

## 75 Years of International Cooperation in Research and Standardization of Thermophysical Properties of Water and Steam

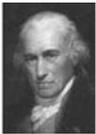
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The article provides a very brief description of the state-of-the-art-in the steam properties research at the beginning of the last century, and the formation of the international cooperation starting with the First International Steam-Table Conference held in London, 1929. The activities in research and standardization of water and steam properties before the establishment of a permanent organization - International Association for the Properties of Steam-(IAPS) in 1972 are shortly summarized. The survey of events and results of the joint work on the IAPS documents between 1972 and 1989 follows. Throughout the article, an attempt is made to remind of the faces of some researchers on the steam properties. The last two parts deal with the trends, aims, and results achieved by IAPWS in the last decade of the 20th century, and with the efforts of restructuring IAPWS and its tasks for the future. Due to the limited space available, the article presents only a selection of most important events and facts, both to put the subject into a historical perspective and to pay a tribute to those who contributed so much to this field.

### 1. Introduction

In 1763 James Watt constructed a curve relating the temperature and saturation pressure of water, probably the first steam table. Since that time many articles or books have been published which included properties of saturated steam and in two cases also properties of superheated steam calculated from a limited experimental data.



James Watt



H.L. Callendar



R. Mollier

In the middle of 1920's, four major steam tables were available, namely those by Mark and Davis (Harvard University), by Goodenough (University of Illinois) in the USA, by Callendar in Great Britain, and by Mollier in Germany. Each table provided values for density of steam as a function of temperature and pressure. However, there were substantial discrepancies in published data.

The industrial importance of steam required further work. As early as 1921, American Society of Mechanical Engineers outlined a program of

research into properties of steam and allocated most of the work to three US research centers. Prof. Callendar soon joined the program, followed by the German Research Authority. During the First World Power Conference, it was found out that the experimental research on properties of steam was carried out also in Czechoslovakia, and the country was immediately invited to cooperate.

The equilibrium properties were in the center of interest. Experimental studies were carried out in the USA at Harvard University by Dr. H.N. Davis and Dr. R.V. Kleinschmidt, at the Massachusetts



N. S. Osborne



H.F. Stimson



J. Havliček



L. Miškovský

Institute of Technology by Prof. F.G. Keyes, and at the U.S. Bureau of Standards by Dr. N.S. Osborne and H.F. Stimson. In England, new measurements were carried out by Prof. H.L. Callendar, in Germany by Professors M. Jakob, O. Knoblauch and W. Koch, in Czechoslovakia by Professors J. Havliček and L. Miškovský.

## 2. Period from 1929 to Establishment of IAPS

In 1929, a general agreement was reached that sufficient data had already been obtained. Engineers and scientists engaged in the design and production of steam power equipment from England, Germany, United States of America and Czechoslovakia met at the **First International Steam-Table Conference** to remove the discrepancies in steam properties with the aim to create one table of the highest quality. The material was not too extensive. It covered the region up to 30 MPa and 400 °C. The result of these negotiations was the proposal of **skeleton tables**, i.e., a set of relatively limited number of values at a regular grid and their tolerances, which formed the base of steam tables. The participants of the First Steam-Table Conference are shown in Fig. 1.

The amendment of the proposal was discussed at the **2nd Conference in Berlin, 1930**. The **first International Skeleton Tables, IST'34**, reaching up to 40 MPa and 500 °C were agreed upon at the **3rd Conference** convened in Washington, Sept. 1934. The IST'34 were used in the construction of Steam Tables by Keenan and Keyes in USA (1936), in VDI Tables by Koch in Germany (1937), and Tables by Callendar and Egerton in UK (1939).

The new measurements continued and discussion on the new experimental results and the improvement of the high-pressure and high-temperature region was to be realized at the next conference planned for 1939 in Czechoslovakia. However the outbreak of the World War II interrupted the international cooperation for the next twenty years.

The increasing parameters of the power generating equipment in the middle of the past century demanded new experimental data. This was also the impulse for the new international cooperation in formulating unified computational data.



A. G. Egerton



E. Schmidt



E.J. LeFevre



J. Kestin

The **fourth Conference** renamed to the **"International Conference on the Properties of Steam - ICPS"** took place in Philadelphia (1954). The participants were from Canada, France, Federal Republic of Germany (FRG), India, Japan, UK and USA. Above all, new experimental data were

studied and the correlation of the transport properties, viscosity and thermal conductivity, was included into the program for the next period.



R.W. Haywood



R.C. Spencer



D.M. Newitt



C.A. Meyer

The proposal of the Skeleton Tables submitted at the **5th ICPS** (London 1956) was not accepted, as it did not include important experimental data. The **International Coordinating Committee (ICC)**, consisting of delegates from UK, FRG and USA, was established and entrusted with the preparation of new Skeleton Tables. The leading U.S. and USSR scientists are shown in Fig. 2.

New data for the skeleton tables were adopted as late as at the 2nd ICC-meeting in Munich (1962), attended by delegates from Canada, Czechoslovakia, FRG, Japan, the Netherlands, Switzerland, UK, USA, and USSR. However, the concord on the skeleton tables for viscosity and thermal conductivity was not reached.

The **6th ICPS** held in New York in 1963, attended by the representatives of 11 countries, adopted the new **International Skeleton Tables, IST'63**, and the skeleton table for viscosity. The working panel for the preparation of the skeleton table for thermal conductivity was established. At the same time the **International Formulating Committee (IFC)** was set up, the task of which was to develop thermodynamic properties of water and steam suitable for computers and complying with the new skeleton tables. One year later, the skeleton table for the thermal conductivity devised by the Coordinating Committee for Transport Properties was agreed upon.

The 1st IFC meeting in Prague 1965, besides others, adopted the maximum acceptable discontinuity values at the boundaries of subregions. The delegates of the meeting are shown in Fig. 3.

New faces appeared as delegates and observers or researchers contributing with experimental or correlation works at the IFC meetings and Conferences. It is difficult to enumerate all of them, nevertheless at least some of them being shown at several places in the text.

The IFC, composed of members from FRG,

Czechoslovakia, Japan, UK, USA and USSR developed two formulations "for scientific and general use", whose aim was the accurate description of properties regardless of the complexity of the equations, computing time, and memory, and for industrial calculations with simpler equations but sufficient accuracy. The final versions of both formulations were agreed-upon at the IFC meeting in Paris, 1968, under the name of "The 1967 IFC Formulation for Industrial Use" and "The 1968 IFC Formulation for Scientific and General Use".

The 7th ICPS, held in Tokyo (1968), adopted both formulations as international standards and the base of international steam tables. The IFC activity was thus brought to an end. Another important item of the Conference was the recommendation to form a permanent organization that would replace the loose cooperation of engineers and scientists involved in the research on steam properties. The Executive Committee including representatives from the USA, USSR, France, Japan, Czechoslovakia and FRG was entrusted with this activity. Three Working Groups on equilibrium, transport and other properties were established.



S. Angus



M.P. Vulakovich



J.Júza



S. Sugawara

### 3. From 1972 to Establishment of IAPWS

The first meeting of the Executive Committee, held in Moscow in 1970, was devoted, besides the technical issues, to the elaboration of the Statutes of the new organization, which was founded at the beginning of 1972 as the



#### International Association for the Properties of Steam - IAPWS.

Thus, the informal organization of International Conferences, which had been working from 1929, was replaced by a permanent organization steered with the international Executive Committee (EC) and having permanent Working Groups (WG).

The main objectives of this international voluntary, non-profit association composed of national organizations include to define research needs, to promote and coordinate research on steam, water and selected aqueous systems important in

thermal power cycles, to collect and evaluate the resulting data, to prepare and promulgate critically evaluated internationally agreed-upon formulations for the properties of light and heavy water substances, and selected aqueous solutions significant for scientific and industrial applications, and finally to provide an international forum for exchange of experiences, ideas and results in this field.



I. Tanishita



R.K. Schmidt



D.L. Timrot



U. Grigull

IAPS and its successor IAPWS are organized as an association of member countries or groups of countries. Its highest authority is the General Meeting. The Executive Committee, consisting of the official representatives of all member countries, is responsible for the overall management and operation of the Association. More details are in the Statutes and By-laws of IAPWS, revised and issued in Orlando 1994.

The international Working and Task Groups, Subcommittees, and Working Panels ensure the expert activities of the Association. The Executive Committee and Working Groups meet annually, the Conferences are held in four to five year intervals.

The internationally agreed-upon formulations of thermophysical properties of ordinary and heavy water, and aqueous solutions are published in the form of Releases, Supplementary Releases, Guidelines, Advisory Notes and Conference Proceedings.



A.A. Alexandrov



E. Whalley



S.L. Rivkin



G.S. Kell

The 8th ICPS took place in Gienès, France (1974). One of its very important tasks was to elaborate new skeleton tables of viscosity and thermal conductivity, which would replace those of 1964, and to prepare the surface tension formulation. At the conference, the necessity of a new Working Group concerned in the properties of aqueous solutions in the power plant cycles was discussed.



G. Bohnsack    S.R. Beitler    A.M. Sirota    O.I. Martynova

Between the 8th and 9th Conferences the Executive Committee was extended by Canada. Works on the proposals of the new Skeleton Tables, on the extension of formulations for thermodynamic and transport properties of ordinary water, and formulations for heavy water started. The tables of surface tension and dielectric constant were submitted, and the correlations of ionization constants and refractivity index were under study. The fourth Working Group referred to as "**Chemical Thermodynamics in Power Cycles**" was established.



The 9th ICPS, held in Munich (1979), on the occasion of the 50th Anniversary of the international cooperation in research on the properties of water and steam,

decided to elaborate new skeleton tables and new thermodynamic formulations, simpler, more accurate and valid in a wider range of parameters.

The EC and WGs meetings between 1980 and 1983, taking place in London, Prague, Moscow and Tokyo, were engaged in coordinating of planned works, evaluation of the obtained results and treatment of the given tasks.



A. Nagashima    H.J. White, Jr.    K. Watanabe    O. Sifner

The 10th ICPS in Moscow (1984) adopted the new formulation for thermodynamic properties of ordinary water for scientific and general use, IAPS-84, and formulations of thermodynamic and transport properties for heavy water. A number of additional documents were prepared.

As the majority of tasks had been fulfilled, the works were focused on the special regions, solid-liquid phase equilibria, metastable states, dissociating steam and into the field of aqueous mixtures. The original four Working Groups were dissolved and replaced by Working Group A for

thermophysical properties of water and steam and aqueous mixtures, and Working Group B for the chemical thermodynamics and thermophysical properties of aqueous systems.



V.V. Sytchev    B. Vodar    E.U. Franck    J.M.H. Levelt Sengers

At the EC and WGs meetings between 1985 and 1987 taking place in Gaithersburg, Düsseldorf, Reading and Vancouver, the attention was paid to the selection of topics, consolidation of working teams, and elaboration of some formulations in the field of aqueous systems. Apart from the description of melting pressure of various modifications of ice, the development of two additional more exact equations of state, including the critical region with extended range of parameters was under way.

Since 1987, **specialized symposia** have become an integral part of the annual meetings.



At the 11th ICPS held in Prague (Czechoslovakia), in 1989, in contrast to the previous Conferences, the focal point moved from thermophysical properties of pure ordinary water and steam to the aqueous solutions and to the corrosion in real steam power cycles, which have the crucial influence on the reliability and service time of fossil and nuclear power stations. The General Meeting, besides the adoption of the research program for the next years and publication of three new releases, agreed-upon the change of the name of the association to



#### 4. Aims and Results Achieved at the Close of the 20th century

In the course of time, some researchers became permanent coworkers, some left the Association, and were replaced by new colleagues. In the period 1968 to 1990, of about 161 members interchanged in the Working Groups.



B. Le Neindre



J. Straub



P.G. Hill



J.V. Sengers

The **Annual IAPWS Meetings between 1990 and 1993** were held in Buenos Aires, Tokyo, St. Petersburg, and Milan. At that time, it was decided to develop new scientific (NSF) and new industrial (NIF) formulations. The survey of 16,000 critically evaluated experimental data was published. The skeleton tables IST'85 were revised and some previous documents were converted from the IPTS-68 into the new temperature scale ITS-90.



The **12th ICPWS** entitled "Physical Chemistry of Aqueous Systems Meeting the Needs of Industry", held in Orlando, FL, USA (1994), was

devoted, except the traditional topics, to molecular modeling of aqueous systems, supercooled, superheated and stretched water, hydrothermal oxidation, and alternative power cycles.

At the **1995 IAPWS Meeting** in Paris, the new scientific formulation of thermodynamic properties and description of the static dielectric constant were discussed. Noticeable progress was achieved in the development of the new industrial formulation. It was also decided to include the high temperature region from 800 to 2000 °C up to 10 MPa. New documents **IAPWS Certified Research Needs (ICRN's)**, representing the considered opinion of experts in the field that research in a particular subject is needed were created. Since 1995, the competition for the **IAPWS International Collaborative Young Scientist Projects** has been opened.



K. Oguchi



L. Haar



V.L. Marshall



W. Wagner

At the **1996 IAPWS Meeting**, held in Fredericia, Denmark (1996), the final wording of the NSF was adopted. It fully supercedes the former scientific formulation IAPS-84. A new industrial formulation was submitted for testing. A one-day

Symposium dealt with the processes in supercritical water.

At the **1997 IAPWS Meeting**, Erlangen, Germany, the new industrial formulation IAPWS-IF97 was adopted. The validity of the former industrial formulation IFC-67, used in power engineering and other industrial applications for nearly 30 years, finished. The Working Groups were engaged in the preparation of new formulations for transport properties, ion product, fast algorithms for computation of thermodynamic properties, pH-measurements under high temperatures, Fe-H<sub>2</sub>O system, and other tasks.



R.J. Cooper



J.S. Gallagher



V.P. Skripov



R. Fernandes-Prini

The **1998 Annual IAPWS Meeting** in London adopted a revised formulation for the thermal conductivity. The Symposium was devoted to the power plant chemistry and high-temperature aqueous systems.



The **13th ICPWS** entitled "Steam, Water and Hydrothermal Systems" took place in Toronto, Canada in 1999. Professor Franck from the University of Karlsruhe,

Germany, became the first recipient of the IAPWS Gibbs Medal for his lifetime contributions to the science of supercritical water. More than 140 contributions were presented. Great attention was devoted to the critical phenomena, especially to the binary aqueous systems. At an advanced stage is the description of the thermodynamic system NH<sub>3</sub>-H<sub>2</sub>O, under way is the fast calculation procedure of thermodynamic properties based on the method of Tabular Taylor Series Expansion. An agreement was reached on cooperation on "ATLAS", a compendium of thermophysical properties of binary systems for application in power engineering, geochemistry, and further branches using hydrothermal reactions.

The **2000 Annual Meeting**, held in Prague, Czech Republic (2000), was attended by 57 specialists from the field of thermophysical properties and power plant chemistry. The one-day symposium dealt with processes in steam and material protection in power plants. At the meeting

the first IAPWS Helmholtz Award was granted. A new task group was formed to provide guidelines to users for the evaluation of computer models and data bases for aqueous systems. The Guideline on the critical locus of aqueous sodium chloride, which correlates  $p$ ,  $\rho$ ,  $T$  and composition at the critical point of this solution, was formally adopted. The Executive Committee agreed-upon the development of additional backward equations for the industrial formulation IF97. The Working Group on power plant chemistry exchanged information on chemical problems in steam power plants, on the significance of sources and methods of removal of organic chemicals, and copper transport in power systems.



D.A. Palmer    B.R. Dooley    B. Rukes    A. Bursik

The **Annual IAPWS Meeting 2001** in Gaithersburg, MD, USA, was attended by more than 60 specialists from 13 countries. In spite of the terrorist attack on New York and Washington, the program of the EC and WGs agendas was completed. Two Guidelines on the computation of thermodynamic properties of water-ammonia system, and fundamental physical constants for water substance were agreed-upon. Another supplementary release on the backward equations of the IF97 was adopted. The electronic download of IAPWS documents was discussed and two new forms of IAPWS publications were accepted. The scope of the one-day symposium was "Electric Power of the Future". On the occasion of the 100th anniversary of the NBS/NIST, a visit to specialized laboratories was arranged, followed by two lectures "A random walk through the hundred years history of NBS/NIST research" and "Research into the properties of steam in NBS".

The **2002 Annual Meeting**, took place in Buenos Aires, Argentina. Two new directions were recognized in the power industry: The first direction is the interaction of steam with materials in advanced power plants with temperatures above 600 °C and pressures above 30 MPa. The second direction is driven by the use of gas turbines with pressures of 3 MPa, where older formulations for the properties of air and combustion products are inadequate. Three new Certified Research Needs for experimental data on thermodynamic properties

of metastable steam and for new formulations of thermophysical properties of humid air and combustion gases were approved. The electrochemical monitoring of power cycles and corrosion were discussed in the Power Cycle Chemistry-working group. Greece was welcomed as an associate member of IAPWS.



M.L. Japas    J.C. Bellows    K. Daucik    R. Svoboda

At the meeting, attention turned again to the structure of IAPWS. The Committee on Restructuring of IAPWS was established. The questions about the vision of the future directions in electric power generation, new technologies and reduction of environmental impact, alternative WG structures, different ways of organizing the working week, and different spacing of ICPWS, were discussed.

The **2003 Annual IAPWS Meeting** in Vejle, Denmark, was attended by scientists and engineers from 12 countries. The agenda concentrated traditionally on the science underlying the thermodynamics and chemistry in the steam power plants but also on other aspects of power generation at high temperatures and aqueous systems. Approved were further backward equations for the Industrial formulation IF97, and the Tabular Taylor Series Expansion (TTSE) was applied successfully to the transport properties. Two Advisory Notes on the uncertainties of enthalpy in the IAPWS-1995 and IF97 formulation, and roles of various IAPWS documents concerning the thermodynamic properties of ordinary water substance were published.



T.I. Petrova    D.G. Friend    H.-J. Kretzschmar    K. Miyagawa

Detailed information on the development of the new formulation on viscosity developed in the joint project by IAPWS and IUPAC was delivered. The workshop on pH measurement in high purity water at temperatures up to 300 °C was a significant exchange of knowledge in this field. Project on a new ultrasupercritical plant with steam temperature up to 700 °C was discussed together with problems

that such a plant could face. The Restructuring Committee submitted conclusions and recommendations following from the evaluated questionnaire on the "Future of IAPWS".



J.G. Bingham



V. Majer



J. Stodola



P.R. Tremaine

## 5. Future of IAPWS

Let us wish IAPWS continuing successful international cooperation and support in the future which will allow it to realize the following recommendations of the Restructuring Committee:

- i) Formation of new committees on nuclear power systems, fuel cells, hydrogen technologies, effectiveness of ICRNs, and awards;
- ii) Establishment of the proposed task groups on properties and formulations for high-temperature aqueous systems, electrochemical processes in high-temperature aqueous systems, education and outreach projects, environmental issues, and metastability, nucleation, early condensate, droplet sprays, and cavitation.

### APPENDIX

#### Updated list of member countries of IAPWS

Argentina-Brazil, Britain and Ireland, Canada, Czech Republic, Denmark, France, Germany, Italy, Japan, Russia, United States of America and associated member Greece.

#### Working Groups (WG) of IAPWS

- WG on Thermophysical Properties of Water and Steam
- WG for Industrial Requirements and Solutions, formerly WG for Industrial Calculations
- WG on Physical Chemistry of Aqueous Solutions
- WG on Power Cycle Chemistry.

At the end of 2003, 14 Releases, 3 Supplementary Releases, 8 Guidelines, 1 Advisory Note and 5 active ICRNs were in force.

#### The Title Honorary Fellow of IAPWS

is awarded to distinguished scientists or engineers, members of IAPWS, who made substantial long-life contribution to the organizing and the scientific activity of the Association. Since 1981, thirty-two titles have been granted.

#### IAPWS Honorary Fellows:

Prof. H. Hausen, Prof. N.B. Vargaftik, Prof. S. Sugawara, Prof. J. Jůza, Prof. S. Beitzler (1981), Prof. B. Vodar (1982), Prof. E. J. LeFevre, Prof. I. Tanishita (1985), Dr.

S. Angus, Mr. R.C. Spencer, Prof. U. Grigull, Prof. J. Kestin, (1987), RNDr. K.R. Schmidt, Dr. H. J. White, Jr., (1988), RNDr. G. Bohnsack (1990), Prof. O. I. Martynova (1991), Prof. E.U. Franck, Prof. A.A. Alexandrov (1992), Dr. E.T. Whalley (1993), Dr. J.M.H. Levelt Sengers (1994), Dr. A. Bursik (1996), Prof. P.G. Hill, Prof. J. Straub, Prof. K. Watanabe (1997), Prof. W. Wagner (1998), Mr. J. R. Cooper (1999), Prof. J.V. Sengers, Prof. B. Le Neinder, (2000), Dr. O. Sifner, Prof. A. Nagashima (2001), Prof. R. Fernández-Prini (2002), Mr. Karol Daucik (2003).

Additional IAPWS Awards were introduced in 1997:

**Gibbs Award** is given to a distinguished scientist or engineer who has made substantial contribution to the development of knowledge on properties of water, steam, and aqueous solutions at high temperatures and pressures, as well as to other areas of underlying science and technology of interest to IAPWS.

1999 - Prof. E. U. Franck.

**Helmholtz Award** is given to promising mid-career scientists and engineers, who are making significant contributions to improve existing knowledge of the properties of water, steam and aqueous solutions, or other areas within the scope of IAPWS interests. (Age of nominee under 40):

2000 - Dr. Andrzej M. Anderko; 2001 - Dr. N. Matubayashi; 2003 – Dr. E. Luiten.

A regular part of the Annual Meetings and Conferences is a half-day technical excursion, the traditional IAPS/IAPWS Dinner, and a program for accompanying persons organized usually by wives of the local scientists, which both contribute to mutual understanding and to establish friendship.

#### Executive Secretaries of IAPS and IAPWS

Mr. R. W. Haywood, University of Cambridge, UK (up to 1970), Prof. S. R. Beitzler, ASME, NY, USA (up to 1978), Dr. Howard J. White, Jr., NIST Gaithersburg, MD, USA (up to 1989), and Dr. Barry Dooley, Electric Power Institution, Palo Alto, CA, USA

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- Beitzler S.R.: *International Association for the Properties of Steam*. – History. August 1974.
- *The Contribution of the IAPS and ICPS on the Research of the Properties of Steam. Over-a Fifty Year Period (1929-1979)* Volume I and II. Compiled by the Japan National Committee on the Properties of Steam, July 1981.
- *IAPS and IAPWS Minutes of the Executive Committee of International Association for the Properties of Water and Steam in the years 1976 to 2003*.

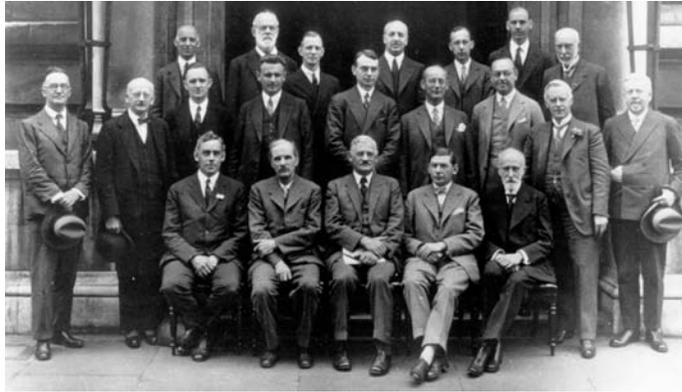


Fig.1. Delegates to the First International Steam-Table Conference Held in London 1929  
(Reprinted from Mechanical Engineering 51, 10 (1929) 792.)

Top row: H.C. Dickinson, W.H. Patchell, S.J. Davies, D.V. Onslow, N.S. Osborne, J.H. Keenan, G. Stoney  
Middle row: E.B. Wedmore, G.A. Orrok, H. Hausen, L. Miškovský, B. Pochobradsky, M. Jakob, W. Koch, I.V.  
Robinson, R. Mollier  
Bottom row: H.N. Davis, H.L. Callendar, F. Samuelson, J. Havliček, O. Knoblauch



Fig.2. Profs. J.H. Keenan, M.P.Vukalovich and  
F.G. Keyes in Moscow, 1958  
(from the left to the right)



Fig.3. Participants of the 1<sup>st</sup> IFC Meeting in Prague 1965.

National delegates were: *from FRG*: Dipl.-Ing. J. Bach, Prof. Dr.-Ing. H.-D. Baehr, Prof. Dr.-Ing. E. Schmidt, Dr. K.R. Schmidt, Dipl.-Ing. D. Schwarz, Dipl.-Ing. H. Tratz, Dipl.-Ing. H. Vesper; *from Japan*: Prof. Dr. T. Sato, Prof. Dr. I. Tanishita; *from USSR*: K.t.n. A.A. Alexandrov, K.t.n. S.L. Rivkin, Prof. Dr.t.n. M.P. Vukalovich; *from UK*: Mr. S. Angus, Mr. H.W. Bradly, Dr. E.A. Bruges, Mr. A.J. Ede, Mr. J.S. Gatehouse, Mr. M.R. Gibson, Mr. R.W. Haywood, Prof. E.J. Le Fevre, Mr. R.I. McLeod; *from USA*: Mr. E.H. Garbinski, Mr. Ch.A. Meyer, Mr. R.C. Spencer Jr.; *from ČSSR*: Dr. Ing. J. Jerie, Prof. Dr. Ing. J. Jůza, Dr. Ing. V. Kmoníček, Ing. O. Šifner, CSc and Ing. K. Výška.  
Underlined are names of Heads of Delegations.

More details on the IAPWS and their products you can find on the IAPWS Website <http://www.iapws.org>.