Woodhead Publishing in Food Science and Technology

Instrumentation and sensors for the food industry

Second edition

Edited by
Erika Kress-Rogers and Christopher J. B. Brimelow

WOODHEAD PUBLISHING LIMITED

Instrumentation and sensors for the food industry

Related titles from Woodhead's food science, technology and nutrition list:

Food chemical safety Volume 1: Contaminants (ISBN: 1 85573 462 1)

This volume provides comprehensive information about contaminants in the food industry. The book opens with an explanation of risk analysis and analytical methods used for detecting contaminants in food products. This is followed by full details of relevant EU and USA regulations. The second part of the book provides information about specific contaminants.

Food chemical safety Volume 2: Additives (ISBN: 1 85573 563 6)

This volume provides comprehensive information about additives in the food industry. The book opens with an explanation of risk analysis and analytical methods in relation to the use of additives in food products. This is followed by full details of relevant EU and USA regulations. The second part of the book provides information about specific subjects including flavourings, sweeteners and colourings.

Food process modelling (ISBN: 1 85573 565 2)

A major trend within the food industry over the past decade has been the concern to measure, predict and control food processes more accurately in search for greater consistency, quality and safety in the final product. This book explores the current trends in modelling, their strengths and weaknesses and applications across the supply chain. It will be a valuable guide for production and technical managers within the food industry.

Details of these books and a complete list of Woodhead's food science, technology and nutrition titles can be obtained by:

- visiting our web site at www.woodhead-publishing.com
- contacting Customer services (e-mail: sales@woodhead-publishing.com; fax: +44 (0) 1223 893694; tel.: +44 (0) 1223 891358 ext.30; address: Woodhead Publishing Ltd, Abington Hall, Abington, Cambridge CB1 6AH, England)

If you would like to receive information on forthcoming titles in this area, please send your address details to: Francis Dodds (address, tel. and fax as above; e-mail: francisd@woodhead-publishing.com). Please confirm which subject areas you are interested in.

Instrumentation and sensors for the food industry

Second edition

Edited by

Erika Kress-Rogers and Christopher J. B. Brimelow

CRC Press
Boca Raton Boston New York Washington, DC

WOODHEAD PUBLISHING LIMITED
Cambridge England

Published by Woodhead Publishing Limited
Abington Hall, Abington
Cambridge CB1 6AH
England
www.woodhead.publishing.com

Published in North and South America by CRC Press LLC
2000 Corporate Blvd, NW
Boca Raton FL 33431
USA

First published 2001, Woodhead Publishing Limited and CRC Press LLC

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library.

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress.

Woodhead Publishing Limited ISBN 1 85573 560 1
CRC Press ISBN 0-8493-1223-X
CRC Press order number: WP1223

Cover design by The ColourStudio
Project managed by Macfarlane Production Services, Markyate, Hertfordshire (e-mail: macfarl@aol.com)
Typeset by MHL Typesetting Ltd, Coventry, Warwickshire
Printed by TJ International, Padstow, Cornwall, England

Contents

Preface

The optimization of industrial food processing

The enjoyable, everyday food in an industrialized society relies not only on agriculture and fishing but also on efficient food processing. Few people mill their own cereals, preserve and store their fruit and vegetables from harvest to consumption, churn their butter, ferment milk into yoghurt and cereals into beer, turn meat carcasses into joints, sausages and pâtés, or pound mustard seeds to prepare meal accompaniments. Few wish to restrict themselves to the local products in season and most prefer instead the variety that modern food production, processing and distribution can offer. Many use ready-prepared meals so as to spend their evenings with the children or with friends rather than in the kitchen.

In the early stages of the industrialization of food processing, the competition between manufactured goods centred mainly on the price at which they were offered; now quality and safety are in the foreground. A wider range of attractive food products has become affordable for a large proportion of the population through advances in food science and technology together with the development of a diverse range of efficient large-scale processing plant.

Many traditional batch processes have now been replaced by automated production methods, helped by the introduction of advanced process control systems in the 1980s. The signal processing and actuating capacity of process control systems is now adequate. The full potential of these systems, however, can be realized only if they are supplied with full and up-to-date information on the process to allow feedback or feedforward control. The development and knowledgeable application of sensors and instruments have become the key elements in meeting the consumer's expectations in the food industry to provide affordable, enjoyable, safe and nutritious products.

This has prompted the development of a wider range of sensors and instruments suitable for on-line and at-line measurements in the food industry, and also of modern instruments for the quality control (QC) laboratory. Many of the new instruments rely on a complex interaction with the food in order to determine properties of the food itself (such as composition) during processing. They extend the range of data inputs for

'sensible' process control (equipped with senses) well beyond the measurement of pressure, temperature, level and flow rate.

Other new instruments widen the range of applications for the measurement of the established variables, now allowing the reliable measurement of flow rate or temperature in food processes where this was previously impossible. Progress has also been made in the development of instruments for the assessment of food freshness and food safety, so that results are now often available within a day and a higher proportion of food ingredients and products can be screened to ensure good manufacturing practice.

In the choice of instrumentation, an analysis of the processing operation as a whole, together with an overview of the characteristics of the sensors and instruments available for on-line, at-line and QC laboratory measurements, will be the basis of optimum process control design. On-line and off-line instrumentation interlink in guiding process control and are therefore both included here. Calibration samples need to be chosen and correctly prepared, and a representative sampling technique and suitable reference methods must be selected.

For the reliable installation, calibration and operation of the new instruments, and for the correct interpretation of their readings, it is essential to understand the principles underlying the functioning of the instruments, the properties of the food and its processing environment, and their interplay. This approach also helps in assessing the many novel sensors and instrumental techniques now emerging to provide better long-term planning of process control optimization.

Special application details for instrumentation

Instrument engineers coming from the aerospace, defence, nuclear or petrochemical sectors sometimes underestimate the challenges of designing sensors and instruments for the food industry. They find adequate challenges for their skills when they encounter a wide range of temperatures, pressures and pH values; mixing paddles continuously scraping container walls where a sensor is to be mounted in contact with the product; the rejection of guards around fragile sensor components as germ traps; and a limitation of the choice of engineering materials to those compatible with food hygiene considerations. The occasional fracture of a sensor in the chemical industry may be an inconvenience; in the food industry it is a major incident when any sharp fragments, however small, are lost into the process stream, requiring the screening or safe disposal of many thousands of food product items.

A standard procedure for the maintenance of hygienic conditions in food processing is cleaning-in-place (CIP). This may sound harmless enough, but the periodic flushing of the food processing system with hot caustic soda (NaOH) solutions or pressurized steam places restrictions on the design of contacting sensors, particularly in the development of chemical sensors. Instruments based on non-contact methods are especially attractive to the food industry, being both intrinsically hygienic and easy to maintain. Such instruments are covered in the first part of this book.

In some applications, hostile conditions and restricted access to the contents of a process vessel are the main challenges, for example in a cooker extruder which allows the continuous production of intricately shaped and textured snack foods at a throughput rate of 400 kg/hour. High pressures, high temperatures, a feed/mixer screw scraping the interior surface of the heavy metal barrel and sometimes abrasive raw materials combine here to render the construction of reliable sensors difficult, even for pressure and food mix temperature.

More often, it is the variable and complex nature of the food itself that presents problems in the design and application of instruments. This is the case for non-contact volume and mass flow rate metering of many foods. The most interesting problems arise, however, in the measurement of food properties such as composition or rheology. An interdisciplinary approach is needed here to take account of the interaction between the instrumental method and the chemical and physical properties of the food and its environment (beyond the variables to be determined). This applies also to the assessment of food freshness or conversely to the determination and prediction of changes due to microbial activity or oxidative processes. A further aspect is the perception of the consumer which needs to be represented in instruments for the assessment of appearance and texture.

A rapid accurate measurement is often needed to maintain specifications within narrow margins. A pH value or water activity above specifications could lead to food spoilage during storage and distribution; a deviation to lower values could reduce the palatability. Too little preservative could endanger food safety; too much would be unacceptable to many consumers. Too high a water content could be infringing legal requirements or be associated with a water activity above specifications (with implications for food stability); too little water could result in an unattractive texture and an uncompetitive price for the food product.

Line speeds in automated continuous food processing and packaging are high, and this is both a motivation for the application of on-line instrumentation (or of rapid at-line methods) and a challenge in the design of instruments for this purpose. A further constraint in the design of instrumentation for the food industry is the fact that the price of the sensor or instrument will be important in the purchasing decision. Whereas the aircraft constructor may well buy the best instruments at any price, the food industry cannot afford to do so.

Instrument types and aspects

Instruments relying particularly on an interaction with the food or an environment typical for the food industry are described in this book. Practical applications already established are discussed and newly emerging applications are introduced. The considerations that will allow the best use of the interplay of the instrumental method, the food and the process are outlined as a basis for the successful development and implementation of instrument applications. Both on-line and QC laboratory instruments are included as they have to interlink in guiding process control.

Instrument users often wonder why the flood of novel sensors and measurement techniques described in scientific and technical journals or at conference results in a mere trickle of novel commercial instruments. This has been the case particularly in the field of biosensors and chemical sensors based on microelectronic devices where rapid developments have taken place in recent years. Part III of the book illustrates the complex and expensive process of developing a novel instrument from concept to commercial fruition with the help of two examples. The basis of recent commercial instrument developments based on novel chemical sensors and the feasibility of further food applications are also examined there.

For each instrument type, the underlying principles are described with emphasis on aspects relevant to food applications. The authors show the significance of the variables to be determined, and identify the variables actually measured (unless identical) and their

relation to the desired information about the food product. Considerations in the design, choice, calibration and running of instruments within a given group are discussed and illustrated with examples.

Aspects covered include hygienic design (e.g. flush fitting sensor heads or choice of non-contact techniques) or the adaptation of techniques to the variable nature of food ingredients. (In three cases, two chapters deal with different aspects of the same technique.) Factors influencing the accuracy and reliability of the technique (for a particular group of food products if applicable) are spelled out and compared with alternative techniques where applicable.

Instrument systems requiring a high computing capacity (such as real-time image acquisition and processing), employing ionizing radiation (such as gamma-ray density gauges) or relying on principles beyond the realms of classical physics are omitted to allow a full description of the instruments covered.

The authors' background

To promote an interdisciplinary understanding, these aspects are discussed here by scientists and engineers from a wide range of backgrounds including electronics, physics, chemistry, microbiology, food science and food technology. Their professional experience spans an equally wide range of areas within the fields of the development and application of instrumental methods for the food industry. The authors have worked in the management and optimization of quality control and quality assurance in the food industry, in the development of new techniques for this area, in applications development or overall management at an instrument supplier's laboratory, or in a research institute or association in close contact with the food industry.

It would be difficult to find a single author with full and detailed knowledge and practical experience in all the aspects of physics, electronics, chemistry, microbiology, food science, food technology and process control that are relevant to instrumentation in the food industry. Nor would it necessarily be helpful to set up a committee of authors to compose a text together. Instead, each chapter reflects the particular expertise of the author(s) based on their scientific or engineering background and their professional experience acquired in the practical application or development of instruments.

Aims and scope

For a wide range of established and emerging instrument types, this book treats the underlying principles and their implications for industrial applications. It sets out the complementary roles and characteristics of both the on-line and at-line instrumentation linked to the process control system and of the off-line instruments in the quality control laboratory. The significance of the measured variables for quality assurance and process management and the technical and commercial factors that determine the success or failure of an instrument are considered.

The book is intended to assist engineers and managers responsible for process optimization and quality assurance in the food industry in choosing, setting-up and maintaining instruments and in using their readings to best effect. It is also intended for use by engineers in the instrumentation sector who develop new instruments, adapt existing instruments for new applications or liaise with instrument users. In the choice

and installation of an instrument in a process line, the effective cooperation between instrument supplier and user is essential and this book aims to promote this by facilitating the communication between engineers and managers, from different backgrounds.

The chosen approach is also designed to help advanced students of instrument engineering, food science, physics or biochemistry who seek an introduction to instrumentation in the processing industries. Further, the book will be of interest to scientists active in research and pre-commercial development in the fields of process engineering, industrial instrumentation and process control.

Erika Kress-Rogers and Chris J. B. Brimelow

This page intentionally left blank

Contributors

Chapters 1, 13, 19 and 20

Dr Erika Kress-Rogers
(Alstom)
Hamannstr 75
D-40882 Ratingen
Germany

Tel: +49 2102 51192
Fax: +49 2102 705204
E-mail: ErikaKressRogers@compuserve.de

Erika Kress-Rogers has a background in experimental solid-state physics (Universität Karlsruhe) and in the physics of semiconductor devices (University of Oxford). She has carried out and coordinated a wide range of interdisciplinary R&D projects in the area of instrumentation and sensors for process control and quality assurance for the food industry while at the LFRA (Leatherhead Food Research Association), an international association that provides R&D, consultancy and technical services to food companies, government bodies and agencies. For seven years, she has served as Member of the International Editorial Board for the journal *Food Control*. She is the editor of the *Handbook of Biosensors and Electronic Noses: Medicine, Food and the Environment* and of the first edition of *Instrumentation and Sensors for the Food Industry*, the first handbook to provide a detailed account of a wide range of on-line and at-line measurement technologies for the determination of physical, chemical and microbial properties in the food industry. Dr Kress-Rogers now works as a Technical Editor for ALSTOM.

Chapter 2

Dr Alain Hugi
Nestlé Research Centre
Vers-chez-les-Blanc
P.O. Box 44
CH-1000 Lausanne 26
Switzerland

E-mail: alain.hugi@rdls.nestle.com

Dr Alain Hugi heads the Sensory Science Group in the Nestlé Research Center (Lausanne – Switzerland). Prior to joining Nestlé in 1996, he spent nine years at the Confectionery R&D Center of Kraft Jacobs Suchard, in Neuchâtel (Switzerland), occupying various positions ranging from analytical chemistry to sensory evaluation and to product development. His current interests include sensory texture assessment, the development of novel sensory and consumer testing tools, and sensory-instrumental relations. His academic background is in analytical chemistry (University of Lausanne)

Elisabeth Voirol is a sensory analyst at the Nestlé Research Center (Lausanne – Switzerland). In more than 20 years with Nestlé, she has worked on topics related to sensory perception, product optimisation, development of quality control methods and data acquisition systems. She has experience in a wide range of food products such as milk products, coffee, dehydrated food, pet-food, meat products, cereals, etc. More recently she has focused on sensory analysis of colour and the impact on consumer behaviour. Her background is in biology and neuro-physiology (Université Pierre et Marie Curie, Paris)

Chapter 3

Dr Douglas B. MacDougall
School of Food Biosciences
University of Reading
4 Japonica Close
Wokingham
Berks RG41 4XJ
England

Tel: +44 (0)1189 780174
E-mail: douglas.macdougall@talk21.com

Dr Douglas B. MacDougall lectured in sensory analysis at Reading University until his retirement in 2000. His research at Reading concentrated on the use of sensory analysis techniques to quantify food quality and the relationship of instrumental methods of colour measurement with the visual colour/appearance of food. Earlier, he worked in the Consumer Science Section at the AFRC (Agricultural and Food Research Council) in Reading and before that as co-project leader and Head of the Colour Group at the AFRC Meat Research Institute in Langford, Bristol. Projects at the Institute of Food Research included studies of the effects of animal stress and meat processing on the colour appearance, translucency and colour stability of fresh meat; optical instrument development for detection of meat faults; mathematical modelling of the colour and

texture of composite meat products and studies on the visual appeal of meat as affected by processing conditions, storage and display illumination.

His background is in food science; colour stability of food (Royal College of Science and Technology, now Strathclyde University, Glasgow, Scotland; Rutgers, The State University of New Jersey, New Brunswick, USA).

Chapter 4

Dr Pallavi Joshi
Nestlé Research Centre
Vers-chez-les-Blanc
Case Postale 44
CH-1000 Lausanne 26
Switzerland

Tel: +41 21 785 8540
Fax: +41 21 785 8554
E-mail: pallavi.joshi@rdls.nestle.com

Pallavi Joshi is a research scientist in the Department of Quality & Safety Assurance, Nestlé Research Center for Food and Life Sciences, Lausanne Switzerland. Her current research focuses on the use of colour physics and measurement as a tool for product development and quality control within the food industry.

Christopher J. B. Brimelow is head of Nestlé R&D Centre Shanghai Ltd. He was formerly Vice President of R&D at Nestlé/Westreco (Connecticut – USA). He has worked on the on-line and off-line measurement of the compositional and physical properties of foods, particularly colour.

Chapter 5

Dr Sarah Bee
Research Co-ordinator
R&D Department
Sortex Ltd.
Pudding Mill Lane
London E15 2PJ
England

Tel: +44 (0)20 8522 5136
Fax: +44 (0)20 8519 3232
E-mail: sarah.bee@sortex.com

Sarah C. Bee is Research Co-ordinator for Sortex Limited (London, UK). Sarah has worked in the R&D department for over three years, initially providing technical support for R&D, customer care, applications, production and sales and marketing. She currently initiates and subsequently manages Sortex's external research interests, either with universities or commercial consultancies. Sarah has a background in radiation physics (University College London), is a Chartered Physicist and Member of the Institute of Physics.

Mark J. Honeywood is Sortex's Technical Director. Through Sortex's membership of the DTI's Insider UK Enterprise (IUKE) scheme, Mark has been invited to present at the DTI Successful Product Development Seminars, held across the UK. Mark has first hand experience of implementing 'fast cycle time' techniques, including rapid prototyping, concurrent engineering and quality functional deployment. His background is in applied optics (Reading University). Mark is also a Chartered Physicist and a Member of the Institute of Physics.

Chapter 6

Dr Ian B. Benson
NDC Infrared Engineering
Maldon
Essex CM9 4XD
England

Tel: +44 (0)1621 852244
Fax: +44 (0)1621 856180
E-mail: ibenson@ndcinfrared.co.uk

Dr Ian B. Benson joined Ilford films in 1978 as a photographic research chemist. After a period in product development he joined Infrared Engineering as an applications engineer in 1981. After establishing laboratory and development facilities in the company's head office in Maldon and developing a wide range of measurements he moved into the sales management role and is now Director of Marketing for the Instrument Gauging Business.

James Millard studied applied physics at Coventry Lancaster Polytechnic, graduating with an honours degree. Having spent an industrial training year at Infrared Engineering he returned as an applications engineer in 1987 and was seconded to the USA operation in 1990. After managing the Technical Support Group for the global business he has now become a Product Manager for the instrument gauging business.

Chapter 7

Mr Ian Ridley
Land Instruments International Limited
Dronfield S18 1DJ
England

Tel: +44 (0)1246 417691
Fax: +44 (0)1246 410585
E-mail: ian.ridley@landinst.com

Ian Ridley studied applied physics at Sheffield City Polytechnic and since starting with Land Infrared in 1978 has been involved in the design and development of a wide variety of infrared-based temperature measurement equipment. He is now the Products Group Manager within the New Developments and Applications Department of Land Instruments International Ltd.

Chapter 8

Dr Ing. Christoph Reh
Nestlé Research Centre
Nestec Ltd
Vers-chez-les-Blanc
1000 Lausanne 26
Switzerland

Tel: +41 21 785 8990
Fax: +41 21 785 8553
E-mail: christoph.reh@rdls.nestle.com

Dr Ing. Christoph Reh works within the Nestlé Research Center (Lausanne – Switzerland).

Chapter 9

Dr Michael Kent
Kent and Partners
Scientific Services
162 High Street
Biggar ML12 6DH
Scotland

Tel: +44 (0)1899 220305
Fax: +44 (0)1899 220305
E-mail: mkentandp@aol.com

Mike Kent runs his own consultancy, Kent and Partner. He was formerly Head of Physics Section at the Torry Research Station, Aberdeen, where he carried out work on the dielectric properties of foods and the applications of such properties to compositional measurement.

Chapters 10 and 11

Dr Peter G. Berrie
Endress+Hauser Process Solutions AG
Christoph-Merian-Ring 23
4153 Reinach BL
Switzerland

Tel: +41 61715 7340
Fax: +41 61715 7301
E-mail: peter.berrie@solutions.endress.com

Dr Peter G. Berrie works as Marketing Communications Manager for Endress+Hauser Process Solutions AG, Reinach, Switzerland. A graduate of Imperial College, London, he spent five years in research at Euratom in Karlsruhe, Germany and Loughborough

University, England, before turning to technical communication in 1978. Dr Berrie arrived at Endress+Hauser GmbH+Co, Maulburg, Germany in 1990, as a technical author responsible for digital communication, level and pressure products. In 2000, he moved to his current position, where he is concerned with fieldbus technologies and process solutions that include sensors, monitoring and control. Endress+Hauser has an international reputation in the field of process instrumentation for the food and beverages industries.

Chapter 12

Mr Nicholas Denbow
ND Technical Marketing
7 Carisbrooke Close
Alresford
Hants SO24 9PQ
England

E-mail: nickdenbow@aol.com
www.nickdenbow.com

Nicholas J. Denbow is currently a self-employed consultant in industrial instrumentation, specialising in ultrasonic techniques particularly for liquid level and fluid flow measurement. Previously employed as Marketing Manager for Platon Instrumentation at Basingstoke and Technical Marketing Manager for Solartron Mobrey in Slough, he has worked in industrial instrumentation for the process industries for 25 years.

Chapter 14

Dr Ian Roberts
R&D/ QS
Nestlé Research Centre
Nestec Ltd.
Vers-Chez-Les-Blanc
1000 Lausanne 26
Switzerland

Tel: +41 21 785 8469
Fax: +41 21 785 8553
E-mail: ian.roberts@rdls.nestle.com

Ian Roberts performed his undergraduate and postgraduate studies in the department of Chemical and Biochemical Engineering at the University of Wales, Swansea. Here, he obtained Bachelors and Masters degrees, before focussing on rheology in his PhD entitled ‘Rheometry for Gelling Systems’. Having performed his thesis in collaboration with Nestlé UK, he then moved to the Nestlé Research Center in Lausanne, Switzerland in 1997, and now works at the Nestlé Product Technology Centre in Orbe, Switzerland.

Chapter 15

Dr James G. Lyng
Department of Food Science
University College Dublin
Belfield
Dublin 4
Ireland

Tel: +353 (0)1 7067710
Fax: +353 (0)1 7061147
E-mail: james.lyng@ucd.ie

Professor Brian M. McKenna is the Head of the Food Science Department at University College Dublin (UCD), and is also the Director of the Food Science Centre at UCD, in addition to being Vice President of UCD and editor of the *Journal of Food Engineering*. Professor McKenna lectures in physical properties of foods at UCD. His research interests include the freezing and drying of foods, membrane processing, cook-chill products, process modelling, shelf-life prediction and electroheating. Professor McKenna has experience in the measurement of rheological and many other physical properties of foods through his involvement in national and EU-funded food process technology and product property research projects.

Dr James Lyng is a lecturer in the Department of Food Science at UCD. In addition to giving courses in food process technology and food engineering, he also lectures in physical properties of food with Professor McKenna. His research interests lie in the area of alternative processing systems for meat and meat products (with particular reference to electroheating) and a large proportion of this work involves the measurement of physical properties of these products particularly their thermal, dielectric and also textural and rheological properties.

Chapter 16

Dr Wolfgang Röedel
Director and Professor
Federal Centre for Meat Research
Amselweg 16
D-95326 Kulmbach
Germany

E-mail: roedel.baff@t-online.de

Wolfgang Rödel is Director and Professor at the Federal Centre for Meat Research and Vice Head of the Institute for Microbiology and Toxicology (Kulmbach, Germany). His research interests include development and adaptation of electronic measurement procedures for the determination of the physicochemical parameters (water activity, redox potential, pH, etc.) of meat and meat products within the framework of HACCP and quality control.

Chapter 17

Dr Donald M. Gibson
BIODON International
43 Brighton Place
Aberdeen AB10 6RT
Scotland

Tel/fax: +44 (0)1224 322 777
E-mail: dmgibson@sol.co.uk

Donald M. Gibson is an independent consultant with his own company, BIODON International, established in 1994. He specialises in food microbiology and technology. He spent 30 years at the Torry Research Station, Aberdeen, latterly as Head of Microbiology, covering many aspects of microbiological food safety and quality. He is a Fellow of the Institute of Food Science and Technology, and a member of the Society for Applied Microbiology and of the Association of Official Analytical Chemists International (AOAC).

Chapter 18

Dr David Kilcast
Leatherhead Food Research Association
Randalls Road
Leatherhead
Surrey KT22 7RY
England

Tel: +44 (0)1372 822321
Fax: +44 (0)1372 836228
E-mail: dkilcast@lfra.co.uk

David Kilcast, BSc, PhD, FIFST is Head of Sensory and Consumer Science at Leatherhead Food Research Association and leads a research team working on the sensory quality and consumer perception of food. Research specialities are the perception and measurement of flavour and texture including flavour release from foods. He is past Chairman of the Sensory and Consumer Science Group of the Society of Chemical Industry, a member of the British Standards Institution Committee on Sensory Analysis and a committee member of the IFST Professional Food Sensory Interest Group.

Chapter 21

Dr Ursula Bilitewski
GBF-Ges. Biotechn. Forschung mbH
Mascheroder Weg 1
D-38124 Braunschweig
Germany

Tel: +49 531 6181 390
Fax: +49 531 6181 395
E-mail: ubi@gbf.de

Dr Ursula Bilitewski is senior scientist in the German Research Centre for Biotechnology (GBF), Braunschweig, Germany and lecturer in biochemistry at the Technical University Braunschweig. In the Division of Biochemical Engineering of the GBF she is responsible for the development and application of bioanalytical methods. She has a long experience with electrochemical methods and has used screen-printing technology for the production of enzyme electrodes to be applied in food and bioprocess analysis. There are also strong activities in the design of automated flow-through devices, which were used not only for enzyme, but also for immunoanalysis, and included electrochemical as well as optical detection methods. Recent research activities cover the analysis of proteins and protein activities, the analysis of genes and gene expression in combination with the miniaturization of set-ups.

Dr Anja Schmidt is a food chemist and was a PhD student and postdoc in Dr Bilitewski's group.

Chapter 22

Dr Axel Warsinke
Department of Analytical Biochemistry
Karl-Liebknecht-Str. 24-25
D-14476 Golm
Germany

Tel: +49 331 977 5124
Fax: +49 331 977 5052
E-mail: warsinke@rz.uni-potsdam.de

Dr Axel Warsinke works within the Department of Analytical Chemistry at the University of Potsdam.

Professor Dorothea Pfieffer and Dr Frieder Scheller work for BST Bio Sensor Technologie GmbH based in Berlin.

Chapter 23

Dr Ibitsam Tothill
Institute of Bioscience and Technology
Cranfield Biotechnology Centre
Cranfield University
Cranfield
Bedfordshire MK43 0AL
England

Tel: +44 (0)1234 754131
Fax: +44 (0)1234 752401
E-mail: i.tothill@cranfield.ac.uk

Dr Ibtisam E. Tothill is a senior lecturer in biochemistry and MSc Course Director for the MSc in Environmental Diagnostics at Cranfield Biotechnology Centre, Cranfield

University, Bedfordshire. She has developed strong research activities in immunosensors, affinity sensors, biosensors and diagnostics, which are at the forefront of research into food and environmental analysis. She has established an international and European reputation in these areas and this has enabled her to attract both private and public sector funding. Her recent research activities cover analysis of pesticides and herbicides, algae and cyanobacterial toxins diagnosis, heavy metals detection, bacteria and fungal detection. Dr Tothill has numerous publications and conference papers in the diagnostics and analysis arena. She has received a variety of prizes and awards including the Douglas Bomford Trust Award at the AgEng 2000, Warwick, UK.

Symbols

Chapter 13

c	speed of sound
υ	dispersive ultrasound phase velocity
Z	specific acoustic impedance
α	coefficient of ultrasound attenuation
α_{T}	coefficient of transmission through boundary
f	frequency
λ	wavelength
ω	angular frequency; $\omega = 2\pi f$
k	wave vector; $k = 2\pi/\lambda$
τ	relaxation time
ρ	density
P	absolute pressure
M	molecular weight
η	coefficient of viscosity
r_{p}	radius of suspended spherical particle
V	volume
T	absolute temperature
E_{M}	elastic modulus (as appropriate)
K	bulk modulus
Y	Young's modulus
G	shear modulus
K_{S}	adiabatic bulk modulus
β_P	coefficient of expansion at constan pressure
γ	ratio of principal specific heats c_P/c_V
c_P/c_V	specific heats at constant pressure, volume
κ	coefficient of thermal conductivity
R	universal gas constant
B	second virial coefficients
STP	standard temperature and pressure

Chapter 15

A_n	function in equation (15.22)
B_n	function in equation (15.22)
d	capillary tube diameter
e	distance from bottom of bob to cup or container
f	frequency
G	shear modulus
G'	storage modulus
G''	loss modulus
g	gravitational constant
H	separation of the two plates
h	difference in levels between liquid in reservoirs of a capillary viscometer
h_c	end effects correction in concentric cylinder viscometry
h'	height of bob for a rotary viscometer
I_2	Bessel function
K	constant for capillary viscometer
K_n	root of modifier Navier-Stokes equation
k	apparent viscosity or consistency index for power law fluid
k'	constant in Casson equation
k''	constant in Herschel-Buckley
L	length of capillary tube
L_o	sample length before deformation
L'_o	final sample length after deformation
n	power law exponent
Δp	pressure drop along a capillary tube
Q	flow rate
R_c	radius of cone
R_1	radius of bob in concentric cylinder viscometer
R_2	radius of cup in concentric cylinder viscometer
R_p	radius of the plate (parallel plate systems)
ΔR	$R_2 - R_1$
T	torque
T_e	equivalent torque
t	time (equations (15.8) (15.9) or (15.12))
t'	relaxation time (equation (15.4))
u_p	slope of plot of shear stress versus shear rate once yield stress has been exceeded
V	volume of liquid used in a capillary viscometer
α	conical angle
β	relaxation time
γ	shear strain $(= (L'_o - L_o)/L_o$, dimensionless)
$\dot{\gamma}$	shear rate (or rate of shear strain) $d\gamma/dt$
$\dot{\gamma}_{eff}$	effective shear rate
$\dot{\gamma}_{max}$	shear rate at the outer edge (rim) of the plate
$\dot{\gamma}_{meas}$	measured shear rate
δ	phase displacement angle
μ	viscosity
μ_0	viscosity at zero shear rate

μ_p	slope of straight line plot of shear stress vs. shear rate (equation 15.17)
μ_∞	viscosity at infinite shear rate
ω	angular velocity
π	3.1417
ρ	density
τ	shear stress
τ_b	shear stress at the bob
τ_y	yield stress

Chapter 17

b	number of bits
c	mass concentration of medium, g ml^{-1}
f	frequency, Hz
k	initial specific conductivity, S m^{-1}
l	effective separation of electrodes, m
n	population density, cfu ml^{-1}
n_0	inoculum density, cfu ml^{-1}
n_s	maximum possible population density, cfu ml^{-1}
n_D	arbitrary detection level of population density, cfu ml^{-1}
$\dot{n}$	growth rate, cfu h^{-1}
$\dot{n}/n$	specific growth rate, h^{-1}
$(\dot{n}/n)_0$	initial specific growth rate, h^{-1}
r	correlation coefficient
t	time, h
t_g	generation time, h
t'_g	$1/(\dot{n}/n)_o$, h
t_D	time after inoculation at which population density grows to a value n_D, detection time, h
t_L	lag time, h
A	electrode area, m^2
A_D	conversion gain
C_D, R_D	series capacitance and series resistance due to alignment of polar dipoles in double charge layer in fluid, F, Ω
C_{ox}, R_{ox}	series capacitance and series resistance resulting from the presence of an oxide layer at the electrode surfaces, F, Ω
C_{se}	lumped electrode capacitances C_D and C_{ox} (for R_D, $R_{ox} \ll R_s$), F
G_0	initial conductance of medium in test cell, S
G_s	subsequent conductance of medium in test cell, S
K	increase in specific conductance associated with production of single bacterial cell, per unit volume, S m^{-1} (cfu ml^{-1}) ^{1}
N	number of colonies counted on agar plate
R_{fs}	full-scale range of resistance, Ω
R_s	true resistance of medium in test cell, Ω
S	substrate mass, g
S_0, S_s	initial and final stationary mass of substrate, g
ΔS	mass of substrate metabolised by one bacterial cell, g

V, i	instantaneous voltage, current, V, A
$\|V\|$,$\|i\|$	peak voltage, current, V, A
$\|V_{\mathrm{m}}\|$,$\|i_{\mathrm{m}}\|$	mean voltage, current, modulus, V, A
X_{s}	reactance of C_{s}, Ω
X_{se}	reactance of C_{se}, Ω
Y	admittance, S
Z	impedance of R_{s} and C_{s} in series, Ω
ϕ	phase angle
γ_D	number of generations after inoculation at which growth is detected

1

Instrumentation for food quality assurance

E. Kress-Rogers, ALSTOM, Ratingen

1.1 Introduction

1.1.1 The role of quality assurance in the food industry

Quality control is essential in the food industry, and efficient quality assurance is becoming increasingly important. The consumer expects a wide range of competitively priced food products of consistently high quality. Each food item has to be safe, wholesome and attractive in appearance, taste and texture, and needs to be consistent with the product image. Variations within the same batch or between batches will have to be kept to a minimum as they are often interpreted by the consumer as indicating a fault, even when the differing product is of high quality.

The availability, quality and price of raw materials will place conditions on the food manufacturing operation, as will the prevailing structure of the retailing sector. More and more frequently, the product palette has to be adapted to changes in tastes and nutritional ideas, and to the appearance of competing products on the market. In the manufacture of each new product, there is the challenge of getting it right first time. Increasingly, food processing operations are technology-based rather than skill-based. Legislation on food composition and labelling will also play a role. Changes in legislation are driven by consumer demands and by international harmonization.

Food processing has a long history (Georgala 1989) and has always had two main purposes. The first is the conversion of agricultural products (or of fished, hunted and gathered foods) into palatable, attractive, digestible and safe foods. Cereals, for example, are virtually inedible without prior milling and cooking or fermenting; some fruits and pulses are toxic without prior cooking; and large proportions of the Asian and African populations can consume lactose only after conversion to lactate by fermentation. The second purpose is the preservation of foods for availability out of season, for years of lean harvests, and for transport to areas distant from agricultural producers.

The assessment of food still centres on its taste, aroma, appearance and nutritional value, and on its safety and stability. Optimized process control plays an essential part in maintaining the commercial viability of a food manufacturing operation in the face of changes in the food market and in the structure of the food industry. Advances in

Table 1.1 Food and drink market sectors in the UK (Bailey *et al.* 1991)

(a) Market sectors in 1990 by value (£ million)

Alcoholic beverages (inc. duty)*	21 864
1 Meat and meat products	9 882
2 Dairy products (inc. ice cream)	5 884
3 Soft drinks	5 286
4 Fresh fruit and vegetables	4 598
5 Bakery products	3 790
6 Confectionery	3 700
7 Frozen foods	2 250
8 Canned foods	1 686
9 Fish and fish products	1 606
10 Snack foods	1 287
11 Hot beverages	1 281
12 Cereal products	1 230
13 Oils and fats products	971
14 Ready meals	715
15 Meal accompaniments	678
16 Sweeteners, preserves	535

(b) Increase of market sector values in the UK from 1989 to 1990 (per cent)

Alcoholic beverages*	8.2
1 Frozen foods	11.2
2 Soft drinks	10.9
3 Ready meals	10.5
4 Confectionery	8.8
5 Fresh fruit and vegetables	8.2
6 Snack foods	6.5
7 Cereal products	5.4
8 Meal accompaniments	4.3
9 Hot beverages	4.0
10 Dairy products	3.5
11 Meat and meat products	3.5
12 Fish and fish products	3.3
13 Bakery products	2.1
14 Oils and fats products	1.4
15 Canned foods	1.1
16 Sweeteners, preserves	0.6

Notes:

* As much of the market value of the alcoholic beverages sector is the duty, the value has not been used to rank this sector.

1. For the cost/benefit assessment for a potential instrument development, the market values listed here need to be seen together with other factors such as the relative values of raw materials and final product or the growth rate and profit margins in a sector. For snack foods, for example, the added value would, in general, be higher than for canned foods or meat. Additionally, the viability of an instrument development is increased when it is relevant to health and safety (where legislation is linked to the availability of instruments) or to the price of commodities (for example, in the case of the water content of wheat) or where the specifications for the proportional content of an expensive ingredient need to be met.
2. All market sectors increased in value, but not all growth rates exceeded the rate of inflation.
3. Categories are not mutually exclusive.

microelectronics have provided fast data processing and have made efficient process control systems possible. In the 1980s, programmable logic controllers (PLCs) were widely installed in the food industry. Massive control centres were designed earlier for integral plant control; these centres were subsequently replaced by distributed control systems (McFarlane 1983; Vidal 1988).

Whichever control system is used, it still has to make do with a small number of continuously updated product variables, and often relies largely on inputs at long time intervals and with long delays depending on the assay time and the distance to the quality control (QC) laboratory. The effective application of both established and novel sensors and instruments will play a key role in gaining the full benefit of the potential that modern control systems offer.

Table 1.1 shows the sizes and growth rates of food and drink market sectors in the UK.

1.1.2 On-line, at-line and off-line instrumentation

For optimum quality assurance the manufacturer requires cost-effective methods for the rapid assessment, and preferably the on-line measurement, of the chemical and physical properties and the microbial status of raw materials, process streams and end products. Monitoring during the processing operation helps prevent expensive rework or disposal of out-of-specification product. Tight control is needed for variables that influence the stability of the end product towards microbial spoilage or oxidative rancidity. This concerns particularly the monitoring of temperature profiles during heat processing and storage, the control of cleaning-in-place procedures, and the measurement of the pH, water activity, solute concentration and preservative levels of the product. Water activity, usually measured as equilibrium relative humidity (ERH), cannot be measured rapidly. From an on-line measurement of the moisture content, the ERH can be deduced if the isotherm is well defined.

The trend towards continuous automated production in place of batch processing necessitates tight feedback loops based on on-line monitoring methods or, failing that, on rapid at-line techniques. Even when a laboratory method provides a result within one hour of taking a sample from the line, over a tonne of product or over 10 000 jars, tins or packs of food may already have passed the production line. The cost of rework or disposal for such a quantity is considerable. Alternatively, excessive safety margins with respect to legal requirements or customer specifications on the minimum content of expensive ingredients will lead to an uncompetitively priced product.

Prolonged holding times to await the outcome of assays, as a regular part of the process, lessen the benefits of continuous processing. Nevertheless, holding times of around eight hours are currently observed prior to filling certain sterilized foods, for example, in order to await test results from impedance monitoring for microbial assessment (Chapter 17). Refinements of this technique, based on more sensitive oscillometric detection of impedance changes with microbial growth, for example, have been investigated in order to shorten the assay time (Cossar *et al.* 1990).

The advances in plant for automated continuous production and in the signal processing capabilities of process control systems have stimulated progress in the development of many novel sensors and instruments for the food industry, often by technology transfer from other industrial sectors or from the clinical sector (Kress-Rogers 1985, 1986). These have since matured; sensor concepts have been developed into prototypes, and instrument types already available in the 1980s have become more

versatile and can now be applied reliably to a wider range of foods and processing situations or determine a wider range of target variables.

With the help of these advances in on-line and at-line instrumentation (Fig. 1.1), quality assurance (QA) is employed increasingly in the management of manufacturing operations. The quality control (QC) laboratory supports QA by checking and updating the calibration of on-line and at-line instrumentation and by providing a wide range of analyses and assessments that are not feasible for QA implementation.

The variables measured on-line and those measured off-line in the QC laboratory do not necessarily coincide. The process stream at the on-line measurement point will often be quite different from the sample taken to the laboratory, either due to changes during sampling and transporting, or because the laboratory test measures properties of the end product, whereas the on-line instrument measures precursors of these, or other properties of the process stream or the process environment that will determine the relevant properties of the product.

When the time taken for a QC laboratory result exceeds a day, as would be the case for many microbiological tests or trace analysis assays for toxins, it is often impractical to hold the food in quarantine during this time, as a perishable food may be well into its shelf-life by the time the result is available. Even when prolonged holding times can be observed, it is not usually possible to provide 100 per cent screening of the product with QC methods, and so a negative result is no absolute guarantee that the whole production volume is 'clean'. The test then becomes a means of checking that good manufacturing practice (GMP) is being observed, and the process has to be analysed to define the product and process variables that can be monitored and controlled in order to minimize the possibility of manufacturing a product having too high a microbial load, carrying pathogens or containing toxins. This approach is known as hazard analysis critical control point (HACCP) system.

For the overall control of the process, the monitoring of level and flow rate as well as pressure and temperature are essential (Chapters 10–13). Important for the stability of foods towards microbial spoilage are product properties such as the water activity and the pH as well as the microbial load and the concentration of preservatives and nutrients (Chapters 16, 17, 20–23). The integrity of the food packaging is also vital, and in modern modified atmosphere packs (MAPs) the initial headspace gas composition and its retention during distribution and storage will be relevant. The adherence to appropriate storage temperatures (and ambient humidities) throughout the shelf-life needs to be ensured. An important process variable influencing the shelf-life is the time-temperature profile of the process stream and, related to this, the excess pressure in the headspace. Also relevant are the concentration and temperature of cleaning liquids and their efficient application to process plant surfaces (Chapters 10, 12, 13).

In conventional cooking and canning operations, heating the interior of a solid food item (or a highly viscous liquid) relies on thermal conduction, often resulting in overcooking of the outer layers in order to ensure adequate temperatures in the centre. This is not to say that high surface temperatures are not desirable in processes such as roasting, where the Maillard reaction provides a range of flavours and colours in the presence of reducing sugars and amino acids at elevated temperatures. The flavour changes caused by prolonged boiling are, however, usually considered undesirable. Microwave or radiofrequency waves, on the other hand, can penetrate food and heat deeper layers directly. Direct ohmic heating is also possible by mounting electrodes in contact with a conductive food, and ohmic heaters allowing continuous automated heat processing are available.

With these methods, it is possible to retain more of the flavour and vitamins of the food, and yet to ensure a given minimum temperature to be reached throughout. In order to optimize such processes for the manufacture of products that combine adequate cooking, pasteurization or sterilization (as required for the product) with good flavour retention, analysis of the spatial distribution of the time-temperature profiles is necessary.

Several variants of time-temperature integration are used to assess the effect of heat processing on a food. The most common is the F_0 value, which expresses the degree of sterilization of a food. The F_0 value (expressed in minutes) is obtained by calculating the integral

$$F_0 = \int L \, \mathrm{d}t$$

where $\lg L = (T - T_{\mathrm{ref}})/Z$ defines the lethality L, and the temperature T has been measured in the coldest part of the food. For F_0 evaluation, $T_{\mathrm{ref}} = 121$°C and $Z = 10$.

For canned foods and ultra heat treated (UHT) products, F_0 values of 3 to 18 are used, depending on the types and numbers of spores present. This treatment results in commercial sterility, that is the remaining microorganisms will not cause spoilage or disease or have a detrimental effect on the product quality during its stated shelf-life (usually in excess of six months) (Lewis 1987).

Other values of T_{ref} and Z apply for the loss of nutrients by protein denaturation, vitamin destruction and certain other chemical reactions. A cook value can be defined, in analogy to the sterilization value F_0, to quantify the degree of cooking or overcooking and thus predict the loss of quality (flavour, nutrient levels) by heat processing.

Figure 1.2 summarizes the roles of on-line, at-line and off-line instrumentation in process management, quality assurance and quality control. Measurements relevant for product safety, stability and quality and for process management are listed in Tables 1.2 and 1.3. Instrument requirements and measurements for special concepts are given in Tables 1.4 and 1.5.

1.1.3 Technology transfer: opportunities and pitfalls

Instruments for measurements in quality control and in the control of processing operations in the food industry are often the result of technology transfer from other industries. The history of such new introductions has, in some cases, been characterized by initial successes, followed by a phase of disappointment with the instrument performance when the range of applications was widened. Subsequently, lost confidence had to be regained by defining the range of suitable application areas and by adapting the instrument or the setting-up and running procedures to particular applications. To avoid setbacks, it is necessary to understand both the instrument design and its underlying principles as well as the properties of the food and its processing environment.

Problems have, for instance, been experienced with some early applications of ultrasound flow meters in the food industry. These flow meters have the attraction of providing a non-contact measurement which facilitates maintenance and is intrinsically hygienic. However, for certain food process streams, unacceptable errors in the readings were observed until it was recognized that special designs or other types of flow meters were needed for samples with non-Newtonian flow profiles, or containing large particulates with flow rates differing from that of the carrier liquid, or where high attenuation of the ultrasound signal by the food liquid restricted the sampled flow volume to the outer layer (Chapters 12, 13, 15).

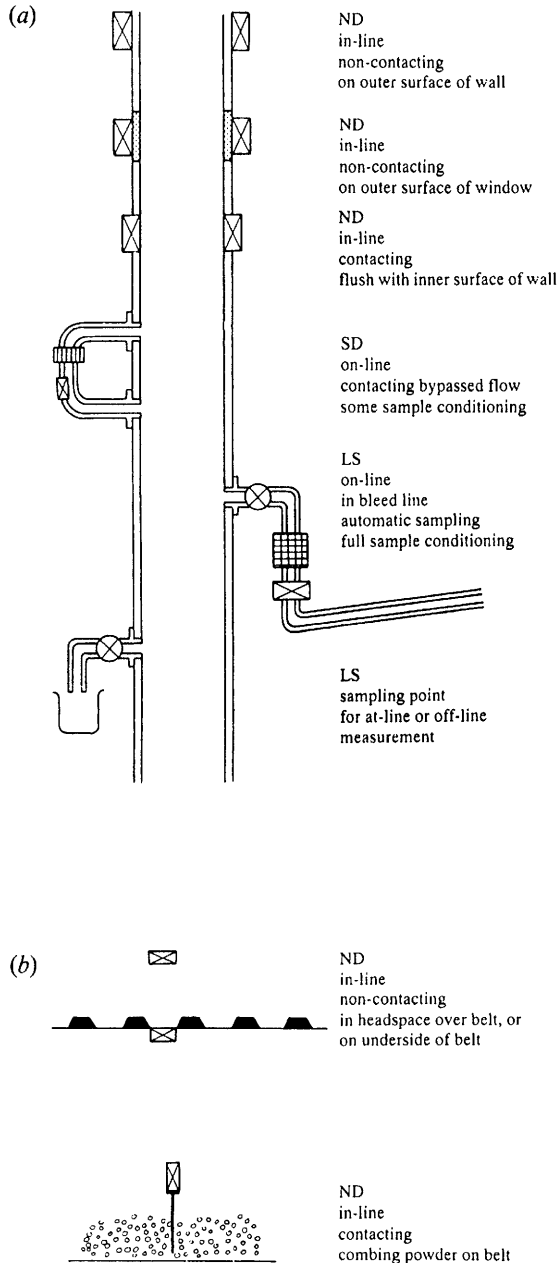
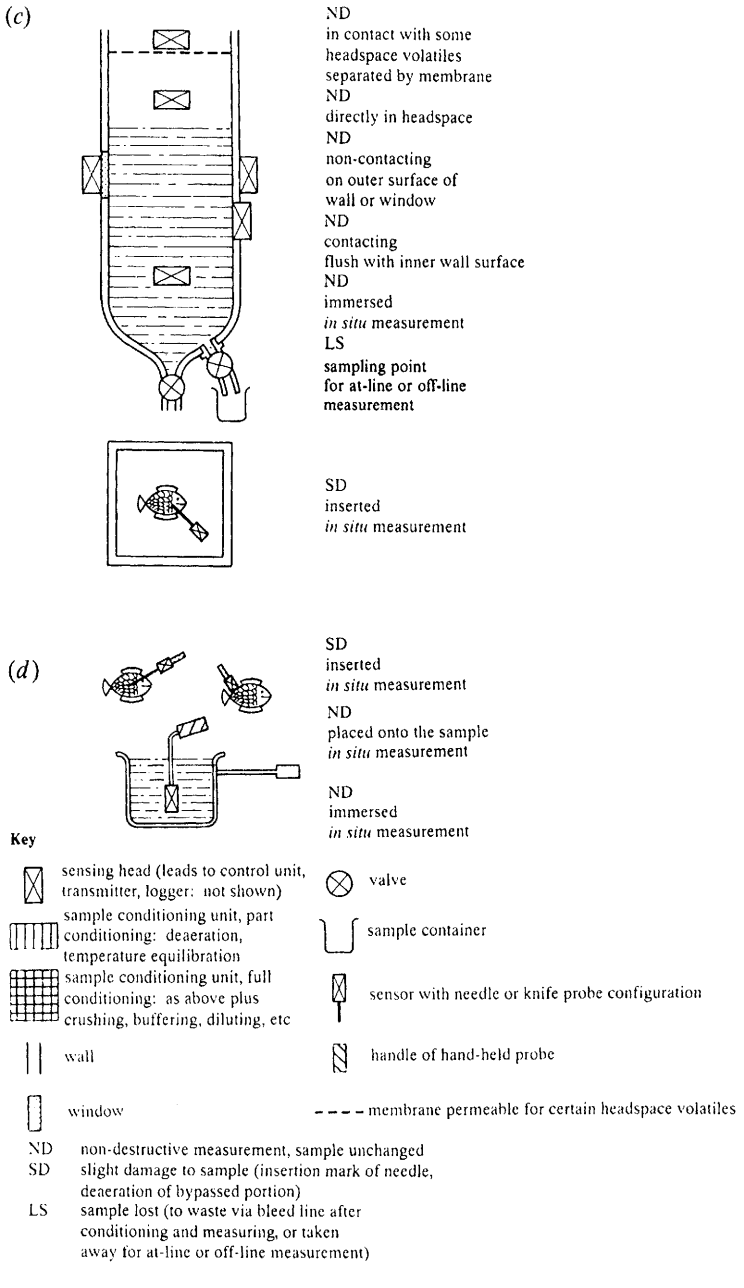


Fig. 1.1 Sensor configurations: (a) sensors on continuous processing lines (b) sensors on conveyor belts (c) sensors in batch processes (d) handheld sensors. The window material will depend on the instrument principle, for example Teflon for microwave transmission. Conditions for at-line measurements (not on-line, but in the production area) are more stringent than for off-line measurements (in the QC laboratory). At-line instrumentation and accessories should be free of glass components (potential foreign body hazard) and of toxic reagents that are not fully contained at all times. Also, mechanical robustness, tolerance of the processing environment (for example, of steam) and simple and rapid operation are essential.



1.2 Challenging conditions for sensors

1.2.1 Complex and variable samples

Many foods are highly complex in their chemical composition and in their physical structure. Gaseous, liquid and solid phases often coexist in the same product. Each phase may incorporate many different chemical compounds. One phase can be finely dispersed in another, or samples can be highly inhomogeneous or even largely separated. Within the

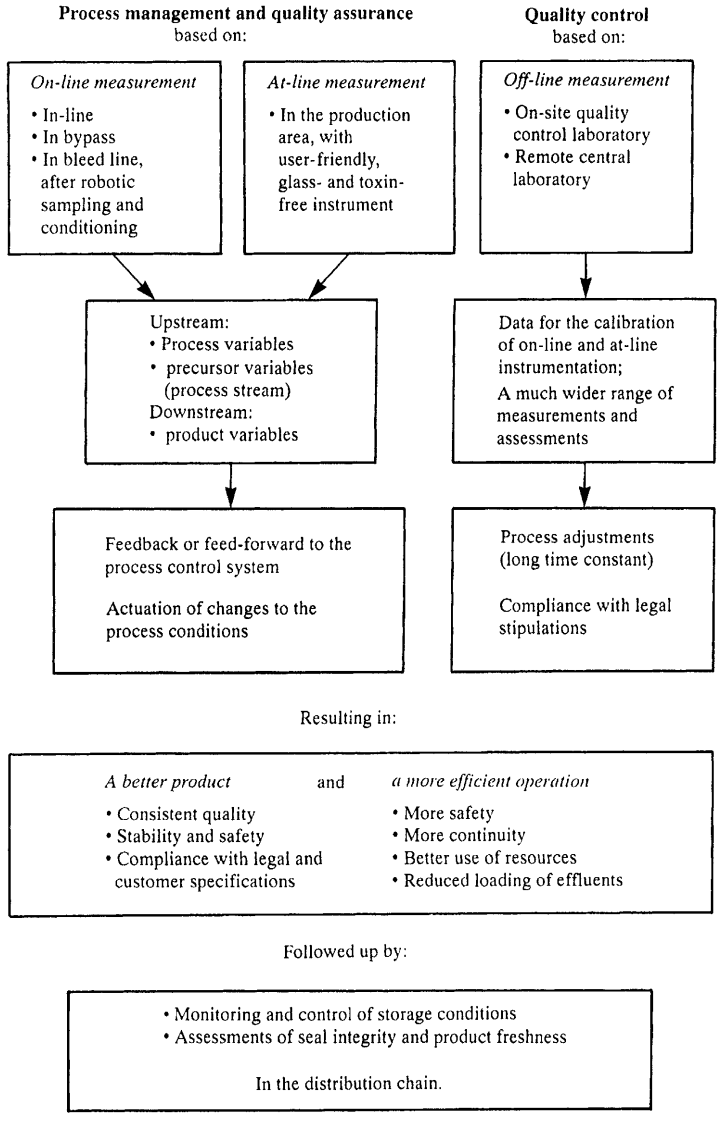


Fig. 1.2 Quality assurance (QA) and quality control (QC) in food processing operations.

Actuation of process changes

A programmable logic controller (PLC) may be used to operate actuators that cause changes in process conditions in dependence of a measured variable. Where complex relationships exist between the measured variables and the process, an expert system can provide an automatic evaluation of a set of measured values and a decision on corrections to the process conditions. Combined inspection/sorting systems are used to identify and remove, for example, products that contain foreign bodies or that are mis-shaped.

In-situ measurements in batch processes

The scheme needs to be adapted for industrial batch processing operations, for batch processes in catering establishments and for measurements in food distribution. *In-situ* measurements with dip- or stab-probes, or with instruments installed during the batch process or permanently in a processing vessel or storage container can be used here.

Calibration

The choice of the reference method can influence the calibration. Systematically different values can be obtained, for example, between drying and titration methods for moisture determination in the laboratory.

Table 1.2 Measurements in quality assurance and quality control

Measuring properties relevant for product quality

- appearance (colour, gloss, shape)
- texture, mouthfeel, pouring characteristics
- flavour (aroma, taste)
- nutritional value
- functional properties
- composition according to specifications

Screening for product safety
chemical contamination (agricultural residues, endogenic toxins, ...)
microbial contamination (total load, presence of pathogens and spoilage organisms, ...)
contamination with unwanted genetically modified organisms
foreign matter (metal or glass fragments, insects, stones, ...)
unwanted matter (nutshells, fruit calices, ...)

Assessing product stability towards
- chemical reactions (such as oxidative rancidity)
- microbial growth (due to inappropriate pH, water activity, preservative concentration, either in the product as a whole or in a small region within the product)
- microbial or chemical contamination (due to defective or inappropriate packaging) (including the migration of compounds in the packaging material into the food)
- migration of water or fat (between pastry shell and filling, between food and environment)
- loss of protective atmosphere (due to defective seal) (for products packed under a modified atmosphere designed to suppress microbial growth or oxidation)

liquid portion, fat and water may be combined in an emulsion, or even in a double emulsion. Water can be present as free water or bound in many different ways: as water of crystallization, bound to protein or starch molecules, entrapped in biopolymer networks or absorbed on solid surfaces of porous food powder particles. Active enzymes may be present, either in the tissues of fresh meat or produce, or within the cells of the microbial flora.

Table 1.3 Measurements in process management

Objectives
- ensure safety and continuity of the processing operation
- maintain conditions for in-spec. products
- use resources efficiently (labour, raw materials, energy, machinery)
- reduce loading of effluents (e.g. of waste water with organic matter)

Measurements
- pressure
- temperature (also spatial distribution of temperature and time integral over temperature),
- pH
- mass and volume flow rates of liquids and particulate solids
- fill levels of liquids and particulate solids bulk density, weight apparent viscosity

Also wanted, but more difficult to achieve on-line:
- chemical composition (gross and fine)
- complex rheological properties (yield value, elasticity, ...)
- particle, droplet, bubble size, (average size and distribution)
- volatiles evolved in cooking, baking, roasting, drying operations

Table 1.4 Instrumentation requirements, on-line

- hygienic sensing head
- contaminant-free (no reagents, no microbes)
- no foreign body hazard (no fragile glass components), robust
- CIP (cleaning-in-place) tolerant if permanently installed on-line (alternatives for specific chemical measurements: instruments with disposable sensing element which must be easily replaced and inexpensive, or, in certain applications, robust, easily cleanable dip-probes or stab-probes for *in situ* measurements)
- reproducibility in accordance with task, reliable, low maintenance effort suitable for complex chemical and physical sample properties
- total cost (capital, maintenance, running) in good proportion to benefits

Samples in the food industry are, moreover, very diverse and highly variable. The season, the region of origin, the harvesting and storage conditions as well as the processing steps (such as the fermentation of cocoa beans) will all influence the properties of the raw materials. New food-processing technologies are being introduced to provide an ever wider range of food products that require frequent adaptation to changing consumer preferences and market structures.

1.2.2 Hostile conditions and stringent hygiene requirements

The pH extends over a wide range, with low values for vinegar or citrus fruit juices and high values for caustic cleaning solutions used regularly in-line. A wide range of pH values is also encountered in the monitoring of effluents, that is waste liquids formed in washing raw materials or in cleaning container surfaces, for example.

Table 1.5 Measurements for special concepts

HACCP – Hazard analysis critical control points
On-line measurements
- pressure, temperature (spatially resolved, time integral)
- relative humidity
- product pH product solute content
- strength and surface coverage of solutions used for periodic cleaning of machinery

Off-line measurements
- water activity (as equilibrium relative humidity)
- pH (spatially resolved) preservative concentration
- microbial contamination of ingredients including water
- microbial contamination on machinery and on other surfaces in the production area

Marker (indicator) approach
For the on-line, at-line or *in situ* assessment of
- microbial pre-spoilage status
- oxidative rancidity status
- level of heat-induced deterioration
- progress of ripening or conditioning browning potential
- end of heat processing operation

Measured are chemical or physical variables that have first been identified as indicative of the complex condition of interest. Usually, a given marker (or indicator) variable will be valid for a particular group of products only. (See Section 1.3.4 and Chapter 19.)

Temperatures vary from freeze-drying conditions (−50ºC or lower) to hot frying fat conditions (up to 250ºC) and roasting operations (320ºC or higher). Processing and packaging under vacuum is employed, and excess pressure is used in cooking and canning operations. A retort would typically operate with pressures of 60–600 kPa, that is 0.6–6 bar (McFarlane 1983, see Appendix B, Tables 3 and 4). Particularly severe conditions can prevail in a cooker extruder, where both high pressures (over 10 MPa, that is, over 100 bar) and high temperatures (around 200ºC) can be encountered. Moreover, the inner barrel surface is scraped by the extruder screw, and access to the food mix within the barrel or in the extruder head is certainly restricted. The food mix itself can be quite abrasive in the early part of its passage through the extrusion cooker. Maize grits, for example, may be present, expanding later on in the fashion of popcorn. These conditions present a challenge even for the design of pressure and temperature (p/T) probes. (For a description of extrusion cookers see McFarlane 1983; O'Connor 1987; Wiedmann and Strecker 1988.)

Nevertheless, sensors for the measurement of moisture and other variables are under development for this hostile environment. Radiofrequency open-ended coaxial probes have been designed to fit into the openings foreseen for the bolt-type p/T probes designed for extrusion cookers, and a microwave stripline has been constructed for mounting in an extrusion head (Chapter 9).

In general, the conditions in the food industry are more favourable than in a cooker extruder. A common challenge for *in situ* sensors is, however, the cleaning-in-place (CIP) procedures used in many processing systems in the food industry (Kessler and Weichner 1989). These usually involve flushing with hot caustic soda solutions (NaOH) which can corrode probe surfaces, and this is particularly unfavourable for many chemical sensors. High-pressure steam cleaning is another effective CIP procedure; this will challenge the mechanical and thermal stability of a sensing head.

The strict hygiene standards in the food industry also demand that in-line probes in contact with the sample must have crevice-free surfaces. This applies both to the sensing head and to the mounting flange area. For aseptic processes, any sensor surfaces in contact with the sample need to be tolerant to CIP procedures. In fermentation processes, the use of a disposable sterilized sensor can be an option.

Any danger of chemical contamination of the food by sensor reagents or components of slight solubility must be eliminated. The introduction of foreign bodies, particularly glass or metal fragments, in the case of damage to the sensor, must also be prevented. Food powders with a very low moisture content can accumulate high electrostatic charges, and sensors that may come into contact with such powders (typically starch-based products) must be designed to minimize the risk of a dust explosion.

The transducer and electronics may have to withstand exposure to water, steam or airborne dust. Occasionally, they may be enrobed in chocolate or coated with a thin film of condensed polymerized frying oil. Sensors in contact with food or food volatiles are often subject to fouling by proteins, fats or starch particles (Kessler and Weichner 1989).

Electromagnetic interference (EMI) will be encountered in industrial microwave ovens or in direct ohmic heating appliances. There will also be electromagnetic noise and mechanical vibrations from pumps, hoppers and other plant. Rotating mixer paddles scraping the walls of a vessel may be in the way of a radiated signal or restrict the positioning of a wall-mounted probe.

1.2.3 Non-contact techniques and robotic sampling and conditioning

Given the often hostile conditions for invasive sensors, either during the processing of foods or during the periodic cleaning operations, and the always stringent hygiene and other food safety requirements, non-contact measurements are particularly attractive to the food industry. These can be based on the interaction of electromagnetic waves, including gamma-rays, light, infrared radiation, microwaves or radiofrequency waves, or of ultrasound signals with the sample. Such methods do, however, require an awareness of the nature of the interaction of the applied signal with the food, its headspace and container. This understanding is needed at all stages of instrument development, in the choice of suitable applications and installation points, during the setting-up and calibration procedures (including the preparation of training samples), in the running of the instrument and in the evaluation of the readings (Chapters 6, 7, 9, 11, 12, 13).

To develop the wide range of sensors desirable for in-line measurement in the food industry would be prohibitively expensive. Not only different target variables, but also different analytical ranges and variable chemical and physical environments, would have to be catered for. The recognition of the cost that would be associated with the development of in-line sensors for a wide range of chemical, physical and microbial properties, each for a wide range of diverse applications, has led to an interest in techniques that make the best of the sensors available.

Robotic sampling and sample preparation systems allow rapid measurements at short intervals by enabling the use of sensors that would otherwise be confined to laboratory applications. This approach has been implemented particularly in Japan. An example is shown in Fig. 1.3 (see also Chapter 20, Section 5).

1.3 Interpreting the readings

1.3.1 Measured variables and target variables

In non-contact measurements, the relationship between the measured variables and the target variables is often complex, so that a given calibration will apply only to a limited range of food products and processing conditions. For instance, a water content measurement based on near infrared reflection analysis will have to rely on a predictable relationship between surface moisture and average bulk moisture content; or, the monitoring of solute concentration by a measurement of ultrasound velocity depends on a

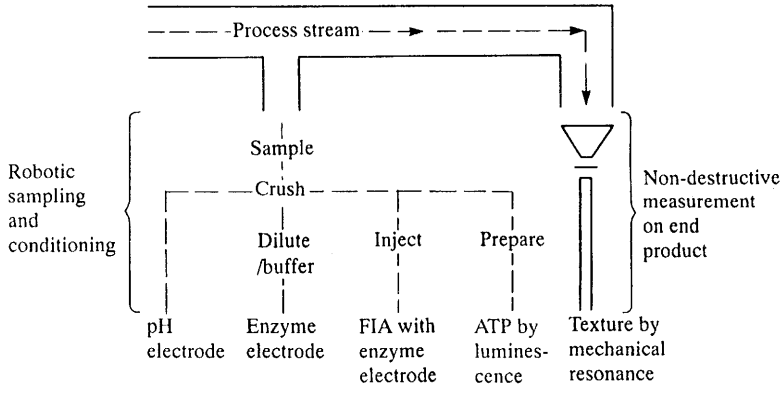


Fig. 1.3 Robotics approach.

constant composition of both the solute and the carrier liquid (and on compensation for temperature changes, as is the case with most measurement methods). Care in the setting up and calibration are essential, as is the choice of appropriate applications. Non-contact in-line techniques will then provide highly reliable continuous measurements that allow process adjustments before an out-of-specification situation arises (Chapters 6, 9, 12, 13).

In contact measurements also, the measured variable is not always the target variable. For example, pH is often measured as an indicator of acid concentration (provided that the acid composition is known). Ion activity is often measured in place of ion concentration. Frying oil samples are taken for an at-line measurement of colour or free fatty acid (FFA) content in order to infer the degree of frying-induced polymerization and oxidation. Yet, both colour and FFA-content are highly dependent on other factors such as the oil type, the food fried and the frying conditions. (See Chapters 19 and 20 on oil quality and pH, respectively.)

In the QC laboratory, the assay of chemical composition can involve deductions from the proportion (by weight) of sample becoming volatile or dissolved under certain conditions. Clearly, such assay types, and many others, need to take into account the nature of the sample. Indeed, the official methods prescribe sample-specific assay procedures.

In addition to these relationships between measured and target variables, the significance of a target variable for the manufacturing operation needs to be considered. This can reside in assuring the safety and stability of the food, the enjoyment in handling and eating it, and the efficiency in producing it or in complying with legal regulations or customer specifications. These aspects are discussed in Section 1.4.1.

1.3.2 Relationship between in-line and QC laboratory methods

Differences between the readings of the in-line instrument and the off-line quality control (QC) laboratory results are, at times, unjustly blamed on the in-line method. The QC reference assay can be applied only to a small fraction of the sample volume passing the sampling point, and this alone can lead to a result differing from an in-line method that provides 100 per cent screening. Moreover, different laboratory methods will often give systematically differing results between them for a particular food sample type, even though they may give identical results for other sample types (see, for example, Fig. 1.4).

Often, the definition of the measured variable depends on the laboratory reference method used. For example, for an oven-drying procedure, moisture is defined as that part of the sample that will be driven off at the applied temperature and pressure. For a titration procedure, on the other hand, the relevant part of the water is that which can be extracted from the food matrix (or dissolved and dispersed together with food solids) and brought into contact with the reagent. For this reason, official analysis protocols exist for different food types; for accurate results to be achieved, an instrument used in the QC laboratory needs to be calibrated for each food type against the official method.

In some situations, the comparison between the on-line reading and the chemical or rheological QC result, for example, is not strictly valid because the sample changes on removal from the line and during the preparation and analysis steps in the QC laboratory. Oxidation, thinning, thickening, fermentation or other changes can occur during this time, and homogenization steps can cause the breaking up of tissue cells, leading to changes in the composition of the juices and also exposing the cell contents to oxidation or other reactions.