PROGRESS WITH THE DEVELOPMENT OF HIGH TEMPERATURE FIXED-POINTS IN THE EU THROUGH THE HIMERT PROJECT PROJET EUROPÉEN HIMERT : LE POINT SUR LA RÉALISATION DE POINTS FIXES À HAUTE TEMPÉRATURE

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Abstract

The EU FP5 funded research project HIMERT (Novel High temperature Metal-carbon Eutectic fixed points for Radiation Thermometry, Radiometry and Thermocouples) aims to develop high temperature fixed points above the freezing point of copper to approximately 2500 °C with a repeatability of less than 0.1°C. NPL and BNM-INM have constructed fixed-point blackbody sources, while BNM-LNE has constructed cells up to 1950 °C (Ru-C) for the calibration of contact sensors. PTB will perform absolute radiometry of the cells constructed by NPL and BNM-INM. Pt-Pd thermocouple studies will be undertaken by PTB and BNM-LNE. Also a major materials compatibility study has been undertaken by BNM-LNE to identify thermocouple sheath materials that are compatible with graphite to 1950 °C. The University of Valladolid is investigating the background physics of the eutectic process and seeking to develop physically realistic models. The two industrial companies will test whether improved traceability at lower uncertainties can be achieved by using metal-carbon eutectics. This paper describes the HIMERT project and current progress.

Résumé

Le projet de recherche européen HIMERT (Novel High Temperature Metal-carbon Eutectic Fixed-points for Radiation Thermometry, Radiometry and Thermocouples), financé par le FP5, a pour but de développer des points fixes à haute température au delà du point de solidification du cuivre et jusqu'à environ 2500°C avec une répétabilité inférieure à 100 mK. Le NPL et le BNM-INM ont construit des sources corps noirs points fixes tandis que le BNM-LNE a construit des cellules pour la calibration de sondes par contact jusqu'à 1950°C (Ru-C). Le PTB va effectuer une radiométrie absolue des cellules construites par le NPL et le BNM-INM. Des études sur le thermocouple Pt-Pd vont être prises en mains par le PTB et le BNM-LNE. Egalement, une étude majeure de compatibilité de matériaux a été menée par le BNM-LNE pour identifier les matériaux de gaine de thermocouple qui sont compatibles avec le graphite jusqu'à 1950°C. L'Université de Valladolid étudie les fondements physiques du processus eutectique et cherche à développer des modèles physiques réalistes. Les deux entreprises industrielles vont tester si des progrès dans la traçabilité à plus faible incertitude peuvent être réalisés en utilisant des eutectiques métal-carbone. Ce papier décrit et fait le point sur le projet HIMERT.

Introduction

There is a pressing and continuing need for reliable and repeatable standards at high temperatures (>1100 °C). Until recently work has focused on developing and improving instruments for the precise measurement of temperature. Radiation thermometers, radiometers, high stability lamps, thermocouples, resistance thermometers and fibre-optic devices, can all, with varying degrees of success, be used as temperature standards. It was thought not possible to easily utilize fixed-point technology (as is done at the copper point and below) because either the crucible materials were too fragile (e.g. alumina or some other refractory material) or alloying between the crucible material (e.g. graphite) and the metal precluded their use. However it was shown in 1999 by Yamada *et al.* [1] that metals that have a eutectic reaction with carbon can be used and precise reproducible fixed points can be made of such materials. Since that time there has been a great deal of research into the utilization of metal-carbon eutectics as temperature standards [e.g. 2-7].

After the presentation of Yamada *et al.* [1] it was decided to initiate a programme of research in the European Union into metal-carbon eutectic development. This was initially established as a EUROMET project (no. 550, Study and realization of metal-carbon eutectic fixed points for radiation thermometry purposes) between PTB, BNM-INM, BNM-LNE and NPL. However the opportunity arose to seek funding from the European Commission under the Framework 5 Competitive and Sustainable Growth

Programme (GROWTH). A proposal was formulated and submitted in March 2001 under the title "Novel HIgh temperature Metal-carbon Eutectic fixed points for Radiation Thermometry, Radiometry and Thermocouples" (HIMERT). This was selected for funding in July 2001 and was formally started with a kick-off meeting at the University of Valladolid (UV) in January 2002. The number of partners increased beyond the original EUROMET project participants to include direct industrial participation and UV, which is specifically charged with a theoretical elaboration of the eutectic process. The project held its mid-term meeting in April 03 at BNM-LNE and it is projected to be complete by Dec 04.

This paper gives an outline of the technical work to be undertaken within the framework of the HIMERT project. It also gives some first results of the research programme and gives a forward look at some potential applications of metal-carbon eutectics and their impact on temperature metrology.

Description of project

The HIMERT project itself is formally divided into six technical work-packages and one concerned with project management. In this paper we describe only the technical aspects of the project.

The six technical work-packages are as follows:-

Work-package 1 (WP1): NPL, BNM-INM and BNM-LNE are to construct metal-carbon eutectic fixed-point cells. The former two for radiation thermometry applications (to Re-C point of 2474 °C) the latter for contact sensors such as thermocouples and fibre-optic probes (to Ru-C point of 1953 °C).

Work-package 2 (WP2): NPL and BNM-INM will evaluate the cells constructed in WP1 for repeatability and longer term stability. In addition the University of Valladolid will undertake a detailed theoretical elaboration of the eutectic process to understand why the melt and freeze profiles of these materials are not the same as those of pure metals (see Figure 1 below).

Work-package 3 (WP3): BNM-LNE and PTB will evaluate the cells constructed for thermocouple calibration with high temperature thermocouples (type B, W/Re and Pt/Pd). A comparison of Pt/Pd thermocouple measurement results at metal-carbon eutectic melting/freezing points will be performed. Finally the National Measurement Institute of Japan (NMIJ) is providing cells and Pt/Pd thermocouples for the comparison phase of the project.

Work-package 4 (WP4): PTB will perform absolute radiometry on radiation thermometry cells supplied by BNM-INM and NPL. In addition it is planned that a comparison of a select number of NPL cells will take place with those of NMIJ.

Work-package 5 (WP5): BNM-INM and BNM-LNE will radiometrically compare the cells developed for radiation thermometry and contact thermometry to ensure that the cells are in close agreement.

Work-package 6 (WP6): This is concerned with assessing the possibility of improving the traceability to industrial laboratories at high temperatures. NPL will develop an industrial high temperature Co-C point (1324 °C) with a large aperture for qualification of radiation thermometers. LAND Instruments will construct two silicon photodiode (based) transfer standard radiation thermometers. In addition a multi-spot thermometer will be produced to assess radiance profile across the fixed-points. BNM-LNE and Thermocoax will co-operate on materials compatibility studies [8] and the construction and use of a Co-C cell for thermocouple calibration applications.

Technical progress

The technical progress will be split into four main topics, radiation thermometry, contact thermometry, modelling and international comparisons. Early results are presented below.

Radiation thermometry

NPL and BNM-INM have constructed metal-carbon fixed points for radiation thermometry applications. The approximate radiance temperatures of these eutectics are: Co-C (1324 °C), Pd-C (1492 °C), Pt-C (1738 °C), Ru (1953 °C), Ir (2290 °C) and Re (2475°C).

The NPL eutectics cells are made of of Co (99.998 %, all purities are expressed as mass fractions), Pd (99.998 %), Pt (99.999 %), Ru (99.99 %) and Ir (99.995 %) and Re (99.999 %). The materials were sourced from Alfa-Aesar with the highest purity metals available. The graphite powder, also supplied by Alfa-Aesar, is 99.9999 % purity. The high-purity graphite for the fabrication of the crucibles is supplied by Poco Graphite Inc (grade SFG-2) and has an ash content of <5 ppm. The cells are of ≤25 mm outer diameter, with a length of 38 mm, a blackbody aperture of 3 mm and an overall isothermal emissivity of >0.9995. The dimensions are dictated by the high temperature furnace at NPL [9]. The repeatability of the point of inflection of the melting curve has been found to be less than 50 mK in different furnaces with differing thermal conditions.

The realization of the melt/freeze transition is similar. The fixed-point is heated in the furnace to close to the melting point. A small temperature step of order 5 to 20 °C above the melt transition is made and the fixed-point driven through a melt. After melting the furnace temperature is reduced to close to the freeze temperature a step change is made below the freezing temperature to initiate the freeze. Measurements of the radiance temperature are made with a high quality radiation thermometer [10]. A typical curve for Ru-C is given in Figure 1 below. The uncertainty in the ITS-90 temperature for the pyrometer at this temperature is 0.5°C (k=2). Other NPL results are reported in [11].

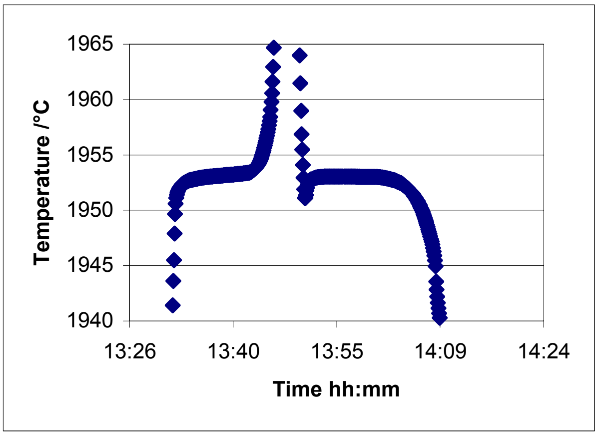

FIGURE 1. Melt/freeze transition of the NPL Ru-C.

BNM-INM has constructed cells based on Fe (99.995 %), Co (99.998 %), Pd (99.95 %), Pt (99.999%), Ru (99.95%) and Re (99.997%). The graphite is 99.9999 %. These were supplied by Alfa-Aesar. The outer diameter of these cells is 25 mm with an overall length of 50 mm. The volume of metal-carbon eutectic is approximately 7 cm^3. The blackbody has an aperture of 4 mm yielding an isothermal emissivity of the cavity of approximately 0.9992. Initially the furnace used for filling the Fe, Co and Pd cells was a vertical furnace with $MoSi_2$ heaters [12]. Latterly the furnace used for filling all cells including new Co-C, Fe-C and Pd-C cells as well as the Pt, Ru and Re cells is a furnace constructed of pyrolytic graphite rings the high temperature blackbody (HTBB) [13] used in vertical mode. Recent results of the BNM-INM work can be found in [14].

The non-contact thermometry cells of NPL and BNM-INM will be transported to PTB in Spring 2004 together with a set of metal-carbon eutectic fixed points of NMIJ. There the ITS-90 and thermodynamic temperatures of the eutectic transition will be determined using a high quality pyrometer (the LP3 [15]) of PTB. Two different procedures will be used to calibrate this LP3, both using a high-temperature blackbody (HTBB), which can operate from 1300 K up to 3200 K [13]. In the first step, determination of the temperature of the HTBB with respect to the PTB gold fixed point and tungsten strip lamps according to the ITS-90 yields the ITS-90 temperature of the HTBB. Using such kinds of calibration, the LP3 measures the *ITS-90 temperatures* of the eutectic fixed-point transition. Additionally, the temperature of the HTBB is measured using absolute radiometry applying a narrow-band interference-filter radiometer with central wavelength around 676 nm. The spectral responsivity of this radiometer is traceable to the cryogenic radiometer of the PTB. A calibration of the LP3 performed in this way provides the *thermodynamic temperature* of the eutectic fixed-point transition. At 2500 °C the expected uncertainty (k=1) of the ITS-90 temperature measured with the LP3 is below 0.65 K, while the uncertainty (k=1) of the thermodynamic temperature is below 0.45 K.

Contact thermometry

Materials compatibility: Obviously the biggest additional complication when using fixed-point cells with contact sensors is that of material compatibility. The graphite crucible materials must be compatible with the thermocouple sheath materials or damage to both will result. Because of this issue BNM-LNE, with the support of Thermocoax have been undertaking a major materials compatibility study at high temperatures up to 2000 °C. The thermocouple sheath materials chosen for study were molybdenum and tantalum. Samples of these were placed inside mini-crucibles of boron nitride, silicon carbide, yttria, zircona stabilised yttria, hafnia and pure carbon. Two sets of crucibles were made. These were then heated for 50 hours in an argon atmosphere, one set at 1750 °C and another set at 1950 °C. The results of these tests showed that it is possible to identify materials that satisfy the compatibility issues (e.g. Ta can be used with SiC or graphite at 1750 °C and Mo can be used (with caution) up to 1950 °C with zirconia). These results are described in detail in [8].

Construction of cells: BNM-LNE has constructed cells for contact thermometry applications. The metals used were Co (99.998 %), Pd (better than 99.998 %), Pt (99.999 %) and Ru (99.99+ %). Graphite of 99.9999 % will be used and the cells constructed from graphite rods of purity 99.9995%. The fixed-point materials are supplied by Alfa-Aesar.

Two types of cells will be constructed, small cells with outer diameter (OD) 25 mm and length 52 mm and large cells with an OD of 34 mm and a length of 103 mm. The latter are for contact sensor evaluation the former are for confirming transition temperatures as measured using radiation thermometry.

Small and large cells of Pd-C and Co-C have been constructed. The small Pd-C cell broke during filling but has subsequently been repaired. A large Pt-C cell and Ru-C cell have been constructed. Initial results for the two Co-C cells (Figure 2) indicate that the transition temperatures of the small and large cells are in agreement to within the uncertainty of measurement.

Thermocouple comparisons The developed cells will be investigated using contact sensors, initially thermocouples. Three type B thermocouples will be calibrated at BNM-LNE and PTB at the traditional Al, Ag, Au or Cu, and Pd fixed points. These thermocouples will then be additionally calibrated using the eutectic fixed-points of Co and Pd (whose ITS-90 temperatures will be determined separately) and a comparison of the two calibration methods undertaken. This will determine whether better uncertainties for thermocouple calibration can be obtained utilizing the new fixed points.

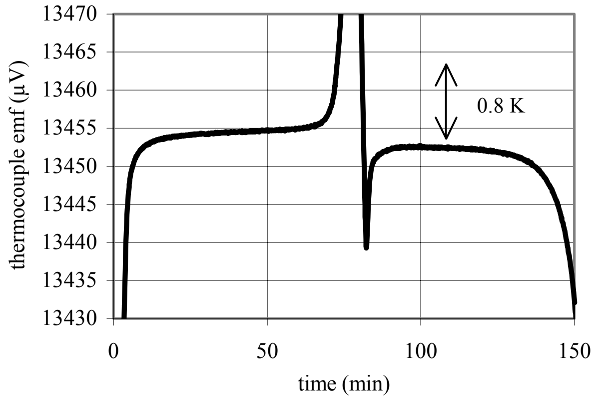

FIGURE 2: The melt curve of the small Co-C cell as measured with a type-S thermocouple

The cells will also be used in metrological studies of Pt/Pd thermocouples, including a comparison and stability testing. This will be performed between BNM-LNE, PTB and NMIJ. Cells of Co-C and Pd-C will be constructed by BNM-LNE and cells of Fe-C, Co-C and Pd-C by NMIJ. Two Pt-Pd thermocouples will be constructed each by PTB and NMIJ. The cells and the thermocouples will then travel to each participating laboratory to undergo evaluation.

High temperature thermocouple investigations: The high temperature cells Pt-C and Ru-C will be able to uniquely assess the metrological characteristics of high temperature thermocouples e.g. W/Re. This metrological study will be performed by BNM-LNE with Thermocoax and will focus on stability and traceability.

Modelling

The University of Valladolid in cooperation with NPL and NMIJ is undertaking mathematical modelling of various thermometry related aspects of high temperature fixed points. The main work centres on modelling the eutectic process and the effect of trace impurities (metallic, non-metallic and gaseous) on plateaux shape and temperature. The effect of impurities will be investigated using a software package—MTDATA [16]. This is a sophisticated software package developed by NPL for calculating phase and chemical equilibria. It can model binary, ternary or multi-component systems. A typical model output can be seen in Figure 3.

Much of this work is new. Therefore input parameters for the models need to be quantified. The effect of impurity on transition temperature will be measured by NPL for Re-C. This will be done by constructing eutectic cells made from three differing grades of Re and measuring their transition temperatures. Dummy cells have been constructed from the material and a micro-structure analysis performed [11].

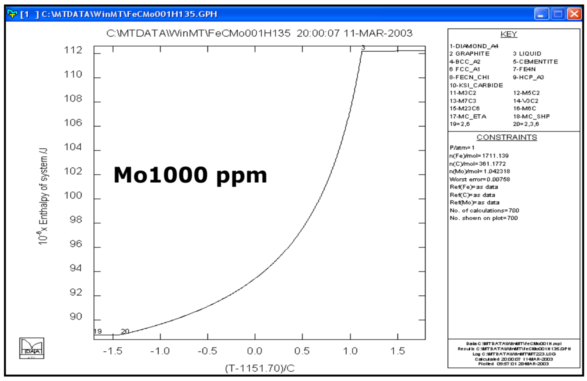

FIGURE 3: Model output of MTDATA – this shows the effect of 1000 ppm of Mo impurity on the melting curve of Fe-C [note x-axis is temperature, y-axis is enthalpy]

An impurity analysis of the three differing grades of Re will be undertaken. Pre-processed samples will have their impurity levels quantified by adhering the powder to an In "pin". Post-processing samples will be obtained by producing "pins" in the same graphite used for constructing the full cells. The method used for determining the level of impurities is Glow Discharge Mass Spectroscopy.

Other aspects of modelling being performed are:-

1. Modelling of a binary system of silver doped with increasing percentages of impurities. Experimental work reported by Anscin [17] detailing this effect provides an excellent laboratory to test theoretical models before the more difficult metal-carbon eutectics are attempted
2. Finite element modelling of the solidification process should lead to a better understanding of the effects of the melt/freeze front on the transition temperature. This will also allow an analysis of the effects of temperature gradients (which can be large in high temperature furnaces) on the transition temperature to be explored.
3. The full calculation of the temperature drop across the wall of the crucible. This is not simple because of radiant exchange both within the blackbody but also with the hot furnace environment outside. Simple calculations overestimate this effect so modelling is expected to produce a more realistic estimate.

International comparisons

Envisaged as part of HIMERT are a series of international comparisons at the very highest level. The aim of these comparisons is to establish whether it is possible to manufacture metal-carbon eutectic cells in different laboratories with different supplied materials and still get the same transition temperature. This is an

essential measurement to be made to ensure that the cells can be used for scale realisation and comparison, as well as forming part of any definition of the future temperature scale (the so called ITSxx).
The first of these comparisons was undertaken in February 2003 at NPL. Blackbody cavities of Pt-C and Re-C were manufactured by BIPM, NMIJ and NPL. These were compared simultaneously using two radiation thermometers and two furnaces. The preliminary results were excellent. The three Pt-C cells at 1737 °C and the three Re-C at 2474 °C cells were shown to have the same transition temperature to within the measurement uncertainty of 200 mK [18].

A second comparison at PTB will be held in Spring 2004. Here cells manufactured by NPL and BNM-INM will be compared along with a selection of those from NMIJ.

International cooperation

The HIMERT consortium has signed a formal cooperation agreement with NMIJ. In this there is to be a mutual exchange of research results with the aim of rapidly progressing the research.

The CCT (BIPM Consultative Committee for Thermometry) WG5 (working group 5 – radiation thermometry) has a strong interest in these developments. It sees these fixed-points as potential candidate reference points for any future redefinition of the high temperature part of the temperature scale. As such it is seeking to coordinate the world effort in this area and has appointed a coordinator, in agreement with the members, to attempt to facilitate this.

Industrial Linkage

The GROWTH programme is concerned to stimulate the industrial uptake of the research that it funds. In view of this two of the HIMERT consortium are manufacturers of thermometry equipment. LAND Instruments International is a well-known manufacturer of IR thermometry equipment as well as diagnostic equipment for the combustion industry. Thermocoax has many years experience in the construction of contact thermometers, both resistance type thermometers but primarily thermocouples of every standard type, including W-Re alloy types.

The inclusion of manufacturers who have such an interest is two fold: a) to demonstrate improved traceability of ITS-90 from a National Measurement Institute (NMI) to an accredited laboratory b) to seek to stimulate ideas on how to apply eutectic technology in a wider industrial forum for the benefit of European industry generally.

At the end of the project in Spring 05 a one-day workshop will be held at PTB, Berlin to give an update on the progress of the eutectic technology developed in the project and to further discuss potential applications of benefit to European industry.

Future prospects

The HIMERT project is approximately half way through and has already demonstrated that fixed points with the required repeatability can be constructed and compared [18].

It is hoped that as the technology is demonstrated that a range of industrial applications will benefit from the application of metal carbon eutectic fixed points. This might be through improved traceability to ITS-90, or through improved process temperature control by the incorporation of a fixed point in the process itself providing a method of self-validation. The latter would have the significant benefit of improving efficiency and reducing waste.

Future ITS

The ITS 90 is now some thirteen years old. The international temperature community is beginning to undertake a critical look at ITS-90 to identify its deficiencies and ultimately propose solutions. One of the biggest problems is the ITS-90 definition above the silver point which is based on an extrapolation of the scale from the silver point upwards using Planck's law in ratio form. This requires a very carefully characterised pyrometer to be employed to perform the extrapolation leading to scale uncertainties of around 1 to 2 °C at 2500 °C [the uncertainties scale as T^2 from the silver point]. Alternative methodologies include absolute radiometry but this will always remain a difficult and, for the temperature community at least, less than practical method. One pragmatic solution is to utilise a series of high temperature fixed points from the copper point to 3000 °C. The thermodynamic temperatures of the fixed-points are pre-determined by absolute radiometry. Then in a direct analogue of the platinum resistance thermometer scale a radiation thermometer can be calibrated over the required range (using a minimum of three fixed-points) and an interpolation equation fitted to the calibration data giving very low uncertainties (less than 0.1 °C) over the range of interest. Another possibility is to use a restricted set of high temperature fixed points, possibly as few as two, and this combined with some knowledge of the spectral response of the radiation thermometer band pass could lead to uncertainties of less than 0.05°C over the entire range up to 3000 °C [19]. Whether these ultra-low uncertainties are achievable in practice remains to be seen. For instance one limiting factor may be the pyrometer size-of-source effect [20] another may be intrinsic fixed-point repeatability, nevertheless the possibility of scale uncertainties of less than 0.1 °C for radiation thermometry, even at the very highest temperatures, remains a real possibility in the five to ten year time frame.

Conclusions

A description of the HIMERT project has been given, early results reported and some prospects described.

The utility of metal-carbon eutectic fixed-points in the field of high temperature standards, and also radiometry, cannot be underestimated. They are potentially powerful technology disruptors and could change the way temperature scales are realised, compared and disseminated from national measurement laboratories to the shop floor. They have the potential of delivering national measurement institute uncertainties to the end user in a robust way obviating the need to return artefacts for calibration.

It is becoming clear that metal-carbon eutectics will feature in any future ITS, possibly becoming the defining fixed-points of the any such scale.

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References

1. Yamada, Y., Sakate, H., Sakuma, F., and Ono. A., in *Proceedings of TEMPMEKO '99*, edited by J. F. Dubbeldam and M. J. de Groot, Nmi Van Swinden Lab., Delft, 1999, pp. 535-540.
2. Yamada, Y., Sakate, H., Sakuma, F., and Ono A., *Metrologia* **38**, 213-219 (2001).
3. Yamada, Y., Duan, Y., Ballico, M., Park, S. N., Sakuma, F., and Ono, A., *Metrologia* **38**, 203-211 (2001).
4. Yamada, Y., Sakuma, F., and Ono, A., *Metrologia*, **37**, 71-73 (2000).
5. Yamada, Y., Sasajima, N., Sakuma, F., and Ono, A., in *Proceedings of TEMPMEKO '01,* edited by B. Fellmuth, J. Seidel, G. Scholz, Berlin, VDE Verlag, 2002, pp. 19-26.
6. Machin, G., Yamada, Y., Lowe, D., Sasajima, N., Sakuma, F., and Fan Kai, in *Proceedings of TEMPMEKO '01,* edited by B. Fellmuth, J. Seidel, G. Scholz, Berlin, VDE Verlag, 2002, pp. 851-856.
7. Lowe, D., and Machin, G., in *Proceedings of TEMPMEKO '01,* edited by B. Fellmuth, J. Seidel, G. Scholz, Berlin, VDE Verlag GMBH, 2002, pp. 519-524.
8. Morice, R., Favreau J.O., Morel E., Megharfi M., in *these proceedings*
9. Brookley, C. E., and Llewellyn, W. E., in *Temperature: Its Measurement and Control in Science and Industry,* edited by J. F. Schooley, AIP, New York, Vol. 6, Pt. 2, 1992, pp. 1195-1199.
10. Schreiber, E., Neuer, G., and Worner, B., in *Proceedings of TEMPMEKO '90*, Helsinki, 1990, pp. 292-306.
11. Lowe, D., Machin, G., in *these proceedings*
12. Sadli, M., Fanjeaux, M., Bonnier, G., To be published in *Temperature: Its Measurement and Control in Science and Industry,* Vol. 7, 2002
13. Sapritsky, V., Khlevnoy, B.B., Khromchenko, V.B., Lisiansky, B.E., Mekhontsev, S.N., Morozova, S.P., Shapoval, V. I., Samoilov, L.N., Prokhorov, A.V., Zelener, M. F., In Proceedings of *TEMPMEKO ' 96*, ed. by P. Marcarino, Levrotto & Bella, Torino, 1997, pp. 321-326
14. Sadli, M., Bourson, F., Fanjeaux, M., Bonnier, G., in *these proceedings*
15. Fischer, J., Neuer, G., Schreiber, E., and Thomas, R., in *Proceedings of TEMPMEKO '01,* edited by B. Fellmuth, J. Seidel, G. Scholz, Berlin, VDE Verlag, 2002, pp. 801-806.
16. Davies, R.H., Dinsdale, A.T., Gisby, J.A., Robinson, J.A.J., Martin, S.M., *CALPHAD* 2002, **26(2)**, 229-271
17. Anscin, J., *Metrologia*, 2001, **38**, 229-235
18. Machin. G., Yamada, Y., Lowe, D., Sasajima, N., Anhalt, K., Hartmann, J., Goebel, R., *Metrologia, submitted* 2003
19. Bloembergen P., Yamada, Y., Yamamoto, N., Hartmann, J. To be published in *Temperature: Its Measurement and Control in Science and Industry,* Vol. 7, 2002
20. Machin, G., Ibrahim, M., in *Proceedings of TEMPMEKO '99*, edited by J. F. Dubbeldam and M. J. de Groot, Nmi Van Swinden Lab., Delft, 1999, pp. 681-686