The Run-up to the ITS-90

Richard Rusby, NPL
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Thank you for your invitation to take part in this commemoration of the first 100 years of International Temperature Scales.

What follows is based on my records of correspondence and documents circulated, and my notes at the CCT meeting (incomplete, but quite copious), my recollections (less reliable), and the extensive official minutes (compiled from a transcript, now probably lost). Quotations are not verbatim, but I believe that they are functionally accurate.

1. Background

Looking at the international scales again, I think we can say that each of them was a momentous step in the art and science of temperature measurement even if, in the end, practitioners became dissatisfied with them and they had to be revised to accommodate new developments and wider temperature ranges.

Thus the ITS-90 was borne of dissatisfaction with the IPTS-68, which, interestingly, was not a truly consensus scale, see Preston-Thomas' keynote address at the 1971 Washington Symposium for a candid review.

The IPTS-68 was the first to extend as far as the hydrogen triple point (via the oxygen triple point and neon and hydrogen boiling points). It also added an oscillatory correction function (known as the Moser wobble) to the Callendar quadratic equation above 0 °C, to make it more accurate. The freezing point of tin was introduced (as a 'permitted alternative' to the steam point), the boiling point of sulphur was finally dropped.

Although it was based on the 'fundamental interval' of 0 °C to 100 °C, the IPTS-68 made no reference to the ice point, as such, but it did give brief guidance on realising the triple point of water: at NMIs at least, R_{TPW} was measured, and then converted to R(0 °C).

So for the first time the scale above 0 °C was based on the tin and zinc points, but beyond this the quadratic was still simply extrapolated to 630 °C. The uncertainties must have been 10-20 mK, but this was small compared with the uncertainty of using Type S thermocouples which then took the scale up to the gold point (whose temperature was increased by 1.43 °C).

Speaking as someone who had to use it, the low temperature extension was awkward, to say the least, but in the wake of Plumb and Cataland's low-temperature acoustic thermometry at NBS, magnetic thermometry at Iowa State University and elsewhere, and Berry's gas thermometry, NPL-75, it became possible to avoid some of the erratic oscillations in T_{68} and bridge the gap between revised helium vapour scales and the IPTS-68 at 30 K. This allowed a Provisional Low-Temperature Scale, EPT-76, to be introduced, see **Figure 1**.

Meanwhile, throughout the 1970s and 80s, pressure was building up for a wholesale revision of the IPTS-68, the most significant objective being to remove the Type S thermocouple, i.e.

to extend the range of the SPRT to the gold point, and much work was done to this end. However, at a conference in Beijing in 1986 this was looking too ambitious and, in an *ad hoc* meeting of CCT delegates (and others) convened by Terry Quinn, it was concluded that HT-SPRTs would have to be restricted to the silver point.
This prompted Ron Bedford's (NRC) immediate reaction 'Oh, then we might as well use Au/Pt thermocouples'! - but surely HT-SPRTs would do better than any thermocouple?

2. The Run-up: 1987-1989

At the CCT meeting the following year we were informed that the CIPM wanted to introduce new definitions of the Josephson and von Klitzing constants in electrical metrology on 1 January 1990, and they wanted to introduce a new ITS on that same date. Driven by this diktat, and under the guidance of Preston-Thomas and Quinn, our minds were focused on achieving a consensus on a new scale within the next two years.

Some of the features, issues to be resolved, and decisions made were:

1. The removal of the Type S thermocouple, and the extension of the use of SPRTs to the silver point, as mentioned. **Figure 2** shows the big slope difference in (T_{90} - T_{68}) at 900 K and the rise to a peak of ~0.4 K at about 1050 K which had been indicated in the literature. (Later, in revising the IEC standard, Type S thermocouples were calibrated against the ITS-90, and the peak was found to be much smaller, at ~ 0.1 K, so in 1994 the scale differences (T_{90} - T_{68}) in this region were revised down.)

2. It was decided that radiation thermometry could be referred to blackbodies at either the silver point or the gold point, or the copper point. Whereas the gold point had traditionally been used, the silver point was now the junction temperature, so both were needed, and the copper point was added, for reasons of economy. New values for the freezing points of silver and gold had been determined using radiation thermometry relative to a blackbody at about 760 K by Fischer and Jung at PTB. The gold point temperature was reduced by 0.25 K. (Note that it is now believed to be too low by 0.05 K, but the value since 1927 is converging!)

3. New SPRT reference functions above TPW were derived, using the HT-SPRTs calibrated at PTB. The conversion to T_{90} was predominantly based on the NBS/NIST Constant Volume Gas Thermometry (CVGT) measurements of Guildner and Edsinger (1976) up to 730 K and Edsinger and Schooley (1989) up to 903 K. These were monumental experiments which, however, disagreed by about 30 mK at 730 K, and it was necessary to chart a course between the two sets of data, see **Figures 3&4**. Then, the radiometry of Fischer and Jung (1989) was used to extend the differences ($T – T_{68}$) up to the silver point.

4. Below TPW, CVGT and other experiments were conducted to improve the thermodynamic foundation of thermometry, most extensively by RC Kemp at NML Australia, Astrov at VNIIFTRI in Moscow, and Steur and Durieux at Leiden university, and also the total radiation thermometry of Quinn and Martin. These seemed to indicate that the differences ($T – T_{68}$) reached a peak of about 13 mK +/- 5 mK at about 150 K, and then plummeted to negative and oscillatory differences below about 60 K, **Figure 5**. This was, to our misfortune,

just before innovatory results using spherical acoustic resonators by Moldover and Ewing and Trusler became available.

5. Meanwhile, Franco Pavese at IMGC and Georges Bonnier at INM, and others, had developed sealed cryogenic triple-point cells, for H_2, Ne, O_2, N_2, Ar, Kr, Xe and CO_2, with the aim of eliminating boiling points, except for hydrogen, and Pavese had co-ordinated a comparison of such cells, showing that they are very precise tools for realising a scale.

6. Also in the 1970s, Ward and Compton at NPL had undertaken an international comparison of some 30 capsule-type SPRTs between 13.8 K and TPW. This allowed the practical status of the IPTS-68 realisations to be established, and the various $(T - T_{68})$ data to be converted to a common basis. Moreover, the SPRT-SPRT differences could be used to test possible scale interpolation schemes, using different functions, different sets of fixed points, and checking their sensitivities to errors and their non-uniqueness, from which ultimately the ITS-90 interpolations were selected.

7. Meanwhile low temperature reference functions were generated, using a chosen reference thermometer whose alpha value (essentially the slope $\mathrm{d}W/\mathrm{d}T$ at TPW) was comparable with that of Jung's HT-SPRT. This was done by WG3 (Kemp), using data from WG4, in **Figures 5 & 6**. Kemp ensured that the first and second derivatives of the reference functions were continuous at TPW. However, the SPRT interpolations above and below TPW were deliberately independent, so that errors or uncertainties would not be transmitted across the junction, and some slope differences were anyway inevitable, because of SPRT non-uniqueness.

8. A particular issue, arising from the extension of the SPRT range to the silver point, was that there should be provision to calibrate SPRTs over shorter subranges, either by proceeding in discrete steps (which had not been successful in the IPTS-68 below TPW), or alternatively by allowing subranges to coexist in parallel – but with the risk of incurring subrange inconsistency. The latter was preferred, and SRI was extensively tested, where data existed.

9. The Ga point had become available in about 1980 and it (informally) replaced the steam point for determining alpha coefficients in the IPTS-68, but Preston-Thomas was (rightly) keen to have another point between TP Ar and TPW. Specifically, he wanted the Xe point, which was best placed, but there had only been a few realisations of it, with mixed success (1-2 mK), and nobody had equipment for using Xe cells with L-SPRTs at -110 °C. Eventually another new point, the triple point of Hg, was chosen because the larger sensitivity to interpolation error should be compensated by its better repeatability. The freezing point of indium was also by then available, and was included. Two further subranges, from Hg to Ga and TPW to Ga, were included to permit the most precise realisations in near-ambient subranges, needed in metrology and environmental measurements.

One fixed point that was *not* included was the boiling point of water – and indeed it was no longer 100 °C. When the new scale was announced, this is what made the news: 'Scientists say that water does not boil at 100 °C!'

10. New SPRT interpolations were provided. These were intended to be as mutually consistent as possible, to minimise subrange inconsistency, but very limited data was (and still is) available for Type 3 non-uniqueness in L-SPRTs. Above TPW the cubic interpolation using freezing points of Sn, Zn and Al (plus an extension to Ag) were not in doubt, as was a quadratic subrange to FP Zn. It was not necessary or useful to include Ga in these subranges, but the In point was inserted into a subrange to FP Sn, and in its own linear subrange. Below TPW, a broad consensus emerged and the main issues were still Xe vs Hg, and the Ne subrange, which did not meet the WG3 target of <0.5 mK for interpolation accuracy.

11. The scale specifies the use of an interpolating CVGT below the TP Ne in order to extend it down to 3 K, overlapping new vapour-pressure equations for ^{4}He and ^{3}He.
The lower limit of the scale is 0.65 K, where the vapour pressure of ^{3}He is ~116 Pa.

In the late 1980s Preston-Thomas and Quinn met quarterly at BIPM supervisory meetings, and a WG1 task group with Bloembergen, assisted by Crovini, Jung, Hudson and me) met three times in 1989. In between, Telex messages and faxes (not yet e-mails!) flew between us and others, and successive drafts of the scale text were circulated to the CCT for comment.

3. The 17th meeting of the CCT: 12 - 14 September 1989

After the usual preliminaries, Quinn quoted from Shakespeare (Julius Caesar): ‘There is a tide in the affairs of men, which, taken at the flood, leads on to fortune,… …we must take the current when it serves, or lose our ventures’!

This committee as a whole, he continued, must take responsibility for the ITS-90 (meaning reach a consensus, unlike for IPTS-68). We have Version E of the ITS-90 text, and we must aim to leave with a copy of the text to be recommended for adoption by the CIPM and then at the General Conference in the following month.

The business opened with reports by the working groups
WG1: H P-T, T Q and P Bloembergen: introduction and background to ITS-90 Version E.
WG2: R Bedford, NRC: Secondary references: revision of the IEC IPRT and TC standards.
WG3: L Crovini, IMGC/INRIM: SPRT Reference functions and interpolations.
WG4: R Hudson, BIPM (ex NIST): thermodynamic data, specifications for I-CVGTs.

The meeting then discussed specific topics, below, often returning to them after further consideration. At the end of the first and second days, R Bedford contacted K Hill at NRC, asking him to check the numerical validity and consistency of particular SPRT interpolations.

The following are the main topics addressed.
Day 1

- The Reference functions of Jung (above TPW) and Kemp (below TPW) were accepted,
- Linear interpolations to the new Ga and In points, and quadratic to FP Sn, were agreed.
- Discussion for and against including the subrange Ne-TPW
- Discussion of the consistency of the Ag, Au and Cu point. No changes indicated,

- Further discussion of IEC thermocouple specifications: NIST to coordinate the revision,
- Tables for (T_{90}-T_{76}) and (T_{90}-T_{68}) needed. NPL to prepare (but they do not define T_{90}!)

Day 2

- Overnight checks by K Hill: Hg-Ga vs TPW-Ga, are not consistent: TP Hg should go down by 2 mK! Ultimately the changes were TP Hg: -0.7 mK, and MP Ga: -0.3 mK, so reducing the slope difference at TPW.
  (Note that assigned fixed-point temperatures could be adjusted, within their thermodynamic uncertainties, as a mechanism for changing their W-values and so improve interpolation consistency.)
- SRI below TPW: the target of +/- 0.5 mK is met except for the Ne subrange,
- TPW to Ga is OK with respect to TPW to Sn, Zn, Al,
- Discussions regarding FP In, using data from IMGC and NIST: settled,
- Possible inconsistency in the the Ag, Au, Cu points: Jung considers that it may be ~6 mK, which does not warrant changing the values (and SPRT reference function).

Day 3

Further discussion, after new checks at NRC,

- Crovini is satisfied that consistency at TPW is <2.10^-5. Supported by Mangum, using data for 11 SPRTs,
- Kemp considers that NonU below TPW is <0.5 mK, except for Ne-TPW.

After this discussion, the President asks Crovini: does WG3 now recommend any changes to the fixed-point temperatures?
Crovini, in reply: based on information available and confirmed by Hill, WG3 does not recommend further changes.

The President, with due gravity, senses that ‘the time has now come for the adoption of the ITS-90 to be put to the vote…’

..,but Pavese interjects: ‘Excuse me Mr President, but is it decided to include the subrange to TP Ne, or not?’
President: ‘Ah, well, my impression is that it does not meet the WG3 criteria, so it is not included..’
Crovini: ‘As Chairman of WG3 I cannot recommend it’.
Pavese does not contradict the figures, but the matter has not been finally discussed. The scale must be realised, and if the Ne subrange is not included there can be no realisation below 54 K without pressure measurements, as required in the TP H_2 subrange.
This is supported by Bonnier, Blanke and me - and Crovini as IMGC Representative.
The President then allows a preliminary vote on this point, and the inclusion of the Ne subrange was approved by 10 votes to 2 (NRC and NIST), Astrov and Swenson abstaining.

The meeting then proceeded to vote on Resolution 1:
‘*The CCT recommends that on 1 January 1990 the ITS-90 come into force and that from this same date the IPTS-68 and EPT-76 be abrogated.*’
Passed unanimously! General applause!

Little did we know how important it was to complete this business during the morning session: the BIPM had put champagne on ice, and we couldn't break for lunch until the vote had been passed.

The afternoon was devoted to discussions of Recommendations 2 (on the need for revised IPRT and thermocouple standards) and 3 (inviting national laboratories to assess the uncertainties in realising the fixed points and in the propagation of these uncertainties).

The President distributes the new version of the ITS-90 text.
The meeting concludes with a vote of thanks to the president in appreciation of his work in steering the derivation of the new scale through to its completion.
The president responds: 'If there was ever a case of shared responsibility, I think this is it and I extend those words right around this table without exception'.
He expresses his thanks to Mr Quinn and his staff and closes the meeting.

Postscript
Following my presentation at the BIPM Dolores asked me if I thought at the time that the ITS-90 would still be in force 40 years later. I replied emphatically 'Yes – it was intended to last for ever!' It was a true consensus and even if we knew that it was not perfect, we believed it would serve its purpose well.

Of course, some of the thermodynamic values were more uncertain than was desirable, and some were soon found to be incorrect, but an ITS is primarily intended to be precise and reproducible, and its accuracy in thermodynamic terms is always limited by the state of the art at the time of its inception. Great strides have been made in this regard, and the urge to revise it (when the picture is complete!) is understandable.

My personal opinion now is that three pressures combine to make a revision of the ITS-90 desirable. Firstly, there is the problem with mercury (this will require at least an amendment). Secondly, there is the need to accommodate the new metal-carbide fixed points, which have already led radiometrists to define a new scale, an 'ITS-in-waiting'. Thirdly, there is the improvement in thermodynamic thermometry at low temperatures, which could in principle make the ITS redundant below 25 K. At higher temperatures, CSPRTs will still be needed to record, transfer and compare new results, and it will be a short step to define a reference function and interpolations – an ITS - to facilitate this, not only at specified, or fixed, points. Truly 'practical primary' thermometry, using devices to measure kT and hence T, seem likely to be limited to lower temperatures, with uncertainties of, perhaps, 1 part in 10^4.

On a point of nomenclature, no scale can define *'T'*: there must always be a qualifier, such as a date (for an international scale) or 'lab' (for a particular source), or both, such as 'NBS-55', 'NPL-75', etc.

Figures 1 to 5: scale differences, taken from Metrologia (1991) 28, pp9-18

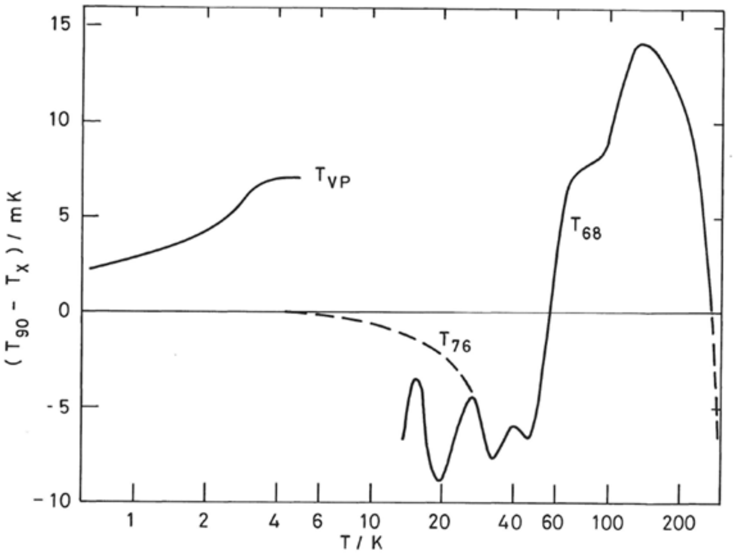

Figure 1: T_{90} with respect to earlier defined scales

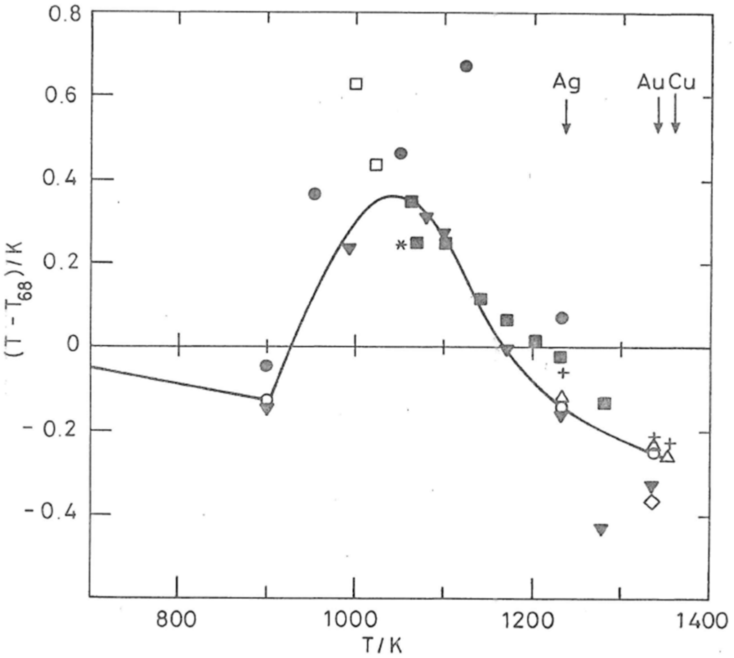

Figure 2: T_{90} with respect to T_{68} above 904 K, using Type S thermocouples

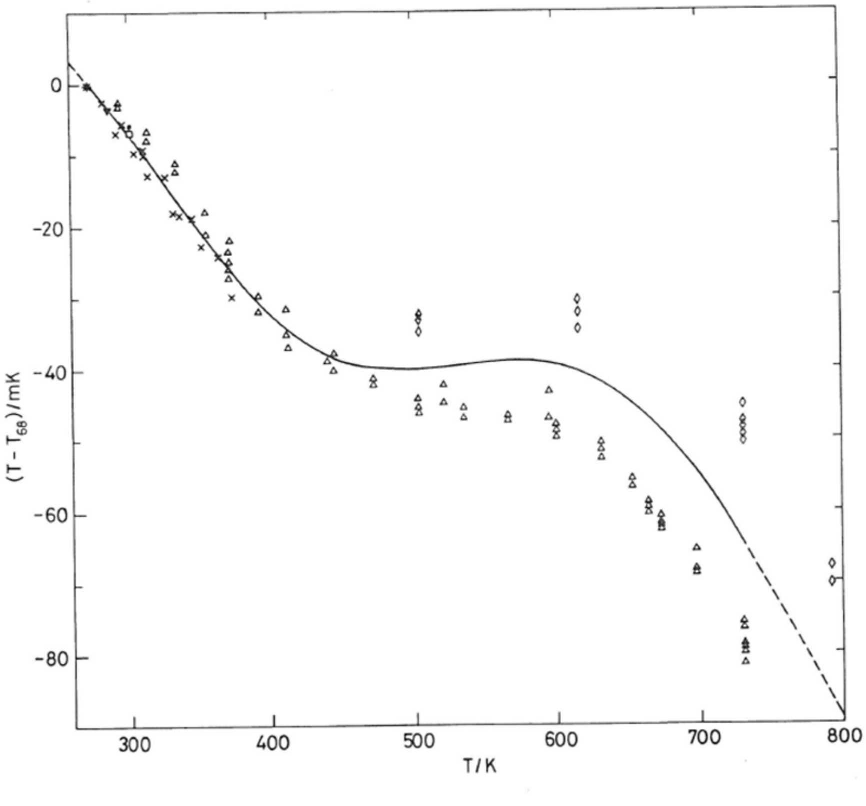

Figure 3: ($T_{90} - T_{68}$), 273 16 K to 730 K

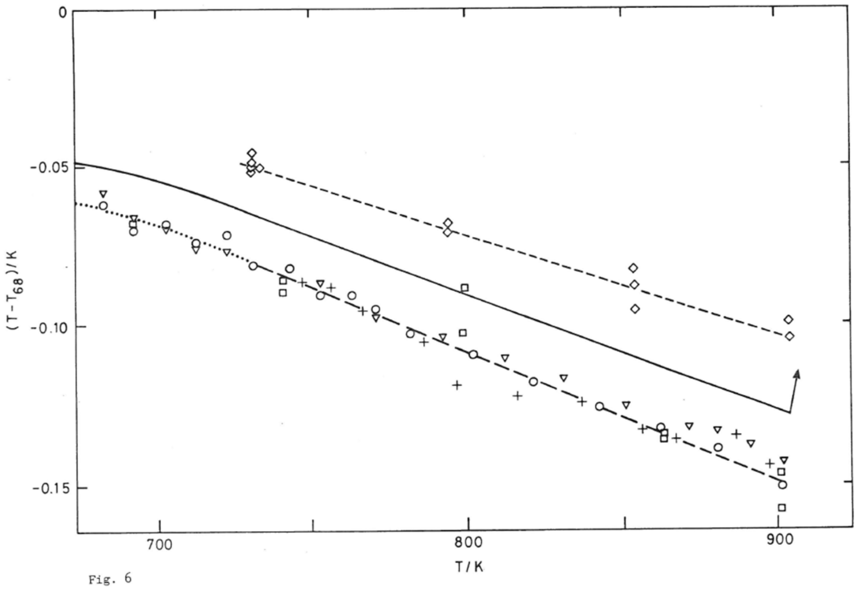

Figure 4: ($T_{90} - T_{68}$), 680 K to 904 K

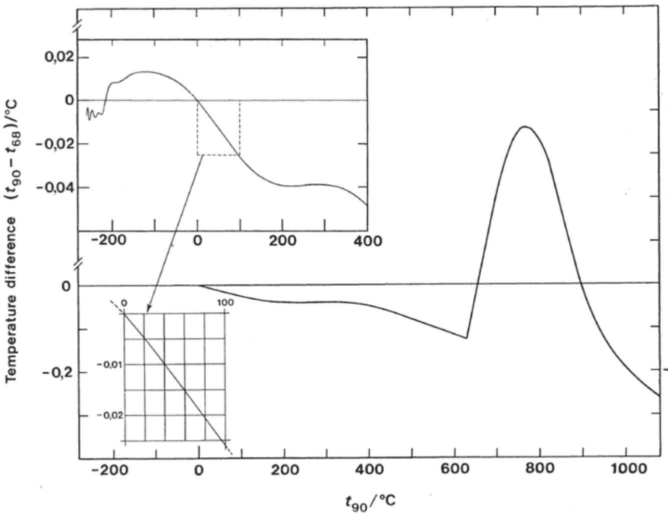

Figure 5: BIPM overview of the differences ($T_{90} - T_{68}$)

Figure 6: Participants at the 17th Session of the CCT, BIPM, September 1989

Rear: DN Astrov (VNIIFTRI), RE Bedford (NRC), G Bonnier (INM), CA Swenson (ISU, USA).
Row 3: M Durieux (KOL), M Borovicka (CSMU), J Bonhoure (BIPM), P Bloembergen (VSL), H-J Jung (PTB)
Row 2: A Pokhodoun (VNIIM), MV Chattle (NPL), RC Kemp (CSIRO-NMIA), RP Hudson (BIPM),
H Sakurai (NRLM-NMIJ), F Pavese (IMGC-INRIM), TP Jones (CSIRO-NMIA),
PPM Steur (IMGC-INRIM), BW Mangum (NIST)
Front: H Maas (ASMW), RL Rusby (NPL), Ling Shankang (NIM), W Blanke (PTB), C Rhee (KSRI),
TJ Quinn (BIPM), H Preston-Thomas (NRC), L Crovini (IMGC-INRIM), WRG Kemp (CSIRO-NMIA)