their 23 and 11 year tenures of leadership of the department contributed very significantly to the development of concepts of physical metallurgy and to establishing an international recognition of the Department's activities; both were also Masters of the Mint. With the exception of W. A. Carlyle who died in post after two years, subsequent Heads of Department also had long tenures: H. C. H. Carpenter (28 years), C. W. Dannatt (16 years), J. G. Ball (22 years) and D. W. Pashley (11 years). The writer having only completed 10 years feels he has not displayed the stamina of his predecessors; perhaps the incumbent, John Kilner will be able to re-establish this longevity.

Others have played key roles in the evolution of scientific and technological concepts underlying the subject of Materials Science and Engineering. Among them Hume-Rothery was a PhD student under the (nominal?) supervision of

Carpenter, developing his early concepts of electron alloy theory before returning to Oxford; Andrade on retiring from the Royal Institution continued his seminal contributions on the creep of metals; Richardson founded and nurtured the Nuffield group on metallurgical thermodynamics that had a lasting and world-wide impact on extraction metallurgy; Constance Tipper quietly worked on the metallographic aspects of fracture that led to her war-time contributions to understanding the causes of catastrophic failure of welds in the liberty ships. An important factor in the Department's continuing success has been its willingness to evolve the subject matter covered in both its teaching and research. This forward-looking characteristic of the Department still exists where our current priorities embrace materials for environmentally friendly energy production, modelling of materials structure/processing/performance and materials for medical applications with a particular emphasis on tissue engineering.

Conferences such as that reported in this volume inevitably focus on current research and, indeed, the Department of Materials has a strong research activity. However, it places at least equal emphasis on the content and quality of its undergraduate teaching. It was the only UK department awarded the maximum possible grading in the UK Quality Assurance Agency assessment of materials teaching. The recognition of changing student demands and industrial requirements in the late 1960s led to the introduction of a Materials Science syllabus, in parallel with the traditional Metallurgy course. Professors Brian Steele and Peter Pratt pioneered this initiative, one of the first of its type, while building strong research activities in structural and electrical ceramics, which remain active and are represented in this volume. Metallurgy and Materials Science have long been incorporated in a single syllabus, which is complemented by courses with Management Studies and Foreign Language. There are also speciality courses in Aerospace Materials and (from 2002) Tissue Engineering. The quality and flexibility of these courses are probably responsible for the growth in student numbers and quality (as indicated by A-level scores) that has occurred in recent years, at a time when student recruitment into the discipline has been declining.

The Department is proud of its history and of its past contributions to the subject. Most of the contributors to this volume were either students or staff in the department who have proceeded to make important contributions elsewhere. This provides a measure of the influence it has had on an international and national dimension. However, we believe that the meeting acknowledges only the first 150 years of the Department's contributions to Materials Science and Engineering. There is a buoyant undergraduate course, a forward-looking research programme carried out by enthusiastic, and predominantly young, members of academic staff. History can have its drawbacks and conducting state-of-the art research in a century-old building has been one of them.

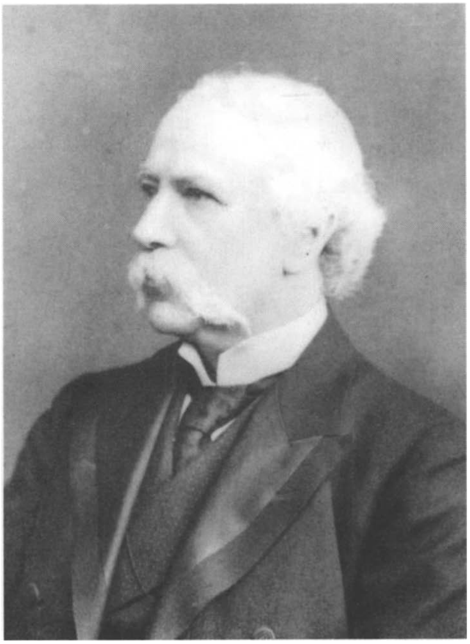
However, the Department is currently in the midst of a major refurbishment that will leave us with the historic exterior of the RSM Building, but modern laboratories and teaching facilities on the inside. The prospects for the future are excellent.

The Department has benefited through the years from many interactions with industry, government bodies and agencies. The meeting that has led to publication of this volume was made possible by generous support from a number of bodies, which we wish to thank. These include:

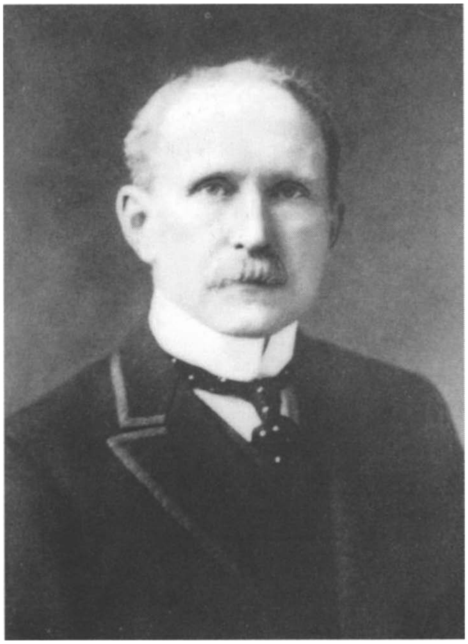
- US Office of Naval Research International Field Office and European Office of Aerospace Research and Development, Air Force Office of Scientific Research, United States Air Force Research Laboratory.
- Corus PLC
- British Nuclear Fuels
- The National Physical Laboratory
- Kobe Steel Limited
- JEOL Ltd
- The Institute of Materials

John Percy
1851–1879

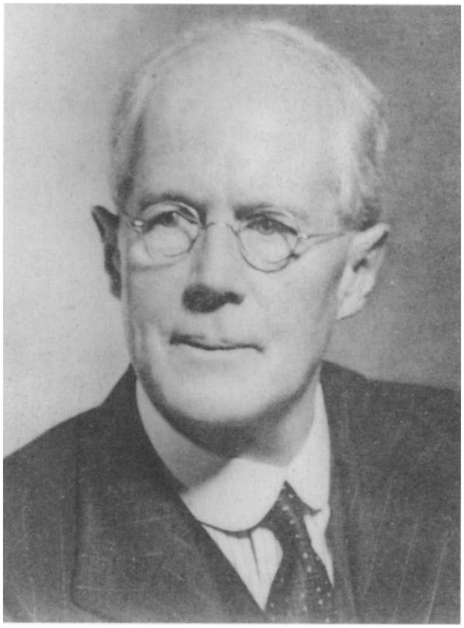
Sir William Chandler Roberts-Austen
1880–1902



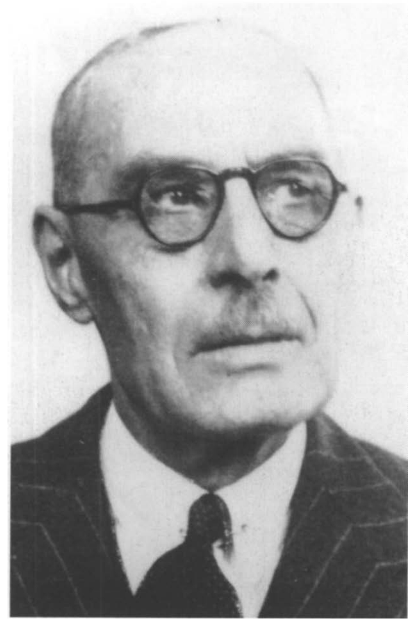
William Gowland
1902–1911



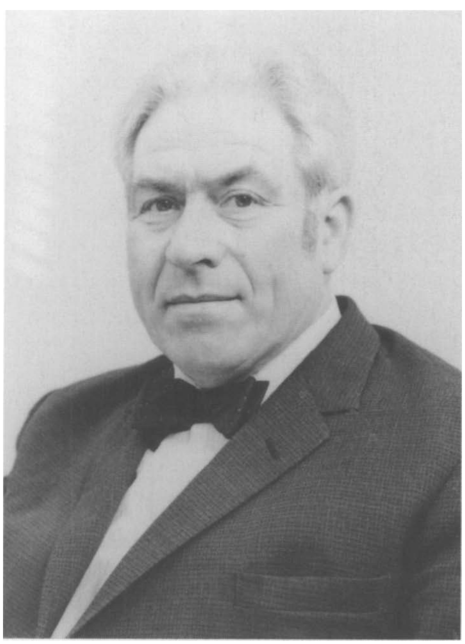
W. A. Carlyle
1911–1913



Sir Henry Cort Harold Carpenter
1913–1940



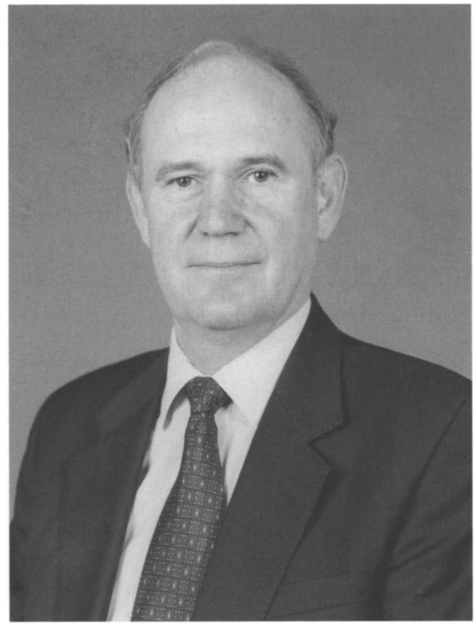
C. W. Dannatt
1940–1956



J. G. Ball
1957–1979

D. W. Pashley
1979–1990

M. McLean
1990–2000



J. A. Kilner
2000–present

List of Contributors

Ben Alcock was a member of the Nuffield Group of the Department of Metallurgy between 1950 and 1969, having been appointed to a Chair of Metallurgical Chemistry in 1964. He was at the University of Toronto between 1969 and 1987, serving as Chairman of the Department of Metallurgy and Materials Science from 1969 to 1977. He was Freimann Professor at Notre Dame between 1987 and 1994. His distinctions include Fellowships of the Royal Society of Canada, the Royal Society of Chemistry, the Royal Society of Arts and the American Institute of Metallurgical Engineers.

Bill Bonfield gained a BSc(Eng) and PhD in Metallurgy from Imperial College in 1958 and 1961 respectively. After a period in industry in the USA he returned to England to a Readership at Queen Mary College. He remained there in various capacities until 2000, notably developing a world-renowned group on biomaterials. Latterly he was Founder Director of the IRC in Biomaterials at QMW. He now holds a Chair in the Department of Materials Science and Metallurgy at the University of Cambridge. Among his many honours are a Fellowship of the Royal Academy of Engineering and the *Acta Materialia et Metallurgia.*

Richard Brook obtained a BSc in Ceramics from the University of Leeds and a DSc from MIT. He has spent periods at the University of Southern California (1966–1970), AERE, Harwell (1970–1974) and as Head of Department of Ceramics at the University of Leeds (1974–1988). In 1988 he became Director of the Max-Planck Institut für Metallforschung in Stuttgart and then Cookson Professor and Head of Department of Materials at Oxford in 1992. He has been Chief Executive of the Engineering and Physical Science Research Council since 1994. Professor Brook is a Fellow of the Royal Academy of Engineering, a Distinguished Life Member of the American Ceramic Society, Membre d'Honneur de la Société Française de Métallurgie et Matériaux.

Robert Cahn holds three degrees from Cambridge: BA (1945), PhD (1950), DSc (1963). After a brief period at AERE, Harwell he moved to academia holding various positions in the Department of Physical Metallurgy at Birmingham. He was Professor of Materials Science at the University of Wales at Bangor, Professor and Head of Department of Materials Science at the University of Sussex and Professor of Physical Metallurgy at Université de Paris-Sud. His many awards include Fellowship of the Royal Society, the Griffiths Medal and the Luigi Losana Gold Medal. His recent book traces the evolution of the discipline of Materials Science.

Jim Charles obtained his bachelor's degree in Metallurgy from the Royal School of Mines in 1947. After a career in industry he returned to academia to the Department of Metallurgy at the University of Cambridge in 1960 where he remained until he retired in 1990. His honours include Fellowship of the Royal Academy of Engineering, the Beilby Medal, the Hadfield Medal and the Kroll Medal. He has taken a particular interest in the history of metallurgy and his recent autobiography *Out of the Fiery Furnace* recalls his experiences in the Royal School of Mines.

Amit Chatterjee was awarded a BSc in Metallurgical Engineering from Banaras Hindu University in 1966, a PhD in Process Metallurgy from Imperial College in 1970 and a DSc in Engineering from the University of London in 1988. He has worked for Tata Steel in various capacities since 1977, apart from a 5 year period as Managing Director Ipitata Sponge Iron Company. He is currently General Manager (Technology) for Tata Steel. His technical achievements have been recognised by a number of prestigious awards, including the National Metallurgist Award of the Government of India, the Application to Practice Award of TMS and the Thomas Medal of the Institute of Materials.

Julie Christodoulou was awarded a PhD in Materials from Imperial College in 1999. She worked for the Office of Naval Research International Field Office while in London. She currently has a research position with the US Navy in Washington.

Leo Christodoulou obtained both his BSc and PhD in Metallurgy from Imperial College. After a post-doctoral research appointment at Carnegie-Mellon University, he joined the Martin Marrieta Laboratories where he was responsible for the development of XD composites. He is currently on leave-of-absence at DARPA from his current position as Reader of Materials Processing in the Department of Materials at Imperial College. He was a recipient of the Grunfield Prize of the Institute of Materials.

Jeff Edington gained his Bachelor and Doctoral degrees in Metallurgy from the University of Birmingham. His career has included periods in universities (Cambridge, Delaware), research laboratories (Battelle) and industry (Alcan, British Steel/Corus). Until his recent retirement he was Executive Director for Technology for the Corus Group. He is a Fellow of the Royal Academy of Engineering and was President of the Institute of Materials.

Tony Evans received his BSc and PhD degrees from the Department of Metallurgy at Imperial College in 1964 and 1967 respectively. He then spent 10 years as a research scientist at AERE Harwell, NBS and Rockwell International Science Center. Since 1978 he has held senior academic positions at the University of California Berkeley and Santa Barbara, Harvard University and (currently) Princeton University. His many awards include the Matthew Prize of Imperial College, the Griffith Medal of The Institute of Materials, Membership of the National Academy of Engineering and Distinguished Life Member (American Ceramic Society). He was elected to Fellowship of the Royal Society in 2001.

Derek Fray entered Imperial College in 1958 with a Royal Scholarship, graduating in 1961 with a BSc(Eng), ARSM and in 1965 with a PhD, DIC and the Matthey Prize. He is currently Professor of Materials Chemistry and Head of Department, Department of Materials Science and Metallurgy, University of Cambridge. He is a Fellow of the Royal Academy of Engineering.

Dr Robin Grimes is Reader in Atomistic Simulation in the Department of Materials at Imperial College, which he joined in January 1995 as a Governor's lecturer after 5 years at the Royal Institution of Great Britain. He obtained his PhD in Chemistry from Keele University, his MS in Materials Science from Case Western Reserve University and BSc in Mathematical Physics from Nottingham University. At the present time he is on leave from Imperial College as the Matthias Scholar at Los Alamos National Laboratory. His research group is concerned primarily with predicting the behaviour of ceramic materials at an atomistic level using computer simulation techniques.

Ken Harris received his BSc in Metallurgy from Imperial College in 1965. He has spent all of his subsequent career in the metallurgical industry. He has been responsible for the development of the most commercially widely-used single-crystal superalloys which power modern aero-engines. He is a Fellow of ASM International.

Larry Hench graduated with bachelor and doctoral degrees from the Ohio State University. He was appointed to the Faculty of the University of Florida in 1965 where he remained until accepting a Chair in the Department of Materials in 1994. He is widely recognised as one of the pioneers of biomaterials; his development of Bioglass and championing it to medical applications has been particularly important. His many honours include election to the US National Academy of Engineering and the Von Hippel award of the Materials Research Laboratory.

Sue Ion gained both her BSc degree in Materials Science and her PhD in Dynamic Recrystallisation of a Magnesium Alloy from Imperial College, London. She joined British Nuclear Fuels in 1979 working in various roles before becoming Director of Technology & Operations in 1992. Dr Ion was awarded the Hinton Medal by the Institution of Nuclear Engineers in 1993 for an outstanding contribution to nuclear engineering and was elected a Fellow of the Royal Academy of Engineering in 1996. Dr Ion is a member of the European Union Science and Technology Committee and she also represents the United Kingdom on the IAEA's Standing Advisory Group on Nuclear Energy.

John Kilner obtained a first degree in Physics from the University of Birmingham and a PhD in Physical Metallurgy in 1975. He then took up a post-doctorial position at the University of Leeds working on ion conducting ceramics with Richard Brook. He moved to Imperial College in 1979 as Wolfson Fellow and was then awarded an EPSRC Advanced Research Fellowship to work on ion beam synthesised materials. In 1987 he joined the academic staff of the then Department of Metallurgy, becoming Dean of the Royal School of Mines in 1998. Professor Kilner is currently the Head of Department of the Materials Department of Imperial College and a Fellow of the Institute of Materials.

David Larbalestier graduated BSc (1965) and PhD (1970) from Imperial College/Royal School of Mines. He has worked in Switzerland, the UK and the USA since leaving RSM. He has been on the faculty of the Department of Materials Science and Engineering, University of Wisconsin Madison since 1976 where he holds the I. V. Shubnikov and David Grainger chairs. His career in superconductivity started during his PhD studies and has continued to this day. He is also Director of the Applied Superconductivity Center which brings together about 5 groups and some 50 students and staff to research the science and applications of low and high temperature superconductors.

Michael R. Notis is a Professor of Materials Science and Engineering at Lehigh University in Bethlehem, Pennsylvania, USA, and his PhD is from this same institution. His main research work concerns mass transport and phase equilibria in multicomponent systems, and he is currently involved in studies on microstructure development at reaction interfaces between metal substrates and lead-free solders. He has a keen interest in the history of materials technology.

William O'Kane gained his BSc, MSc and PhD in Materials Science from UMIST in 1990, 1991 and 1994 respectively. He joined Seagate Technologies in 1994 as a Senior Research and Development Engineer and has held various positions in the company, both in the USA and Ireland, since that time. He was appointed to his current post as Director for Research and Development at the Seagate Technologies wafer fabrication facility in Derry, Northern Ireland in August 2000.

David Pettifor received his BSc from the University of Witswatersrand in 1967 and PhD from the University of Cambridge in 1970. After brief periods at the University of Dar es Salaam, the Cavendish Laboratory and Bell Laboratories he joined the Department of Mathematics at Imperial College where he remained between 1978 and 1992. He was appointed Wolfson Professor of Metallurgy in 1992. Professor Pettifor is a Fellow of the Royal Society.

Julia Polak obtained her Medical Degree in Buenos Aires, Argentina in 1966. She came to the UK in 1968 and worked at the Hammersmith Hospital, first as a Junior Doctor and then as a Head of the Department of Histochemistry (after the retirement of Professor Prearce), from 1980 onwards. She is currently the Director of the Imperial College Tissue Engineering Centre, with dedicated laboratories and offices at Chelsea and Westminster Hospital. She works closely with Professor Larry Hench, the co-Director of the Centre. She has published over 1000 original papers, 24 books and is the recipient of numerous national and international honours. She is the Founder President of the Tissue Engineering Society in Great Britain and the European Editor of *Tissue Engineering*.

Peter Price gained a BSc in Aeronautics and Astronautics from Southampton University in 1980. He is a Chartered Engineer and Fellow of the Royal Aeronautical Society. He joined Rolls-Royce in 1980 as a Graduate Trainee and has held various positions in the company since then, being appointed to his current post as Director of Engineering for the Defence (Europe) business of Rolls-Royce, based in Bristol, in January 1999.

Gary Savage graduated with both BSc and PhD from the Department of Metallurgy at Imperial College. He was a Research Physicist with ICI Advanced Materials from 1985 to 1990 working on the processing of composite materials. He became involved with the application of composites to Formula 1 cars in 1990 and has worked with McLaren International, Arrows, Prost Grand Prix and (currently) BAR Grand Prix. He is a Fellow of the Institute of Materials and the Institution of Mechanical Engineers. He is Visiting Professor at the University of Modena.

Karen Scrivener gained her BSc from the University of Cambridge and her PhD from the Department of Materials, Imperial College. She was awarded a Royal Society Research Fellowship, tenable in the Department of Materials at Imperial College where she was appointed to a Lectureship. She accepted a senior research position in Lafarge in 1994 and has recently been appointed to a professorship at EPFL in Lausanne.

Peter Swann obtained his PhD at Cambridge in 1960 and, after 6 years at US Steel's Fundamental Research Center, became a Reader and then a Professor in the Department of Metallurgy at RSM. In 1978 he left the Department to found Gatan Inc., a scientific instrument company based in Pennsylvania, USA. He has now retired and is living on Jumby Bay Island in the West Indies

Alan Windle graduated with BSc in Metallurgy from Imperial College, in 1963, and with a PhD from Cambridge University. He returned to Imperial, first as an ICI fellow under Peter Pratt and then as a Lecturer, and arising from a period in Andrew Keller's laboratory in Bristol developed a new interest in polymers. Back in Cambridge in 1975, as University Lecturer and Fellow of Trinity, he built up a group concentrating on structural studies of non-crystalline polymers. Interest developed in polymer diffusion and in liquid crystalline polymers which has led to a development of computer molecular modelling. Professor Windle has been awarded the Bessemer Medal and the Royal Society of Arts Silver Medal (1963), the Rosenhain Medal (1987) and the Swinburne medal and prize (1992) and he was elected Fellow of the Royal Society in 1997. He is currently Executive Director of the Cambridge-MIT Institute and a Commissioner of the Royal Commission for the 1851 Exhibition.

The Origins of Metallurgy and the RSM

J. A. CHARLES
Department of Materials Science and Metallurgy, University of Cambridge, Pembroke St, Cambridge, UK

ABSTRACT
The origin of man's use of metals through mineralogical associations, and the subsequent development of metallurgical technology through history, are briefly reviewed. The rate of change in the understanding and application of metals greatly increased from straightforward observation and deduction, through alchemical experimentation and then particularly rapidly after the new atomistic philosophy and the pursuit of science for its own sake in the seventeenth century, as reflected in the foundation of the Royal Society. The development of a scientific basis for understanding during the eighteenth and particularly the nineteenth century was to result in an explosion of metallurgical technology, as for example in steelmaking, and as evidenced by the Great Exhibition and the Government's creation of the School of Mines, both in 1851, the latter to become the RSM in 1863. The initial emphasis in the School was mineralogical, chemical and analytical, an understandable bias at the time that was, however, to persist for many years. The early history of the School and the role of John Percy, the 'father' of English metallurgy as an applied science, are considered.

Metallurgy as a technology has been around for ~6000 years. Neolithic man moved into the recovery of metals and their use through observation and deduction and the Metal Age began. In the beginning the earth's surface must have been an Aladdin's cave of brightly coloured minerals released at each outcrop by geological processes. As well as looking for suitable stones for weapons and tools we know that attractively coloured minerals such as malachite and azurite or interestingly structured minerals such as galena (Plates I, II, III) were collected and used as pigments and stored in bone tubes or pottery vases. In the Neolithic period the use of moulded clay, dried in the sun and hardened by fire, and then the development of kilns for firing pottery, reflected an increasing level of combustion control, essential for what was to follow. Some earthy materials would melt and glazes were developed.

When collecting stones and minerals, Neolithic man would have found intriguing 'stones' that had totally different properties, deforming plastically when hammered. These native metals, gold from stream beds and native

DOI: 10.1201/9781003580201-1

copper associated with copper mineralisation, represent the first metal usage, gradually broadening into the Chalcolithic period during 5000–4000 BC as native copper was purposely sought and the transition to smelting for copper began. Perhaps 'fire setting' to separate associated rock and copper minerals from the native copper resulted in a realisation that more copper was being generated, with the oxide copper minerals easily reduced in charcoal fires at above 700°C, when CO rather than CO_2 is available from combustion. In laboratory tests with CO supplied directly, malachite is completely reduced to copper before the charge is even red hot. It would also be recognised that all these copper sources produced a green flame. The first smelting sites at Timna in the southern Arabah desert (Israel/Jordan border) are dated 4240 BC. With furnace control (draughting etc.) temperatures in excess of 1080°C would be generated giving molten copper. When cooled down it would have been seen that it had taken the shape of the furnace bottom, and the concept of casting to a required shape followed. The incorporation of predominantly brown gossan (limonite) from the top of a weathered pyritic copper deposit, often still showing some green copper mineralisation (Plates IV, V) and a green tinted flame, would have given improved liquid/liquid separation of the copper from 'earths' and the concept of fluxing had arrived, with the subsequent use of ochres generally. If copper could be melted, so could gold, although it was recognised that cold welding could be used to build up bulk in gold, unlike copper.

Such development did not occur everywhere at the same time, although the order of development subsequently was generally similar (Fig. 1) although a Cu–As phase is not always evident. It seems that there were independent centres of origin, notably the Mesopotamian region and the Balkans, with initially limited diffusion of ideas. The Balkan activity is exemplified by cast copper axes from the Vinçą culture, ~4000 BC (Plate VI). The influence of heating on worked copper to give resoftening was known even in the Chalcolithic period as evidenced by general and localised crystal twinning associated with forging artefacts to shape. Deformed annealing twins indicate further work after annealing. We should never underestimate the human powers of observation and deduction demonstrated by ancient peoples, although the speed of change thus generated may have been slow as compared to later millennia, when the ability to record and communicate rapidly existed, with very different social conditions.

After copper, copper arsenic alloys giving superior properties were produced for about 600 years based probably on the determinative minerology of basic copper arsenates ($Cu_3\,As_2\,O_8\,nCu\,(OH)_2$: a green mineral colour such as chalcophyllite (Plate VII), still a green flame, but now with an associated, easily recognised, garlic smell on heating – just the tests we employed as students at the RSM in the 1940s when the identification of minerals was

DATE B.C. (Calendar years)	EGYPT	SUMER	AEGEAN	BALKANS	IBERIA	MALTA	N. FRANCE	BRITAIN	DATE B.C. (calendar years)
1500–2000	MIDDLE KINGDOM	HAMMURABI OF BABYLON	Mycenae Shaft Graves MIDDLE BRONZE AGE	MIDDLE BRONZE AGE	EARLY BRONZE AGE Bronze	EARLY BRONZE AGE Copper	EARLY BRONZE AGE Bronze	WESSEX Bronze —Stonehenge—	1500–2000
2000–2500	EARLY (PYRAMIDS)	SARGON OF AGADE EARLY	(EARLY BRONZE AGE) Phylakopi I Lerna (House of the Tiles)	(EARLY BRONZE AGE)	LATE NEOLITHIC	TEMPLES	BEAKER Copper	BEAKER Copper Silbury Hill	2000–2500
2500–3000	DYNASTIC ↓ Bronze Hieroglyphs (PYRAMIDS)	DYNASTIC ↓ Bronze	(EARLY BRONZE AGE) Bronze Troy I Copper	(EARLY BRONZE AGE) Bronze	Los Millares	EARLY TEMPLES	LATE NEOLITHIC	HENGES	2500–3000
3000–3500	Copper (PREDYNASTIC)	PROTO-LITERATE LATE	FINAL	FINAL	PASSAGE GRAVES Copper	PROTO-TEMPLES	LATER	Newgrange MEGALITHS CAUSEWAYED CAMPS and	3000–3500
3500–4000	(PREDYNASTIC)	URUK EARLY URUK Early writing	NEOLITHIC Occasional Copper	NEOLITHIC	EARLY MEGALITHS - DOLMENS		MEGALITHS	LONG BARROWS	3500–4000
4000–4500		Copper LATE UBAID	Dhimini MIDDLE	GUMELNITSA	EARLY NEOLITHIC		PASSAGE GRAVES FIRST FARMERS	FIRST FARMERS	4000–4500
4500–5000		EARLY UBAID Occasional copper	NEOLITHIC	LATE VINČA Copper and Proto-writing					4500–5000

Fig. 1 Chronology of development in prehistory, Renfrew.

still largely concerned with heating on a charcoal block with a blowpipe flame. Probably at some point, as well as using green copper-arsenates to give the alloys, the green iron arsenates derived from arsenopyrite and then arsenopyrite itself, both still giving the garlic odour, would have been employed to provide the arsenic addition to the copper. Eventually the copper-arsenic alloys gave way to tin bronze of similar properties, probably in an evolutionary sense in relation to the well-being of the smiths. The link from copper-arsenic to the use of cassiterite (SnO_2) added to copper to give bronze may have been that stannite, the sulph-arsenide of tin, could also have given the garlic odour on heating, but it could also have been the frequent juxtaposition of the heavy minerals arsenopyrite (metallic grey) and cassiterite (brown/black) in stream beds (Plate VIII), or perhaps through the presence of immobile cassiterite in gossans, a mineral readily recognised by the weight in the hand. Another possible link is that cassiterite in the powder form, as on a streak plate or a vanning shovel, is very much the same red/brown colour as cuprite (Cu_2O), already identified as a source of copper.

As furnaces improved and gave more strongly reducing conditions in copper smelting furnaces, the adventitious occurrence of iron would have increased and it would be a short step to operate the furnace solely as a bloomery, producing solid iron from an iron-rich charge. On Cyprus, for example, the late Bronze Age advanced almost seamlessly into a period of producing and working iron, and iron nail or small tool has even been found in the protective, reducing, environment of a Bronze Age trackway in Holland. The control of the carbon content of iron, forging and the heat treatment of steel was to develop steadily over subsequent centuries.

This whole period of metal development to Roman times was some four thousand years and the rate of change was obviously slow, but steady none-the-less. The Egyptians of the Late Kingdom (~500 BC), for example, had mastered the technique of lost wax investment casting, even to the point of awareness of the value of high lead additions to bronze to improve fluidity and castability for thin-walled castings (Fig. 2).

In the Greek and Roman periods, as by then recorded by various writers, techniques of manufacture and the application of known metals improved steadily, but without any major change of alloy development, except for the purposeful production of brass by the calamine process in Roman times. Post Roman, for several hundred years metallurgy moved into the secretive alchemical experimentation period, with emphasis on the precious metals, amalgams and chemical properties. No doubt some advances were made and it could be said that the emergence of chemistry as an independent discipline could be traced to the observed need for assaying in relation to standards for trade, as instanced in the work of Agricola and Erkar, writing in the sixteenth century.

Fig. 2 Investment castings, Egypt, Late Kingdom.

In the seventeenth century the alchemical approach was still extant and even Newton continued to have some faith in transmutation, not a good idea for the Master of the Mint! A major acceleration came, however, with the pursuit of science for its own sake in this century of enlightenment, with improved methods of communication through printed books and scholarship, where 'intelligencers' collected and distributed knowledge and met frequently. In Britain this culminated in the foundation of the Royal Society in 1660. Just as Archimedes had foreseen in Alexandria, it was the creation of a truth-seeking philosophy, not the results of immediate practical value, which were seen to be most important in the long term. Men that we now class as scientists began to have a major influence on the way metallurgy developed, for example, in Great Britain Francis Bacon (1561–1626), Robert Boyle (1627–1691), Isaac Newton (1642–1727) and Joseph Priestley (1733–1804) and then Michael Faraday (1791–1867) to name a few. Robert Hooke (1635–1703) began appreciation of the inter-relation between metal properties and their structure through microscopy and contributed largely to the early concepts of mechanical properties, memorably Hooke's law of elastic behaviour.

With steam-power and the Industrial Revolution blossoming in the eighteenth and early nineteenth centuries it became clear that further development required greater scientific understanding of the processes involved, in order that they could be made more efficient in a climate of growing commercial competition, particularly on mainland Europe in iron and steel making. Another feature of the times was the great growth in scientific and technical interest and self education in the population, particularly during the second half of Victoria's reign, which had to be recognised by politicians.

In 1841 the Museum of Economic Geology was opened, attached to the Mining Record office in Whitehall. Amongst its contents were exhibits showing how minerals were treated to produce metals. In this Museum there was rather informal instruction in analytical chemistry, mineral analysis and various metallurgical processes. It has to be understood that analytical methods and their development were essential features of the desire to understand and control existing problems. In 1851 a new building for the Museum, the Geological Survey and for a new Government School of Mines was provided between Piccadilly and Jermyn Street, much due to the efforts of Henry Thomas de la Beche, the mining engineer. It was, in fact, the first important structure in Britain designed for a purely technological or scientific institution and was opened by the Prince Consort less than a fortnight after the Queen had opened the Great Exhibition in Hyde Park. Evening lectures for the public were very well attended, an interest reflecting the first publication of *Boys Playbook of Science* and then the *Playbook of*

Metals by J. H. Pepper in 1861. It is interesting to note that Pepper seemed still to adhere to alchemical connections in both the book cover (Fig. 3) and preface of this latter work. It is none-the-less a very interesting 'popular' text of the time. With Royal patronage the title of the School was changed to Royal School of Mines in 1863.

John Percy (Fig. 4) had been appointed, first as Lecturer and then as the first Professor in metallurgy in the country. He was by repute an excellent lecturer and teacher, innovative and methodical, building up a great collection of mineral and metal specimens to enliven his courses, which collection now resides in the Science Museum. His series of books commencing in 1861, constituting a treatise on metallurgy, sought underlying science in defining practice. He clearly saw the importance of metallurgy to the nation. A famous quote from his first lecture at the RSM: 'In proportion to the success with which the metallurgic art is practised in this country will the interests of the whole population, directly or indirectly, in no inconsiderable degree, be promoted'.

At its establishment the School was under the control of the Department of Science and Art of the Board of Trade, and then under the Education

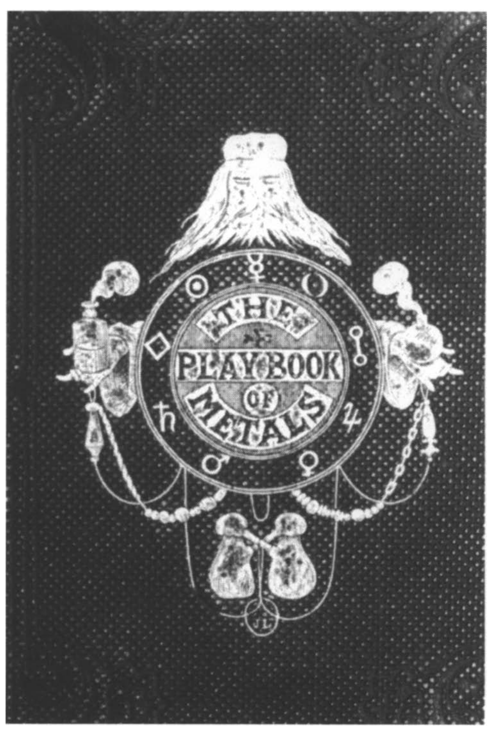


Fig. 3 J. H. Pepper *The Playbook of Metals*, 1861.

Fig. 4 John Percy.

Department. From 1863 scholarships for up to three years at the RSM were awarded to the best students, leading to the Associateship Examinations in metallurgy. These were controlled by the Science and Art Department, with scripts submitted from a number of places, including Middlesbrough and Sheffield. Numbers for the Associateship were relatively low and most students at the RSM were sent by industrial firms for short courses. Until 1925 separate examinations had to be taken for the University of London B.Sc(Eng.) degree.

An important event soon after the foundation of the RSM was the Paris Exhibition in 1867 which demonstrated a gulf opening between British industrial capacity and that of our French neighbours, which greatly alarmed politicians and industrialists alike. Disraeli therefore set up a Select Committee in 1868 'to enquire into the provisions for giving instruction in theoretical and applied science to the industrial classes', with Bernard Samuelson, a practising ironmaster and engineer as chairman. There seems to have been a realisation that there was a need for a scientific basis of understanding for the development of technology at a competitive rate to our European neighbours. Even in the first third of the twentieth century it was considered that a knowledge of scientific German and French was an almost vital skill, so far ahead had they become at the turn of the century. Percy in his first book, 1861, underlines the importance of the German scientific contribution at that time (Fig. 5). As recently as 1943 I attended a German course at Imperial College as part of the Inter BSc curriculum.

The forward-looking work of this Select Committee was an important turning point in providing the necessary push for the technical education which enabled twentieth century industrial Britain. A conclusion was that the chief obstacles standing in the way of a technologically-informed and competitive nation were the wholly inadequate provisions for both primary and secondary schooling; nothing seems to change! The report was followed by a Royal Commission on Scientific Instruction and the Advancement of Science set up during Gladstone's first term of office (1870–1875), under the chairmanship of William Cavendish, 7th Duke of Devonshire, an important figure in the ferrous industry and the first President of the Iron and Steel Institute.

One result of this was the introduction of the Higher Grade Schools, the first State-aided secondary schools, which were required to teach science to a recognised educational standard in order to qualify for a grant and recognition. One such school in Cambridge was attended by my father at the end of the nineteenth century. Such schools were a direct result of Gladstone's Education Act of 1870 and, as regards the emphasis on science, the report from the Cavendish Committee. A favourite quote from the report of the Committee – 'considering the increasing importance of science to the material

> The chief writers on Metallurgy are the Germans, to whom we owe two of the most remarkable works on the subject, namely, the treatise of Agricola, in Latin, which appeared in 1555; and the System of Metallurgy of Karsten, in German, published in 1831. The monographs, contributions to periodicals, and compendious treatises relating to the science and practice of Metallurgy which have been published in the German language, are very numerous. We are, probably, indebted to the Germans, to a greater extent than is commonly supposed, for the development of our mineral resources, since the introduction of German miners and metallurgists into England, about three centuries ago, through the wisdom of Elizabeth.

Fig. 5 Percy writing on the significance of German metallurgy, 1861.

interests of the country one cannot but regard its almost total exclusion from the training of the upper and middle classes as little short of a national misfortune'. In relation to the RSM and the Royal College of Chemistry, the Royal Commission's first report was concerned with broadening the curriculum to general science with a primary emphasis shifted to training teachers. This seemed bound to reduce the importance of metallurgy in the courses and, as Almond has pointed out in his excellent thesis Metallurgical Education 1851–1950, it was a miracle that it remained a distinct subject, surviving into the twentieth century. W. W. Smyth, in charge of mining, and J. Percy, the metallurgist, strongly opposed this broadening, and the latter resigned rather than submit to the changes, which involved also moving to a new RSM, in the Huxley Building, South Kensington, offering to rebuild it himself in Jermyn Street. In the aftermath of the Great Exhibition, Parliament had voted £150,000 to add to the Exhibition's profits to enable three Kensington centres to be purchased – in due course to be the homes of the RSM, Science Museum, Geological Museum and the City and Guilds.

Although Percy had resigned from the RSM in 1879, rather than move to the Huxley Building, fearing that metallurgy would lose its identity in a general School of Science ruled over by the younger Thomas Huxley, he should have hung on, since friends rallied round the RSM, influencing the Treasury so that there should not be a complete merging of 'the strictly technical and professional school of mining in a more general scientific institution'. The justification given was 'the development of the mineral riches of this country and of its colonies and dependencies was the foremost object to which the Government intended by its measures in 1851–1853 to direct researches of science and apply their results'. Thus in 1881, after a lengthy period of transition, and no doubt strife, the Normal School of Science (later the RCS) and the Royal School of Mines came into existence in South Kensington, in what we now know as the Huxley Building.

Roberts-Austen succeeded his mentor Percy in 1880 whilst retaining his post as chemist and Assayer at the Royal Mint, to be followed by Gowland, Carlyle, and then Carpenter in 1913, the last supervising the fine new building in 1915 in Prince Consort Road, and then Dannatt in 1940. The relocation of the RSM on this present site commenced with the Bessemer Laboratory of fond memory, where we carried out virtually full-scale mineral dressing experiments (Figs 6, 7) in my time, 1944–1947.

The contribution of the RSM to the metallurgy profession and metallurgical industry has been enormous. For 30 years it was the only school of metallurgy in the country. A close association with the Royal Mint was maintained over many years, from Percy onwards. The foundation of many of the other schools of metallurgy which developed later in the UK was through Associates of the RSM (Table 1), and the alumni list is truly impressive. William Chandler,

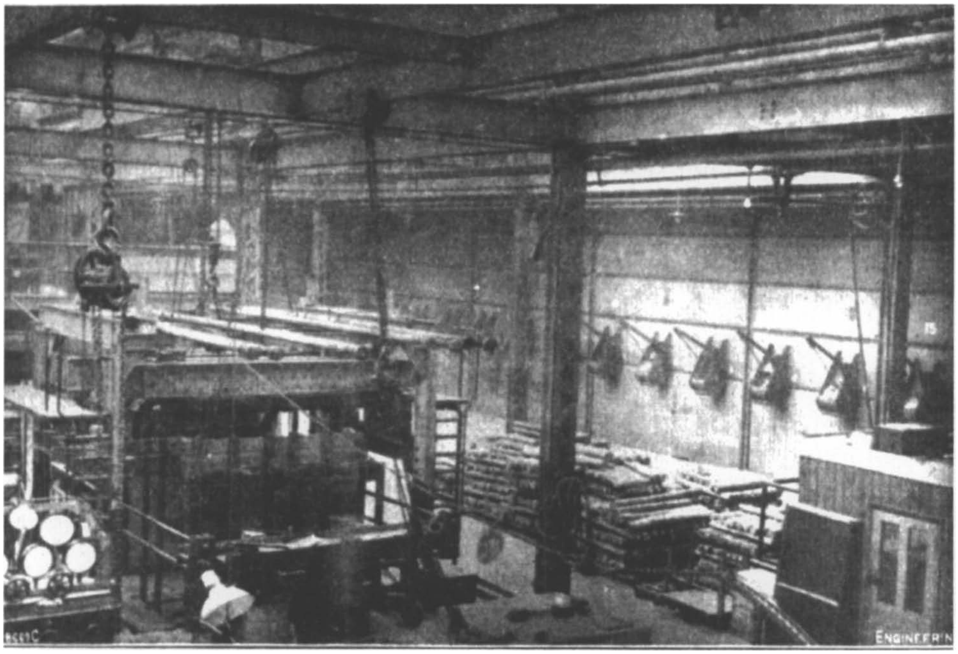


Fig. 6 View of Bessemer Laboratory (*Engineering*, 1951).

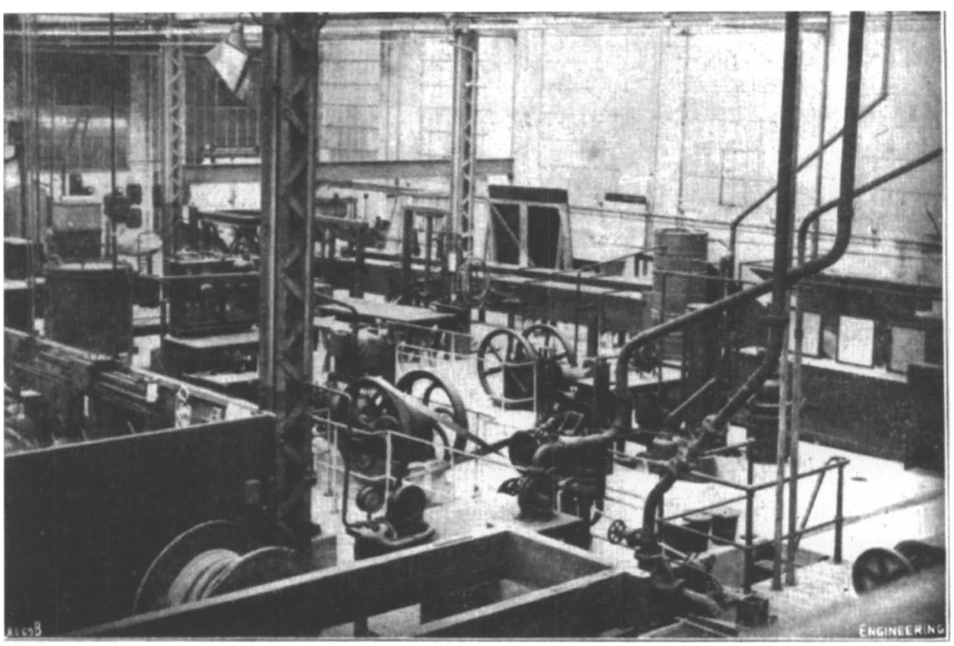


Fig. 7 View of Bessemer Laboratory (*Engineering*, 1951).

Plate I Malachite $CuCO_3$ $(CuOH)_2$.

Plate II Azurite $2CuCO_3$ $(CuOH)_2$.

Plate III Galena PbS.

Plate IV Green flame from copper/copper minerals.

Plate V Gossan or 'iron hat' overlying copper mineralisation.

Plate VI Cast copper axes, ~4000 BC Balkans.

Plate VII Chalcophyllite, copper arsenate, $Cu_3As_2O_8nCu(OH)_2$.

Plate VIII Juxtaposition of arsenopyrite FeAsS (grey) and cassiterite SnO_2 (dark brown).

Roberts-Austen, Clement Le Neve Foster, Sidney Gilchrist Thomas, Percy Gilchrist, George James Snelus, William Gowland, Charles Vernon Boys, Harold Carpenter, Miss Constance Elam (Mrs Tipper), F. W. Harboard, Thomas Kirke Rose, William Hume-Rothery, Andrew McCance, Leonard Pfeil, to name but a few of those in earlier years. May its direct influence and that of its alumni continue to be of great importance to the nation.

Table 1 The Influence of RSM-trained men on British Metallurgical Instruction (after J. K. Almond)

Institution Offering Instruction		RSM-trained Staff in Post
Before 1900		
Class of Artillery Officers, Woolwich	c1861–1888	J. Percy
	1888–1906	H. Bauerman, Lecturer on Metallurgy
Science and Art Department, Kensington	1864–1888	J. Percy
(national exams)	1889–1902	W. C. Roberts-Austen
London, King's College	1879–1919	A. K. Huntingdon, Professor of Metallurgy
Birmingham, Mason's College	1883–1886	T. Turner, Demonstrator in Chemistry
	1886–1894	T. Turner, Lecturer in Metallurgy
Sheffield, Technical School	1885–1889	W. H. Greenwood, Professor of Metallurgy and Engineering
Glasgow, West Scotland Technical College	1886–	A. H. Sexton (not associate), Professor
Camborne, Cornwall. School of Mines		J. J. Beringer, in charge of assaying
Staffordshire, County Council	1894–1902	T. Turner, Director of Technical education
	1892–	A. McWilliam, Lecturer on Metallurgy
Newcastle, Armstrong College (University of Durham)	1890s	H. Louis, Professor Mining and Lecturer on Metallurgy
Nottingham, University College	1895–1897	G. Melland, Lecturer on Chemistry and Metallurgy
The Exception:		
Cardiff, University College (established 1894)		No apparent RSM influence
After 1901		
Birmingham, The University	1902–1926	T. Turner, Professor of Metallurgy
	1906–1912	D. M. Levy, Assistant Lecturer
Sheffield, The Technical School (and University)	1902–1911	A. McWilliam, Lecturer/Assistant Professor
Newcastle, Armstrong College (University of Durham)	1901–1905	G. H. Stanley, Demonstrator in Metallurgy and Surveying
Woolwich, The Polytechnic	1904–1927	G. Melland, Head of Chemical and Metallurgy Department
London, Sir John Cass Technical Institute	1903–1914	C. O. Bannister, Head of Metallurgy Department
	1926–1945(?)	G. Patchin, Principal and Head of Metallurgy Department
London, Chelsea Polytechnic Institute	1911–1940(?)	W. A. Naish, Metallurgy, Lecturer in Department of Chemistry/Head of Metallurgy Section
Liverpool, The University	1920–1941	C. O. Bannister, First Professor of Metallurgy
	1928–1960s	S. J. Kennett, Lecturer
Swansea, Technical College	1901–1904	G. Melland, Head of Metallurgy Department
Swansea, University College (from 1920)	1921–1930	L. B. Pfeil, Assistant Lecturer/Senior Lecturer
	1927–1938	L. Taverner, Assistant Professor, Metallurgy
	1936–1938	G. L. Jones, Assistant Lecturer, Metallurgy
Llanelly, Technical College	1921–1926	H. Etherington, Lecturer in Metallurgy
Leeds, the University	1919–1932	P. F. Summers, Lecturer in Metallurgy
Abroad:		
Montreal, McGill University	1901–	A. Stansfield, Professor of Metallurgy
Johannesburg, University of Witwatersrand	1905–1939	G. H. Stanley, Professor of Metallurgy
	1939–	L. Tavener, Professor of Metallurgy

Bibliography

J. K. Almond, 'Factors Influencing Education in Metallurgy in England and Wales 1851–1950', M.Ed. Thesis, University of Durham., March 1983.

C. Renfrew, *Before Civilisation*, Johnathan Cape, London, 1973.

J. A. Charles, *Out of the Fiery Furnace*, Institute of Materials – Book 729, 2000.

D. R. F. West and J. E. Harris, *Metals and the Royal Society*, Institute of Materials – Book 568, 1999.

J. H. Pepper, *The Playbook of Metals*, Routledge, Warne & Routledge, London, 1861.

J. Percy, *Metallurgy*, John Murray, London, five volumes from 1861.

Anon, *A Short History of Imperial College 1845–1945 on the Occasion of Its Centenary in 1945*, Booklet.