

*Welding
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HEALTH HAZARDS AND BIOLOGICAL EFFECTS OF
WELDING FUMES AND GASES

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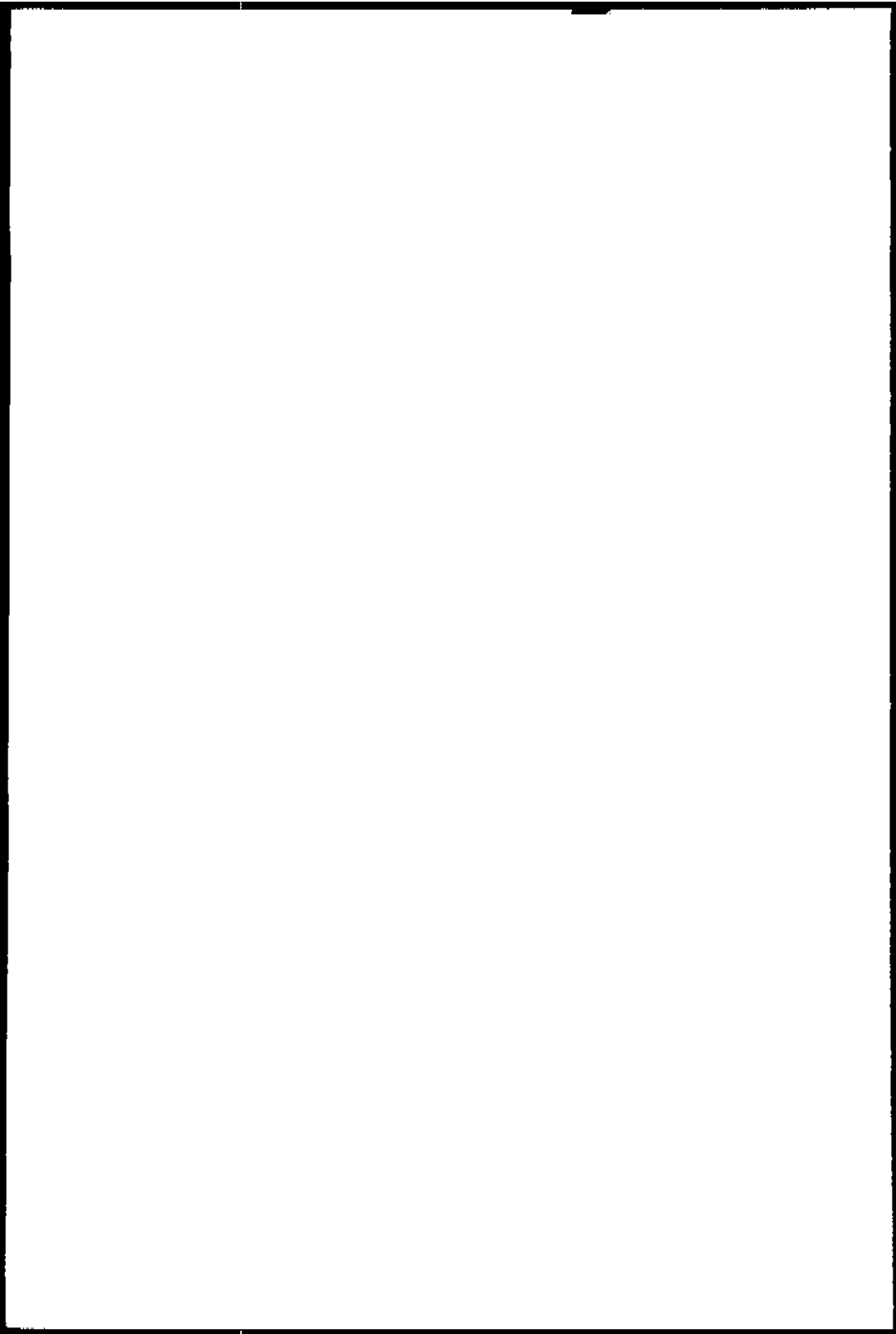
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Introduction

This interdisciplinary Conference, which was organized jointly by the Commission of the European Communities (CEC), the World Health Organization Regional Office for Europe, the Danish Welding Institute and the International Agency for Research on Cancer (IARC), was held at the Regional Office in Copenhagen. Its aim was to establish the current state of knowledge concerning the effects of welding on health, and to discuss priorities for reducing health risks and for future studies within this large industry.

The Regional Office became involved with welding in 1980, together with the United Nations Development Programme on international control of toxic substances, when it was recognized that quantitative risk assessment and risk management of exposure to welding fumes had been neglected. The involvement of CEC in the health and safety of welders is preventive and action-oriented within the framework of the Action Programme on Safety and Health at Work, and research-oriented in the context of the continuing Coal and Steel Medical Research Programme. The Danish Welding Institute has a long tradition in the development of welding technology and has a mandate to assess new techniques with a view to preventing the introduction of hazardous technologies. IARC has a particular interest in the potential carcinogenic effects of welding exposures. The joint organization of this first International Conference reflected the interests of the four organizations in these different aspects of welding.

More than 220 occupational health specialists, research scientists, engineers, industrial managers, trade union representatives and health policy managers from 24 nations attended. The 18 invited papers provided reviews of the major topics, and 28 oral contributions

and 45 poster presentations complemented the scientific aspects of this Conference.

The following four main areas were considered: the nature and quantity of welding fumes and gases produced by the various welding methods currently used; measurement of exposure to welding fumes and evaluation of their effects on experimental animals and cell cultures; epidemiological evaluations of the health of welders; methods for minimizing the respiratory health risks faced by welders.

Background

Welding has been practised as a technology for joining metals throughout the twentieth century, and in industrialized countries more than 1% of the labour force is engaged in welding. Major new developments have occurred since 1940, accompanied by a spectacular growth in the variety and extent of applications. There exist many different types of welding process for the joining of most metals, e.g. mild steel, aluminium and stainless steels. New technologies are continually being developed to join new materials such as high performance steels and light alloys. Most techniques and applications are now almost universal, although different methods have traditionally predominated in certain countries.

Welding consists of those processes whereby the metals to be joined (parent metal) are melted by an electric arc or flame, in most cases using coated electrodes or wires (the consumables) as filler materials, which are designed to contribute metal to the joint area resulting in a weld with the proper metallurgical and mechanical properties.

Joining techniques that make use of low-melting-point alloys, without melting of the parent material, are

called brazing or soldering; these are not used by welders and hence are not discussed below.

Because welders frequently inhale high concentrations of fumes and gases during welding, interest in potential health problems has centred around respiratory effects, including lung cancer, particularly in relation to the presence of chromium and nickel in the fumes of stainless steel welding.

Welding techniques and emissions

Types of technology

One of the most common processes, manual metal arc (MMA) welding, is performed with hand-held electrodes coated with suitable slag-forming flux to protect the arc. One process, tungsten inert gas (TIG) welding, uses only an electric arc produced by a tungsten electrode, the joint being protected from oxidation by an inert gas shield. A more recent development has been the use of continuous wire, with inert or active shielding gas, in a semi-automatic process of high-productivity (metal inert gas (MIG) or metal active gas (MAG)) welding. These four techniques account for 60-80% of all welding, but a number of other technologies are also in use or in development, including oxyacetylene (autogen), submerged arc, laser beam and electron-beam welding.

The material most commonly welded is mild steel, which in the shipbuilding industry is frequently coated with an anti-rust paint or shop primer, but stainless steel and aluminium welding are also widely practised.

Characteristics of emissions

High concentrations of particulate fumes and gases are produced whenever an arc is struck or a flame is used to melt the parent metal, and many systematic studies

have been conducted on the characteristics of fumes and gases produced in the laboratory when different methods and parent metals are used.

A number of factors affect the total amount of fume produced per unit time by a given process and application (fume formation rate (FFR)). In MMA welding, the FFR is proportional to both welding current and, at constant current, voltage (or arc length), but it is also significantly affected by the geometry of the joint. In MIG welding, the FFR is a complex function of the current, voltage and shield gas and depends primarily on the turbulence in the arc, which determines the degree to which air is mixed with the arc gases.

The composition of the fume is determined primarily by that of the consumable, which contributes 80-95% of the fume. The type of consumable used is, however, determined largely by the chemistry and metallurgy of the parent material, e.g. aluminium alloy wire is used only on aluminium parent metal. The fume consists mostly of the condensed vapour of the core wire, but the oxidizing potential of the arc, which depends on various factors, particularly the type of shielding gas or flux, determines the relative amount and composition of the fumes and gases. The presence of flux-forming coating on MMA electrodes, or within flux-cored wire, also contributes significantly to the non-metallic components of the fume. The relative concentrations of elements in the fume are very different from those in the consumable since some elements are preferentially vaporized, and the concentration of elements with lower boiling points, such as F, Mn, Zn, Pb, As, Ca and Si, are significantly enriched in the fume over their (sometimes trace) concentrations in the consumable and parent metals.

Each welding technique and application produces a characteristic range of particulate composition and morphology. MMA fumes consist of particulates that are either condensed metal vapour or a mixture of metal and

slag condensed from the slag-forming coating, which decomposes, melts and vaporizes during welding. For MMA/mild steel, the primary constituents are Fe, Mn, Si, Na, Ca and especially F. The use of stainless steels introduces Cr and Ni into the fume. MIG fumes are less complex because of the absence of flux coating. MIG/mild steel fume consists primarily of Fe, Mn and Si and their oxides, while MIG/stainless steel fume also contains Cr and Ni and their oxides.

Electron microscope studies show that the particulates are morphologically complex. Long chains of similarly sized particulates are frequently formed, which may collapse into spherical or raft-shaped agglomerates in the high humidity of the respiratory tract. MIG and MMA processes produce fumes with mass median aerodynamic diameters in the range 0.1-0.5 μm , which are predominantly deposited in the lower respiratory tract, but larger particles may also be produced by spray from the arc or by spatter from slag from the flux. These larger particles consist largely of light elements such as Al, Si, K, Na, F and water-soluble compounds, while the smaller particulates are predominantly composed of heavy metals such as Fe, Ni, Mo, Mn and Cr and their oxides.

X-ray diffraction studies indicate that a significant fraction (20-90%) of the fume is crystalline. The composition of MMA fumes is complex, but the predominant compound in all MS fumes is a magnetic iron oxide (Fe_3O_4) (a spinel). Other crystalline substances tentatively identified are NaF, CaF, KCaF_3 , MgO, K_2CO_3 , Na_2CO_3 , MnFe_2O_4 and KCaF_3 . The fumes from MMA/stainless steel and MIG/stainless steel welding contain Cr and Ni in a wide range of oxidation states and solubilities. MMA/stainless steel fume contains approximately 3-4% Cr, almost all of which is in the hexavalent state (Cr[VI]) and is soluble in water, while MIG/stainless steel fumes contain 14-18% Cr. Cr[VI] is highly reactive and is

often rapidly reduced to Cr[III]. The relative Cr[VI] content of MIG/stainless steel fumes is apparently very low for spray arc (20-25 volts) conditions (0-0.5%), but has only recently been shown to be higher for short arc fumes (15-18 volts) collected in a liquid rather than on paper filters (0.5-5%). A wide range of methods has been used to analyse the fumes, but quantitative analysis of certain fumes, e.g. MIG/stainless steel, is still difficult.

Welding produces a number of gaseous pollutants, either through the thermal decomposition of the electrode coating (CO, CO₂, F, HF, etc.) or the pyrolytic decomposition of organic substances such as paint, anti-rust coating, etc., present on the workpiece. NO and NO₂ are also produced from the surrounding air. The inert gas welding of aluminium and stainless steel is accompanied by the production of significant concentrations of ozone due to the interaction of ultraviolet radiation and oxygen. Production rates and breathing zone concentrations of gaseous pollutants depend on the process and the process parameter (current, voltage, shielding gas, consumables, etc.).

Assessment of exposure

Ambient air measurements

A number of sampling strategies have been developed for monitoring workplace concentrations of fumes and gases so as to determine time-weighted average (TWA) concentrations in the breathing zone of the welder. Individual breathing zone measurements of particulates are made by placing the samplers behind the face mask. Gas sampling is most frequently performed by the use of sampling tubes in front of the mask. Background particulate measurements are made with stationary (high volume) samplers.

Although many processes have a similar fume formation rate for a given application, workplace monitoring shows that there exists an extremely wide range of TWA breathing zone levels, either for different workers or for the same worker on consecutive days. Variations of an order of magnitude are common, and peak concentrations of both fumes and gases measured over short periods can vary by a factor of several hundred above the background level.

A large number of factors affect the instantaneous and average breathing zone concentrations. One major factor that affects the TWA breathing zone concentration is, of course, the length of time during which a welder actually welds (the arcing time or intermittance), which can vary from under 30% for difficult MMA jobs to more than 90% for certain MIG applications. In addition, effective general ventilation may greatly reduce background steady state fume levels and hence TWAs, while the effective use of local exhaust and point extraction (when available) will reduce both TWA and peak breathing zone levels.

There are large and consistent differences among methods, with TIG/stainless steel producing the lowest and MIG/aluminium the highest average TWA levels. Individual work practices are also important, however, and 10% or more of the welders in any technology/application may have TWA exposures more than four times the average for that technology.

Biological monitoring

Animal and cell culture studies demonstrate that chromium and nickel are the most toxic metallic elements in stainless and high-alloy steel welding fumes; blood and urine levels of these metals are useful indicators of the extent of recent occupational exposure of individual workers. Aluminium and fluoride levels in blood and urine are also useful measures of individual exposure in

aluminium or other welding applications. There is also some evidence that among mild steel welders, manganese levels in blood and urine are higher than those of the general population.

Lung burden assessment

Inhalation of welding fumes causes lung deposition of metals and metallic compounds, some of which can be magnetized, e.g. Fe_3O_4 , gamma Fe_2O_3 and Mn_3O_4 . Magnetopneumographic techniques are now being developed for measuring the lung burden of these magnetic dusts in welders. In these techniques, the individual is either subjected to a uniform and constant external field that magnetizes the lung burden, resulting in an external remanent field proportional to the content of magnetic dust in the lungs, or is subjected to an alternating magnetic field that permits the net magnetic susceptibility of the thorax to be determined. Preliminary results confirm that long-term welding causes accumulation of dust in the lungs and indicate that this noninvasive technique can detect such deposition at its early stages. Different metals are removed from the lungs at different rates, however, and this complex process, which apparently depends on the type of fume, has not been adequately studied.

Experimental studies of biological effects of welding fumes

Genotoxic effects

Welding fumes have been studied in a large number of *in vitro* bioassays. In these assays, fumes from the welding of mild steel and aluminium show relatively low cytotoxicity, although they show some chemical reactivity. There is some evidence that particulates produced by welding alloys or stainless steels are genotoxic to bacteria and transform mammalian cells in

culture. The presence of Cr[VI] and Ni in various solubility states appears to be responsible for the biological activity of these fumes; other fume types, e.g. from mild steel or aluminium welding, do not contain Cr and Ni.

Hexavalent chromium compounds possess genetic activity, damaging DNA and causing mutations in bacteria, cultured mammalian cells and experimental animals in vivo. They have also caused chromosomal aberrations in cultured cells, in fish, and in workers occupationally exposed to chromic acid in plating works. By contrast, tests for genetic activity with trivalent chromium compounds have given either negative or equivocal results. Hexavalent chromium readily crosses biological membranes, whereas trivalent chromium penetrates them poorly. Hexavalent chromium is reduced in cells and biological fluids to the trivalent form, which binds to protein and nucleic acids.

Tests for genetic toxicity of nickel compounds have given inconsistent results, and the positive responses reported have usually been weak. Mutagenicity has been reported for soluble nickel compounds in a few bacterial tests and in a single test for cytogenetic activity. DNA breaks, DNA-protein and DNA-DNA crosslinks were noted in experimental animals. Nickel compounds enhance lipid peroxidation. Both soluble and insoluble nickel compounds have induced transformation of cultured cells. A single study has shown chromosomal aberrations in peripheral lymphocytes of nickel refinery workers.

Carcinogenic and teratogenic effects

Carcinogenicity of welding fume particles has been studied in two experiments with inconclusive results. In one study, repeated intratracheal instillation of MMA/stainless steel welding fume particles caused two malignant pulmonary tumours in 70 hamsters. No such tumours had been seen in 791 historical control animals,

and this difference was statistically significant. In another study, in which MMA/stainless steel fume particulates were implanted intrabronchially, one tumour was noted in the 100 treated animals, although it was found in the untreated lung and no tumours were found in 100 untreated controls.

Experimental studies on chromium have demonstrated respiratory tract carcinogenicity of hexavalent chromium compounds. Comparative studies of intrabronchial implantation suggest that hexavalent chromates of sparing solubility are the most active.

Among nickel compounds, the subsulfide and carbonyl have caused lung cancer in experimental animals, and several other nickel compounds have produced cancers at the site of application.

Both trivalent and hexavalent chromium compounds have been found to cause fetal death in experimental animals, and hexavalent chromium compounds have induced malformations. Nickel compounds have also caused fetal death and malformation in experimental animals.

Epidemiological data on cancer

Welders constitute between 0.5% and 2% of the general working population, and a higher fraction in certain industrial sectors such as shipbuilding. Very few epidemiological studies have been specifically designed to assess the effects of welding on health, but a number of epidemiological studies of cancer incidence among working populations have included large enough numbers of welders for their cancer incidence or mortality to be examined separately.

The major concern is the consistent observation of an excess of lung cancer among welders. The results of almost all studies, including national or regional occupational mortality data, case control studies and cohort studies, are consistent with an increase in relative risk of the order of 30-40% among welders. An excess of this magnitude could be due to smoking if there were a systematic difference in smoking habits between welders and the reference populations, and/or could be related to exposure to other occupational carcinogens, particularly asbestos. It could, however, reflect a progressive and substantial risk caused by welding fumes among workers exposed for many years, diluted by the inclusion in most studies of workers who have been exposed less heavily or for shorter periods, or who have not been followed up for long enough. A few studies have also suggested that cancers of the nose, kidney, bladder or larynx may be somewhat more common than expected among welders, but these require confirmation.

Some epidemiological studies among workers in chromate and chrome pigment production have shown an increased risk of lung cancer. Studies on nickel refinery and electrolysis workers have shown elevated risks of lung and nasal sinus cancer. Insoluble dusts of nickel subsulfide and nickel oxide, aerosols of soluble nickel compounds and nickel carbonyl vapour have been suspected as causative agents.

Fumes generated by stainless steel welding contain certain components, particularly hexavalent chromium, that have carcinogenic potential. The suggestion that the lung cancer risk is higher among welders of stainless steel than among other welders is neither supported nor refuted by the epidemiological evidence. Historical exposure levels to the various components of welding fumes can, however, be estimated approximately, since for many manual techniques current exposure levels are not very different from those that occurred 20 or 30 years ago. Further follow-up and case control studies

comparing lung cancer and other deaths in existing cohorts, together with the results of further retrospective cohort studies of mild steel and stainless steel welders that are now being established, should provide definitive answers to the above questions within a few years.

Epidemiological data on nonmalignant respiratory disease

Many components of welding fumes have effects on the respiratory system. High concentrations of chromium and nickel compounds, ozone and nitrogen dioxide damage bronchial and alveolar epithelium; chromium and nickel compounds may elicit asthmatic responses; and ozone and nitrogen dioxide are respiratory irritants.

Mortality studies

Welders may suffer some excess mortality from chronic bronchitis or pneumonia, but the incidence of these diseases differs widely among countries and social classes, and it is difficult to select an appropriate comparison group. National and regional occupational mortality studies based on the occupation recorded on death certificates have given inconsistent results, and both these data and recent cohort studies suggest that any specific occupational hazard for respiratory diseases may be less now than it was in the past.

Morbidity studies

Conventional measures of respiratory function may sometimes be reduced in welders. These include forced expiratory volume (FEV_1), forced expiratory flow (FEF), peak flow (PF), carbon monoxide diffusing capacity (TL CO) and vital capacity (VC). Acute respiratory effects such as cough, phlegm production, dyspnoea and respiratory infections have also been more common in welders than among other workers in some studies.

Respiratory effects appear to be most marked in stainless steel welders. Most of these effects become more prevalent in the general population with increasing age and are also more common among smokers. An effect of welding has been suggested on the basis of some studies in which these confounding variables have been taken into account.

The severity and prevalence of respiratory effects among welders varies and in several studies there was little difference between welders and matched controls, although this may reflect only different levels of fume exposure. The interpretation of these findings is complicated by selective drop-out of the least healthy workers from the study group(s) (healthy worker effect) or by the fact that many welders may also have been exposed to asbestos.

Other health-related effects

Analysis of absentee statistics, although these are notoriously unreliable, does indicate that the major recorded cause of lost time among welders is accidental injury. Pilot studies suggest that psychosocial and ergonomic problems, including those due to static and dynamic stress, and the effects of physical factors such as heat, ultraviolet light and noise may result in significant health effects, including lost time, among welding populations in certain industrial situations. There are no reports of systematic studies of the impact of all aspects of the working environment on the health of welders, and little evidence on which to base a decision on the relative importance of respiratory versus nonrespiratory effects. However, only problems related to welding fumes and gases could be treated comprehensively at this Conference.

Conclusions

1. Both acute and chronic respiratory effects occur among welders.
2. Sufficiently stringent measures should be introduced and enforced immediately to prevent these effects.
3. Approaches to reducing the established and potential health risks due to welding fumes and gases should include:
 - identification of high exposure situations and their immediate reduction;
 - development of appropriate monitoring programmes using simple and rapid response indicators of ambient air concentrations;
 - development of a worker education programme and active participation of the workers in their own protection;
 - establishment of necessary health assessment programmes and evaluation of the effectiveness of the existing ones.
4. Because of the possible importance of high-level, short-term exposures, short-term monitoring should be introduced for both aerosols and gases in addition to standard working shift exposure monitoring in the breathing zone and in the shop background. Such measurements are essential in better estimating the exposure of an individual welder.
5. Biological monitoring of Cr, Ni, Al, F and possibly also of Mn in urine or blood specimens can provide additional information about the exposure to these metals of individual welders. They can and should be used in

the assessment of current uptake, but should not be used as a substitute for reducing exposure or for exposure monitoring of the working environment.

6. Magnetopneumography appears to be a promising new technique in the estimation of body burdens of magnetic dusts, but it requires validation, and further development.

7. In vitro studies indicate that most welding fumes are cytotoxic and that those from stainless steel welding are genotoxic as well, primarily due to their content of hexavalent chromium and of nickel (which in certain forms are carcinogenic). Further research may help to identify the extent of toxicity and carcinogenicity of stainless steel and other welding fumes under experimental conditions.

8. There is consistent evidence of a moderate increase in lung cancer risk among welders. Available evidence does not permit a determination if this reflects a moderate excess lung cancer risk for all welders or if this is due to a high occupational risk among a subgroup, or is due to a higher than average exposure to other carcinogens, particularly cigarette smoke and asbestos. Retrospective cohort studies of both stainless steel and other welders who have been exposed for many years and followed up for at least 20 years are therefore urgently needed.

9. Special consideration should also be given to nonrespiratory health and safety problems related to welding and the need to prevent them.

10. Exposure reduction strategies should consider in particular:

- the possibility of using the flexibility of welding technology to provide for minimum fume exposures from the use of old and new processes;

- a better use of mechanical ventilation appropriate for each process and application;
 - the enabling and encouraging of workers to make effective use of available ventilation.
11. There is a need for research in the following areas:
- technological assessment of welding processes from the point of view of reducing emission levels;
 - development of better speciation techniques for identifying the various chemical components of welding fumes and of better methods for their toxicological evaluation;
 - continued development of biological monitoring for the assessment of internal dose to welding fume components in the framework of workplace health surveillance.

Annex 1

PARTICIPANTS

Austria

- Mr E.G. Kolany
Österreichische Staub-(Silikose-) Bekämpfungsstelle,
Loeben
- Dr F. Prügger
Ärztlicher Leiter der Sonderkrankenanstalt für
Berufskrankheiten der AUVA, Tobelbad bei Graz
- Dr F. Sluka
Österreichische Staub-(Silikose-) Bekämpfungsstelle,
Vienna

Belgium

- Mr J. de Greve
Administration de l'Hygiène et de la Médecine du
Travail, Brussels
- Dr A. Lafontaine
95 boulevard Brand Whitlock, Brussels
- Dr T. van Peteghem
Chief Medical Officer, Sidmar, Ghent
- Dr P. de Plaen
Institut d'Hygiène et d'Epidémiologie, Brussels

Canada

- Dr A.G. Cecutti
Medical Director, Falconbridge Ltd., Falconbridge,
Ontario
- Mr J.F.K. Froats
Supervisor, Hazardous Agents Management Services,
Ontario Hydro, Pickering, Ontario
- Professor T.L. Guidotti
Professor of Occupational Medicine, University of
Alberta, Faculty of Medicine, Edmonton, Alberta
- Dr G.M. Liss
Medical Consultant, Health Studies Service, Special
Studies and Services Branch, Ministry of Labour,
Toronto, Ontario
- Mr P. Sampara
Canadian Centre for Occupational Health and Safety,
Hamilton, Ontario
- Mr L.G. Wiseman
Section Leader, Process Technology Department
(Process Development), INCO Ltd., Copper Cliff,
Ontario

Czechoslovakia

- Dr B. Malek
Department of Industrial Hygiene, Institute of
Hygiene, Prague
- Dr J. Skrinjar
Welding Research Institute, Bratislava

Dr L. Ulrich
Leader of the Department of Occupational Health,
Research Institute of Preventive Medicine, Bratislava

Denmark

Mr E. Balieu
Danish Toxicology Centre, Bagsvaerd

Mr E. Beck-Hansen
The Danish Welding Institute, Glostrup

Dr N.O. Breum
National Institute of Occupational Health, Hellerup

Dr J.M. Christensen
National Institute of Occupational Health, Hellerup

Professor K. Drenck
Royal College of Pharmacy, Copenhagen

Professor P. Grandjean
Institute of Community Health, Odense University

Dr F. Gyntelberg
Arbejdsmedicinsk Klinik, Rigshospitalet, Copenhagen

Ms B.M. Hansen
BST Center, Aarhus

Mr M.A. Hink
Arbejdstilsynet, Copenhagen

Dr C. Hugod
National Board of Health, Department of Hygiene,
Copenhagen

- Dr C.V. Jensen
Project Engineer, Dantec Elektronik A/S, Skovlunde
- Dr L.D. Jensen
Directorate of National Labour Inspection, Copenhagen
- Mr P. Klahn
Sales Manager, Dantec Elektronik A/S, Skovlunde
- Mr J. Ladegaard
Manager, Product Development, Dantec Elektronik A/S,
Skovlunde
- Mr Z. Litman
Project Manager, Dantec Elektronik A/S, Skovlunde
- Dr O. Lyngenbo
Institute of Social Medicine, University of
Copenhagen
- Mr N.J.B. Madsen
Vice-President, Dantec Elektronik A/S, Skovlunde
- Mr P. Mandrup-Larsen
Institut for Produktion, Aalborg Universitetscenter
- Dr S. Mikkelsen
Arbejdsmedicinsk Klinik, Rigshospitalet, Copenhagen
- Dr M. Silberschmid
Department of Occupational Health, Centralsygehuset,
Slagelse
- Dr K. Stagis-Hansen
Department of Occupational Medicine, Odense
University Hospital
- Dr O. Svane
Chief Medical Inspector, Directorate of National
Labour Inspection, Copenhagen

Mr E. Thomsen
Chemical Analytical Consulting, Skibby

Finland

Dr K. Ahlman
Corporate Physician, Outokumpu Oy, Helsinki

Dr S.L. Anttila
Department of Pathology, Oulu

Dr A.I. Grckula
Department of Measurement Technology, University of
Oulu

Mr T.E. Gustafsson
Institute of Occupational Health, Helsinki

Dr K. Hemminki
Senior Investigator, Institute of Occupational
Health, Helsinki

Dr M.A. Hildén
Occupational Physician, Valmet Oy, Helsinki Shipyard

Dr H.-K. Hyvärinen
Institute of Occupational Health, Helsinki

Mr J. Kaisko
Rautaruukki Oy, Raabe Steel Works, Raahensalo

Dr K. Kalliomäki
Department of Measuring Technique, University of Oulu

Dr P.-L. Kalliomäki
Institute of Occupational Health, Helsinki

- Dr V.K. Karskela
Physician-in-Chief in Occupational Health
Organisation, Oy Wärtsilä, Turku Shipyard
- Mr A. Lisko
Rautaruukki Oy, Raabe Steel Works, Raahensalo
- Dr E. Minni
Turku Regional Institute of Occupational Health
- Dr M. Moilanen
Department of Electrical Engineering, University of
Oulu
- Dr I. Pietikäinen
Outukumpu Oy Porin tehtaast, Pori
- Dr E.T. Rahkonen
Turku Regional Institute of Occupational Health
- Dr R. Selonen
Occupational Physician, Valmet Oy Pansio Works, Turku
- Mr S.J. Sivonen
Director, Institute of Electron Optics, University
of Oulu, Linnanmaa, Oulu
- Dr K.C.I. Sundström
Wärtsilä, Vasa
- Dr V.P. Tanninen
Institute of Occupational Health, Helsinki
- Dr J.K.A. Varjo
Health Officer, Rauma Repola Oy, Mäntyluoto Works,
Pori

France

Mr E. Ansoborlo
CEA Pierrelatte

Mr C. Bozec
Environment Department, Société Métallurgique
Le Nickel-SLN, Paris

Dr C. Chambet
Adjoint du Chef de Service de l'Inspection médicale
du Travail, Ministère du Travail, de l'Emploi et de
la Formation professionnelle, Paris

Mr M. Compagnon
Alsthom Atlantique, Belfort

Dr F. Diebold
Service Chimie toxicologique, INRS,
Vandoeuvre-les-Nancy

Professor J.M. Haguenoer
Laboratoire de Toxicologie, Institut de Médecine du
Travail, Lille

Dr H.F. Hildebrand
Laboratoire de Toxicologie, Institut de Médecine du
Travail, Lille

Dr J. Lecaigard
Professeur de Médecine du Travail, Hôpital Bellevue,
Saint-Étienne

Mr C. Lesné
Programme mobilisateur "Technologie, Emploi,
Travail", Ministère de la Recherche et de la
Technologie, Paris

- Dr J.-C. Limasset
Service Chimie toxicologique, INRS,
Vandoeuvre-les-Nancy
- Mr M. Lomenede
Ingénieur chimiste, Direction des Relations du
Travail, Ministère du Travail, de l'Emploi et de la
Formation professionnelle, Paris
- Dr F. Marini
Alsthom Atlantique, Belfort
- Mr L. Meyer
DCS, Secrétariat d'Etat de la Santé, Paris
- Dr J.-M. Mur
Chief, Service of Epidemiology, INRS,
Vandoeuvre-les-Nancy
- Dr H. Pezzerat
Université P. et M. Curie, Laboratoire Chimie des
Solides, Paris
- Dr D. Riet
Médecin du Travail, Chantier naval, Alsthom
atlantique, Saint-Nazaire
- Dr J.P. Rigaut
INSERM, Unité 263, Université Paris 7
- Dr M. Stupfel
INSERM, Unité 123, Le Vésinet

German Democratic Republic

- Dr G. Konetzke
Chefarzt, Klinik für Berufskrankheiten,
Zentralinstitut für Arbeitsmedizin der DDR, Berlin

Federal Republic of Germany

Dr W. Coenen

Berufsgenossenschaftliches Institut für
Arbeitssicherheit, Sankt Augustin

Dr H. Deden

Ministerium für Arbeit, Gesundheit und Soziales der
Länder Nordrhein-Westfalen, Düsseldorf

Dr R. Dolgner

Medizinisches Institut für Umwelthygiene an der
Universität Düsseldorf

Dr H.-J. Elliehausen

Institut und Poliklinik für Arbeits- und
Sozialmedizin der Justus-Liebig-Universität Giessen

Dr A. Farwer

Messer Griesheim GmbH, Krefeld

Dr R.R. Frentzel-Beyne

Institut für Dokumentation Information und
Statistik, Deutsches Krebsforschungszentrum,
Heidelberg

Dr U. Glaser

Fachtierarzt für Pharmakologie Toxikologie und
Pharmazie, Fraunhofer-Institut für Umweltchemie und
Ökotoxikologie, Schmallenberg

Mr I. Grothe

Norwestliche Eisen- und Stahl-Berufsgenossenschaft,
Hanover

Mr T. Konohira

Kobe Steel Ltd., Düsseldorf Office

- Dr C. Kühnen
Berufsgenossenschaftliches Institut für
Arbeitssicherheit, Sankt Augustin
- Professor E. Lehmann
Direktor, Bundesanstalt für Arbeitsschutz, Dortmund
- Dr B. Marschall
Medizinischer Direktor, Volkswagenwerk AG, Zentrales
Gesundheitswesen, Wolfsburg
- Dr H. Muhle
Fraunhofer-Institut für Toxikologie und Aerosol
Forschung, Hanover
- Mr H. Müller-Wilderink
Blohm & Voss AG, Hamburg
- Mr P. Neuhaus
Blohm & Voss AG, Hamburg
- Professor I.C. von Nieding
Bundesgesundheitsamt, Berlin (West)
- Mr T. Oldenburg
Institut für Schweißtechnische Fertigungsverfahren
der RWTH Aachen
- Dr H. Press
Bundesanstalt für Materialprüfung, Berlin (West)
- Dr K.H. Schaller
Institut für Arbeits- und Sozialmedizin, Universität
Erlangen-Nürnberg, Erlangen
- Dr E. Schwarzbach
Landesanstalt für Umweltschutz, Karlsruhe

Dr W.J. Zschiesche
Institut für Arbeits- und Sozialmedizin, Universität
Erlangen-Nürnberg, Erlangen

Greece

Dr P. Efsthadiadis
Head of Section Chronic Diseases, Ministry of Health
and Welfare, Athens

Iceland

Mr G. Jonsson
Vinnueftirlit Ríkisins, Reykjavik

Ireland

Mr M. Henry
Department of Labour, Dublin

Dr D. Murphy
Department of Labour, Dublin

Dr S.N. Wood
Occupational Medical Adviser, Department of Labour,
Dublin

Italy

Dr L. Alessio
Professor of Occupational Health, Clinica del
Lavoro, Milano

- Dr G. Casciani
Industrial Hygienist, INAIL, Rome
- Dr G. Cecchetti
Istituto di Medicina del Lavoro, Centro di Igiene
Industriale, Università Cattolica, Rome
- Dr F. Ferrario
Servizio di Epidemiologia, Istituto nazionale per lo
Studio e la Cura dei Tumori, Milan
- Professor G. Gambaretto
Institute of Industrial Chemistry, University of
Padua
- Dr P. Malara
Ministero Sanità, Servizio Igiene Publica, Rome
- Dr M. Maroni
Istituto di Medicina del Lavoro, Clinica del Lavoro
Luigi Devoto, Milan
- Dr G. Ripanucci
Industrial Hygienist, INAIL, Rome
- Dr F. Valerio
First Assistant, Environmental Chemistry Laboratory,
Istituto Scientifico Tumori, Genoa
- Dr U. Verdel
Industrial Hygienist, INAIL, Rome

Japan

- Mr S. Tsutsumi
Technical Department, Welding Division, Kobe Steel
Ltd., Fujisawa

Luxembourg

Dr N. Rumé
Chef de Service, Médecine du Travail, Ministère de
la Santé, Luxembourg

Mr A. Schuster
Directeur de l'Inspection du Travail et des Mines,
Luxembourg

Netherlands

Dr A. Broekman
Nederlandse Philips Bedrijven BV, Bedrijfsgezondheid
Midden-West, Baarn

Dr M.G.J. Heijenbrok
NV Philips, Medical Department, Eindhoven

Dr R.N. Hooftman
Division of Technology for Society TNO, Department
of Biology, Delft

Mr W.L.A.M. de Kort
Directorate-General of Labour, Ministry of Social
Affairs and Employment, Voorburg

Dr P.B. Koster
Directorate-General of Labour, Ministry of Social
Affairs and Employment, Voorburg

Mr P.F. van den Oosterkamp
Chemical Engineer, Inspection Medical Service of the
Dutch Defense Ministry, Department of Environmental
Hygiene, The Hague

- Dr W.K. de Raat
Division of Technology for Society TNO, Department
of Biology, Delft
- Dr P.G.J. Reuzel
Institute Civo-Toxicology and Nutrition TNO, Zeist
- Mr J.F. van der Wal
Scientist, TNO Research Institute for Environmental
Hygiene, Delft
- Ms S.P. Wanders
Coronel Laboratory, Academic Medical Center,
Amsterdam
- Professor R.L. Zielhuis
Coronel Laboratory, Academic Medical Center,
Amsterdam
- Mr A. Zijlstra
Chief Security Department, NV Provinciale
Energie-Maatschappij, Arnhem

Norway

- Dr E.G. Astrup
Elkem A/S, Department of Occupational Health, Oslo
- Dr O. Björseth
Head, Occupational Hygiene Group, SINTEF, Division
of Applied Chemistry, Trondheim
- Dr P.A. Drablös
Norsk Hydro, Karmoy Fabrikker, Haavik
- Dr B. Hemmingsen
Department of Occupational Medicine, Porsgrunn

Professor S. Langaard

Telemark Central Hospital, Department of
Occupational Medicine, Porsgrunn

Dr G. Mowe

Institute of Occupational Health, Oslo

Mr E. Nordheim

Manager, Aluminiumindustriens Miljøsekretariat, Oslo

Dr A. Reith

Norsk Hydros Institute for Cancer Research,
Norwegian Radium Hospital, Montebello, Oslo

Dr Y. Thomassen

Institute of Occupational Health, Oslo

Dr H.H. Tjønn

Senior Medical Officer, Directorate of Labour
Supervision, Oslo

Ms E. Wergeland

Arbeidstilsynet, Oslo

Poland

Dr Z. Kowalski

Vice-Director, Institute of Occupational Medicine,
Lodz

Dr J. Krajewski

Head, Department of Chemical Air Pollutants,
Institute of Occupational Medicine, Lodz

Sweden

Dr M.S. Ahlberg

Head, Analytical Chemistry Section, National Defence
Research Institute, Umeaa

Professor R. Akselsson

Department of Working Environment, Lund University
Institute of Science and Technology

Dr M. Berg

Götaverkens Företagshälsovård, Arendal, Gothenburg

Mr R. Björkman

Projekt Lindholmen AB, Gothenburg

Mr G. Blomberg

Executive Senior Officer, National Swedish Board for
Technical Development, Stockholm

Mr N. Hallin

Chief Engineer, Bygghälsan, Danderyd

Dr U. Hjortsberg

Yrkesmedicinska Kliniken, Malmö Allmänna Sjukhus

Dr L.W. Holm

Head, Chemistry Division, National Board of
Occupational Safety and Health, Solna

Dr E. Jannerfeldt

National Board of Occupational Safety and Health,
Solna

Dr B. Järholm

Department of Occupational Medicine, Sahlgrenska
Sjukhuset, Gothenburg

- Dr S. Larsson
Renströms Hospital, Gothenburg
- Dr B. Lavenius
Götaverken Företagshälsovaard AB, Gothenburg
- Professor P. Malmberg
Research Department, National Board of Occupational
Safety and Health, Solna
- Mr B. Remaeus
Head of Section, National Board of Occupational
Safety and Health, Solna
- Mr B. Rudell
Research and Investigation Medical Division,
National Board of Occupational Safety and Health,
Umeaa
- Mr L. Sipek
AGA AB Innovation, Lidingö
- Dr B. Sjögren
Section of Occupational Medicine, National Board of
Occupational Safety and Health, Solna
- Dr B. Svavar
Bygghälsan, Gävle
- Mr L. Svensson
Research Engineer, ESAB AB, Gothenburg
- Mr P. Uhlbäck
Research and Development Laboratory, Dinol
International AB, Hässleholm
- Professor U. Ulfvarson
Research Department, National Board of Occupational
Safety and Health, Solna

Dr H. Welinder
Senior Occupational Hygienist, Department of
Occupational Medicine, University Hospital, Lund

Mr H.B. Westberg
Department of Occupational Medicine, Medical Central
Hospital, Örebro

Switzerland

Dr H.-R. Meier
Schweizerische Unfallversicherungsanstalt, Lucerne

Dr A. Steinegger
Schweizerische Aluminium AG, Zurich

Dr C. Vuilleumie
Castolin, Saint-Sulpice, Lausanne

Union of Soviet Socialist Republics

Dr L.N. Gorban
Kiev Research Institute of Labour Hygiene and
Occupational Diseases

Professor Yu.I. Kundiev
Kiev Research Institute of Labour Hygiene and
Occupational Diseases

United Kingdom

Professor M. Berlin
Scientist WHO, Monitoring and Assessment Research
Centre (MARC), London

- Dr J.E. Cotes
Department of Occupational Health, Medical School,
Newcastle upon Tyne
- Dr M.R. Cross
Department of Occupational Health, Medical School,
Newcastle upon Tyne
- Dr F.M. El-Gamal
Department of Occupational Health, Medical School,
Newcastle upon Tyne
- Dr T.C.E. Gillanders
Chief Occupational Hygienist, British Shipbuilders
(TES) Ltd., Hebburn, Tyne & Wear
- Dr D. Gompertz
Health and Safety Executive, London
- Dr R. Goulding
36 Ashley Court, Morpeth Terrace, London
- Mr P.J. Hewitt
Radiation Protection Service, University of Bradford
- Mr N. Jenkins
Head, Chemical Laboratory, The Welding Institute,
Abington
- Professor P.J. Lawther
Apple Trees, Church Road, Purley, Surrey
- Dr L.S. Levy
Institute of Occupational Health, Birmingham
University
- Mr A. McLean
Health and Safety Executive, London

- Surgeon Commander G.H.G. McMillan
Office of Flag Officer Plymouth, Mount Wise,
Devonport
- Dr R. Murray
Consultant, Department of Occupational Health,
London School of Hygiene and Tropical Medicine
- Dr M.L. Newhouse
TUC Centenary Institute of Occupational Health,
London School of Hygiene and Tropical Medicine
- Professor J. Peto
Division of Epidemiology, Institute of Cancer
Research, Sutton, Surrey
- Dr D. Rassi
Department of Physics, University College of Swansea
- Dr G.S. Sorrie
Deputy Director of Medical Services, Medical
Division, Health and Safety Executive, London
- Dr S. Venitt
Institute of Cancer Research, Sutton, Surrey
- Mr R.M. Wagg
Senior Specialist, Factory Inspectorate, Bootle,
Merseyside
- Professor R. Weck
Abington Hall, Cambridge
- Mr D.C. Willingham
Fume Control Services, Murex Welding Products Ltd.,
Waltham Cross

United States of America

Dr J.J. Beaumont

Associate Director, Occupational and Environmental
Health Unit, Department of Internal Medicine,
University of California, Davis

Dr B.P. Dolan

129 Mabery Road, Santa Monica

Mr M. Kennebeck

Manager, Safety and Health, American Welding
Society, Miami

Professor K.H. Kilburn

Director, Laboratory for Environmental Sciences,
University of Southern California, School of
Medicine, Los Angeles

Professor M. Lippmann

Institute of Environmental Medicine, New York
University Medical Center, Tuxedo

Professor F.W. Sunderman, Jr

Laboratory Medicine and Pharmacology, University of
Connecticut Medical School, Farmington

Yugoslavia

Professor D. Kalic-Filipovic

Institute for Occupational Health and Radiological
Protection, Belgrade

Dr M. Macarol-Hiti

Main Republic Sanitary Inspector, Republic Committee
for Health and Social Welfare of Slovenia, Ljubljana

Representatives of Other Organizations

Arbetsgivarföreningen SFO

Mr S. Sundquist
Occupational Hygienist, Stockholm, Sweden

Danish Employers' Confederation

Mr T. Jepsen
Copenhagen, Denmark

European Metal Workers Federation in the Community

Mr J. Elikofer
Brussels, Belgium

Mr Th. Schumann
Brussels, Belgium

Mr P. Williams
Brussels, Belgium

Finnish Employers' Confederation

Dr H. Suutarinen
Helsinki, Finland

Finnish Metalworkers' Union

Dr K. Koskinen
Consultant Physician, Helsinki, Finland

FNV

Dr E. Buringh
Amsterdam, Netherlands

International Institute of Welding

Professor G. Gerhardsson
London, United Kingdom

International Social Security Association

Mr C. Fälling
Geneva, Switzerland

Norwegian Iron and Metalworkers' Federation

Mr E. Haugsdal
Health and Safety Officer, Oslo, Norway

Mr S. Muffetangen
Secretary, Oslo, Norway

Svenska Metallindustriarbetareförbundet

Dr R. Ählberg
Miljöombudsman, Stockholm, Sweden

Swedish Employers' Confederation

Professor G. Gerhardsson
Scientific Adviser, Stockholm, Sweden

World Health Organization

Regional Office for Europe

Dr J. Järvisalo
Regional Officer for Occupational Health

Dr S. Tarkowski
Regional Officer for Toxicology

Mr J.I. Waddington
Director, Environmental Health Service

International Agency for Research on Cancer

Mr A. Fletcher, Unit of Analytical Epidemiology

Commission of the European Communities

Dr E. Bennett
Director, Health and Safety Directorate, Luxembourg

Dr A. Berlin
Head, Toxicology, Biology and Health Effects, Health
and Safety Directorate, Luxembourg

Danish Welding Institute

Mr B. Hansen
Glostrup

Professor R.M. Stern
Glostrup

