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**The 1998 Calibration of Australian Secondary Standards  
of Exposure and Absorbed Dose at  $^{60}\text{Co}$**

by

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## **ABSTRACT**

New calibration factors are reported for several of the ionization chambers maintained at the Australian Radiation Laboratory (ARL) and at the Australian Nuclear Science and Technology Organisation (ANSTO) as Australian secondary standards of exposure/air kerma and absorbed dose at  $^{60}\text{Co}$ . These calibration factors supplement or replace the calibration factors given in earlier reports. Updated  $^{90}\text{Sr}$  reference source data are given for the ARL chambers, and for two of the ANSTO chambers. These results confirm the stability of the secondary standards.

A re-calibration of the ANSTO reference electrometer is reported. This was carried out using an improved method, which is fully described.

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## 1. INTRODUCTION

This report is part of a continuing series. It updates the calibration factors to be used with the Australian secondary standards of exposure/air kerma and of absorbed dose to graphite and water at  $^{60}\text{Co}$ .

Section 2 gives details of the secondary standard ionization chambers currently used at both ANSTO and ARL. It also highlights those that have been calibrated since the previous report. The responses of these chambers in their  $^{90}\text{Sr}$  reference sources are reported and compared with previous results.

Section 3 gives calibration results for the ANSTO reference electrometer, evaluated using an improved technique. The new calibration parameters are compared with previous results.

Section 4 provides revised  $^{60}\text{Co}$  calibration factors for the Australian secondary standard ionization chambers that have been calibrated since the previous report. Calibration factors are given for exposure, air kerma, absorbed dose to graphite and absorbed dose to water. The new values are compared with previous results.

## 2. SECONDARY STANDARD IONIZATION CHAMBERS AND THEIR $^{90}\text{Sr}$ REFERENCE SOURCES

Three types of ionization chamber are now used as secondary standards at both ANSTO and ARL. The Nuclear Enterprises model NE2561 is a 325 mm<sup>3</sup> graphite thimble chamber specifically designed as a secondary standard; these chambers are no longer available from the manufacturer. The new model NE2611A has the same outer dimensions as the NE2561 and has similar performance at  $^{60}\text{Co}$ . The NE2571 600 mm<sup>3</sup> graphite thimble chambers are typical of the field instruments used for radiotherapy dosimetry in hospitals. They can be used as emergency substitutes for the NE2561 or NE2611A secondary standard chambers, or for a more direct calibration of a field dosimeter of the same physical size as the NE2571, in a radiation beam of arbitrary intensity profile.

### 2.1 ANSTO secondary standard ionization chambers and $^{90}\text{Sr}$ reference sources

ANSTO has two NE2561 chambers, serial numbers 058 and 091A. Chamber number 091A (originally number 091) was repaired in 1997 and has now been recalibrated. ANSTO also has two NE2611A chambers, serial numbers 139 and 140. In addition, ANSTO has one NE2571 chamber, serial number 1181. These details and those of the associated  $^{90}\text{Sr}$  reference sources are shown in Table 1.

**Table 1****ANSTO Secondary Standard Ionization Chambers and <sup>90</sup>Sr Reference Sources***Chambers shown in bold face have been calibrated since the previous report.*

Chamber Type	Serial Numbers	Reference Source	Serial Number
NE 2561, 325 mm <sup>3</sup>	058	NE 2562	054
	<b>091A</b>		
NE 2611A, 325 mm <sup>3</sup>	139		
	140		
NE 2571, 600 mm <sup>3</sup>	1181	PTW 23261	WK 964

**2.2 ARL secondary standard ionization chambers and <sup>90</sup>Sr reference sources**

ARL has four NE2561 chambers, serial numbers 070, 194A, 238A and 328. Chamber number 194A (originally number 194) was repaired in 1992 and chamber number 238A (originally number 238) was repaired in 1995. ARL also now has two NE2611A chambers, serial numbers 150 and 152, as well as two NE2571 chambers, serial numbers 1785 and 2384. These details and those of the associated <sup>90</sup>Sr reference sources are shown in Table 2. Chambers 194A, 238A, 328, 150 and 152 were calibrated in December 1997 and/or April 1998 during an intercomparison with the National Research Council of Canada (NRC). Chamber number 070 was recalibrated in May 1998 along with the ANSTO chamber number 091A.

**Table 2****ARL Secondary Standard Ionization Chambers and <sup>90</sup>Sr Reference Sources***Chambers shown in bold face have been recalibrated since the previous report*

Chamber Type	Serial Numbers	Reference Source	Serial Number
NE 2561, 325 mm <sup>3</sup>	<b>070</b>	NE 2562	024
	<b>194A</b>		
	<b>238A</b>		
	<b>328</b>		
NE 2611A, 325 mm <sup>3</sup>	<b>150</b>		
	<b>152</b>		
NE 2571, 600 mm <sup>3</sup>	1785	NE 2503/3A	2658
	2384		

### 2.3 Reference source responses of the secondary standard ionization chambers

The current from each ionization chamber was measured using the corresponding  $^{90}\text{Sr}$  reference source as shown in Tables 1 and 2, corrected to normal ambient temperature, pressure and relative humidity (NTPH). The results have all been corrected to 0000h Australian Eastern Time (AET) on 1/1/80, to facilitate the assessment of the long term stability of the ionization chambers. The  $^{90}\text{Sr}$  reference source results have not been corrected for ion recombination. The present results are shown in column 5 of Table 3. These were measured with the ARL Current Integrator system described elsewhere<sup>(1)</sup>.

**Table 3**

**Secondary Standard Ionization Chamber  $^{90}\text{Sr}$  Reference Source Responses (pA)**

*reference conditions: 20 °C, 101.325 kPa, 50 % RH, 0000h AET on 1/1/80,  $^{90}\text{Sr}$  T<sub>1/2</sub> 10516 days  
-210 V nominal polarizing voltage*

Ionization Chamber			$^{90}\text{Sr}$ ref. source NE 2562 4	mean current, pA		percentage deviation 100(P-L)/L 7
Owner 1	Type 2	Serial 3		present (P) 5	long term (L) 6	
ANSTO	NE 2561	058 <sup>a</sup>	054	45.909 <sup>a</sup>	45.906	0.01
		091A		45.126	na	na
ARL	NE 2561	070	024	35.854	35.851	0.01
		194A		37.197	37.205	-0.02
		238A		35.773	35.767	0.02
		328		34.272	34.258	0.04
	NE2611A	150		35.748	35.755	-0.02
		152		34.997	34.995	0.01

<sup>a</sup> Chamber number 058 was not calibrated on this occasion. The "present" value shown here is derived from the value reported previously<sup>(1)</sup>.

The long term mean  $^{90}\text{Sr}$  reference source currents shown in column 6 of Table 3 are the means of all the reference source measurements that have been made since the purchase or repair of the chambers. In the case of the ANSTO chambers, these figures were extracted from ARL records of calibrations since 1980; these measurements were made at either ANSTO or ARL, using either the ANSTO or ARL NE2560 electrometers, or since 1990 using the ARL Current Integrator. Measurements made with the NE2560 electrometers were converted from divisions per second to pA using the measured charge sensitivity in pC/division. Measurements that were made to establish the  $^{90}\text{Sr}$  reference source activity ratio<sup>(1)</sup> have been included by adjusting the measured currents by the source ratio as appropriate.

Note that as the ANSTO and ARL NE2562  $^{90}\text{Sr}$  reference sources have now been adequately compared<sup>(1)</sup>, there is no need to transport the ANSTO NE2562 reference source to ARL for future calibrations.



## 2.4 Comparison of the $^{90}\text{Sr}$ reference source results with previous results

Previous  $^{90}\text{Sr}$  reference source results for the six ARL 325 mm<sup>3</sup> chambers are shown in Figures 1 to 6, and results for the two ANSTO NE2561 chambers are shown in Figures 7 and 8. Figures 1 to 4 are updated versions of the similar figures in reference (1). The  $^{90}\text{Sr}$  results were discussed at length in that report. The long term mean values are shown in Figures 1 to 8, with bars of  $\pm 0.15\%$  indicating the typical approximate range of observed results.

The ANSTO chamber number 091A has not previously been calibrated since its repair. While the present  $^{90}\text{Sr}$  reference source measurement is within the typical range of values (long term mean  $\pm 0.15\%$ <sup>(1)</sup>), there may have been a change to the chamber sensitivity during the repair process. Its future reference source response will not necessarily be consistent with that of the original chamber number 091.

It can be seen from column 7 of Table 3 that the present  $^{90}\text{Sr}$  reference source responses of all the ionization chambers are well within the range of values normally observed ( $\pm 0.15\%$ ). This confirms the stability of the standards.

## 3. CALIBRATION OF THE ANSTO REFERENCE ELECTROMETER

The ANSTO reference electrometer is a Keithley model 35040 (K35040), ANSTO stock number 8828 (bar code number 10024290). The electrometer calibrations reported in this section were carried out at ARL in May 1998 and are valid for 12 months. The K35040 was operated under the following conditions:

- ▶ **Power-up screen:** Batt: 6.9 V +0.05 A  
Leakage: NA pA  
IC Bias: 0.0 V OFF

Note that the internal ion chamber bias supply was set to zero volts and turned OFF.

- ▶ **Automatic Leakage Subtraction** was DISABLED by setting the Exposure Start and Stop Thresholds both to 0.0 pA (refer to the K35040 manual, page 9). This also disables the automatic reset feature.
- ▶ **Air Density Correction** was DISABLED (ADC annunciator was OFF).
- ▶ **Charge and Current Scaling Factors** were both set to 1.0000.
- ▶ **All Ion Chamber Correction Factors** (ICCF) were set to 1.000E+00 R/C.
- ▶ **The Rear Input** was used to minimize the chance of moving the cable accidentally.
- ▶ **A Negative Input Current** was provided by an ionization chamber connected via adapter box RBH002, with bias supply RBH001, as previously described<sup>(1)</sup>.

Figure 1. <sup>90</sup>Sr Ref. Source Results; ARL NE2561 #070

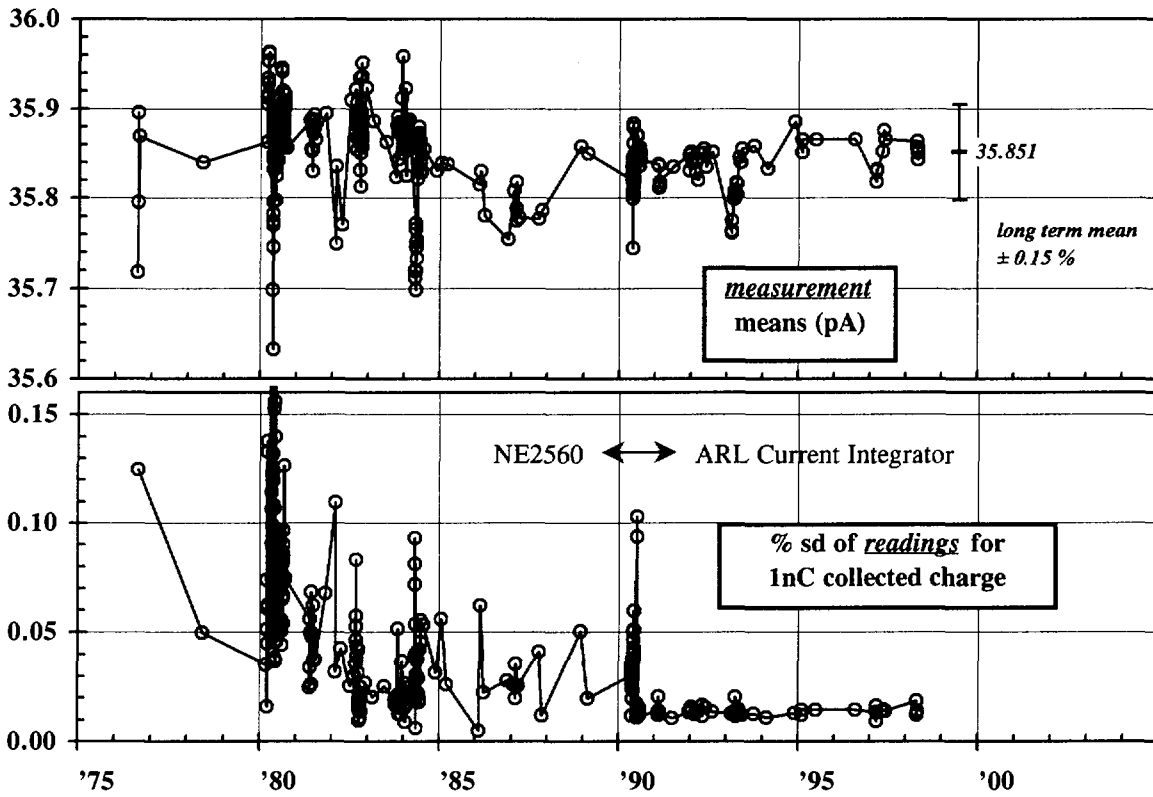


Figure 2. <sup>90</sup>Sr Ref. Source Results; ARL NE2561 #194 / 194A

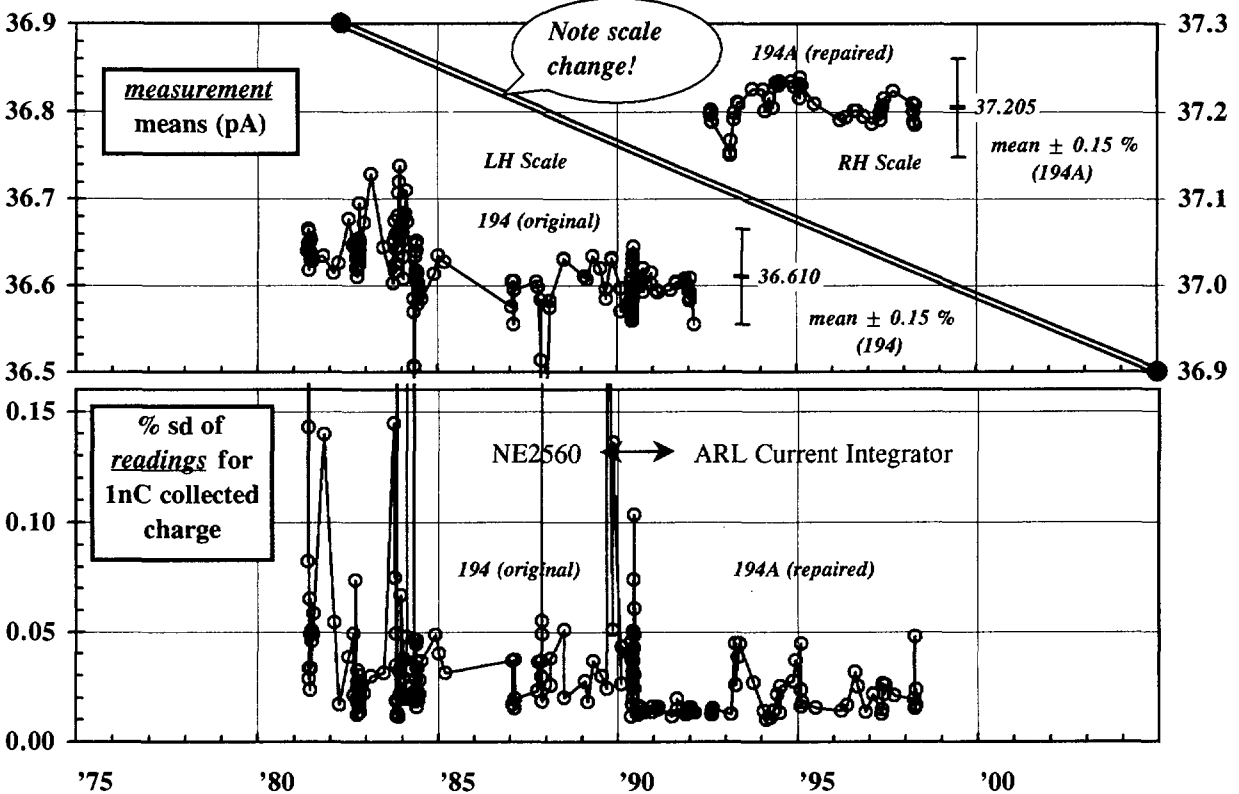


Figure 3. <sup>90</sup>Sr Ref. Source Results; ARL NE2561 #238 / 238A

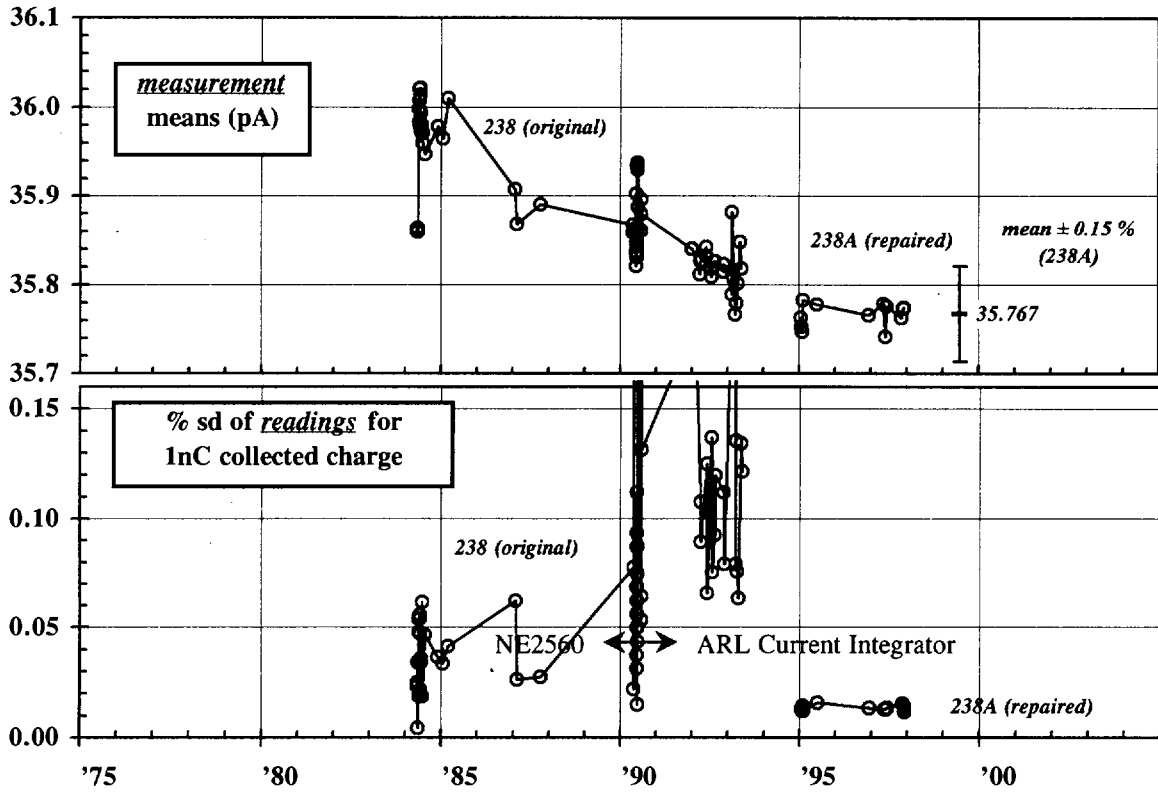


Figure 4. <sup>90</sup>Sr Ref. Source Results; ARL NE2561 #328

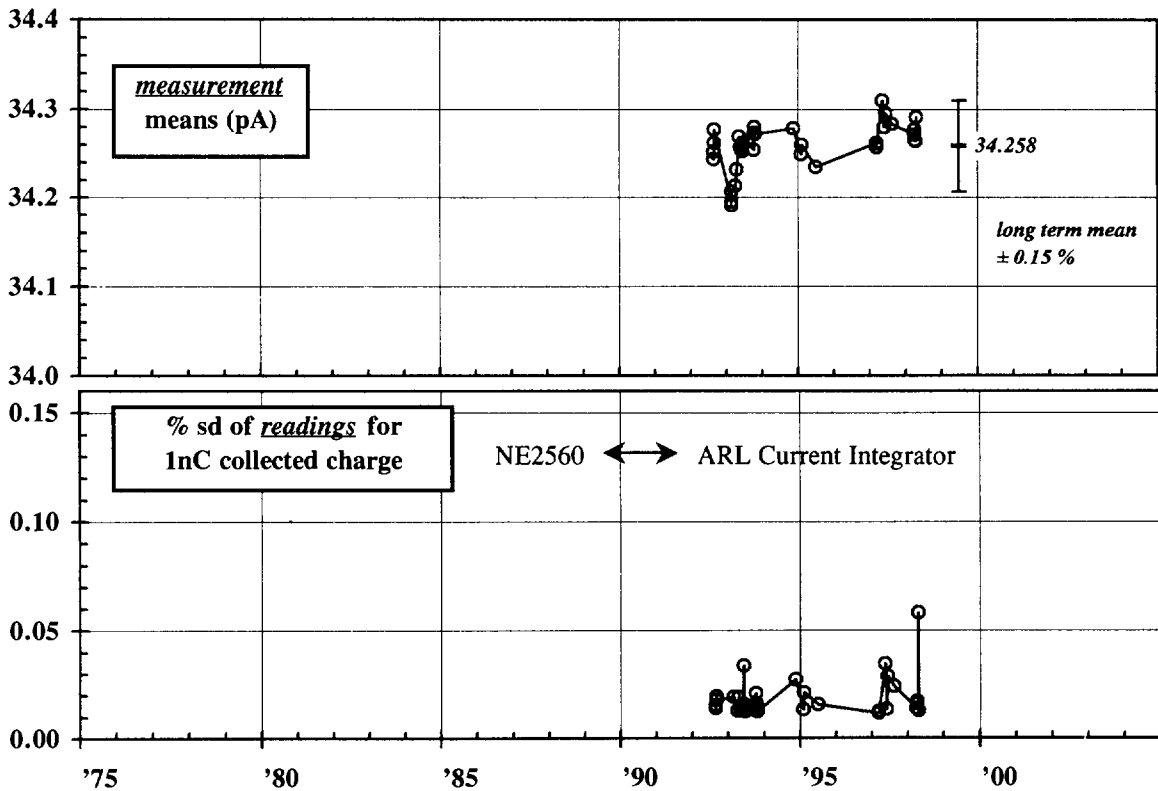


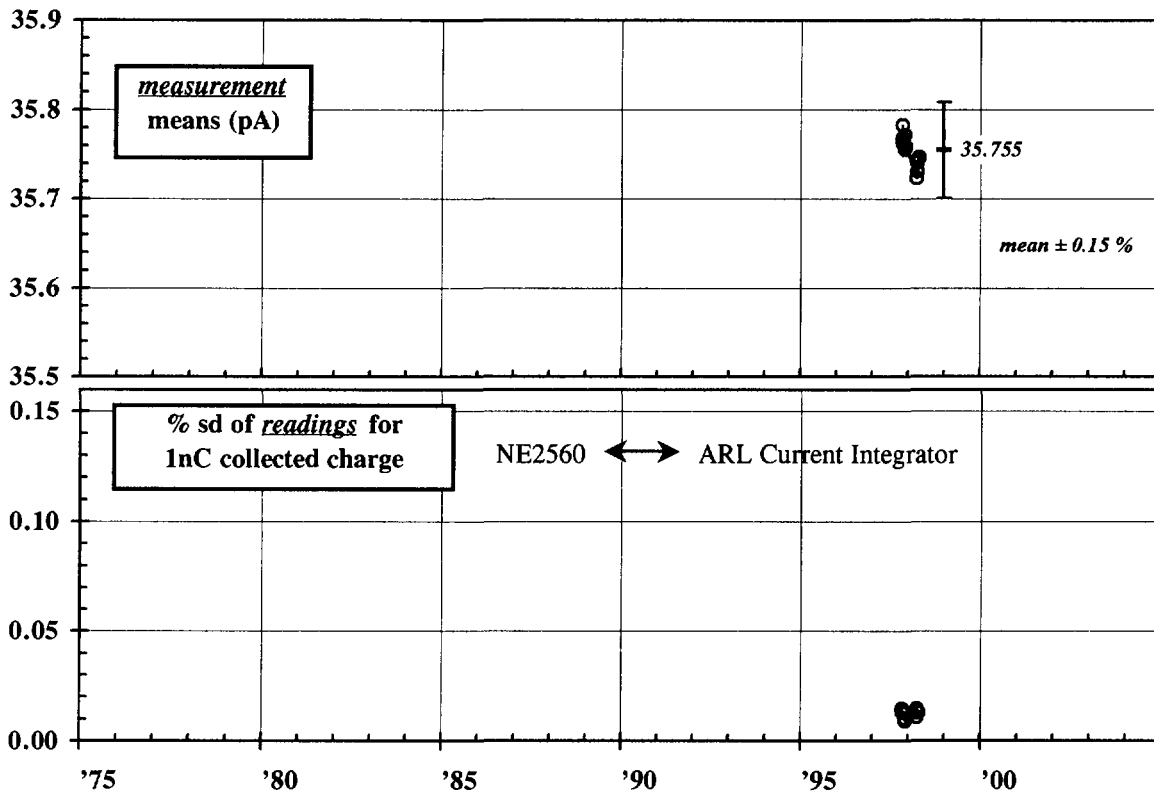
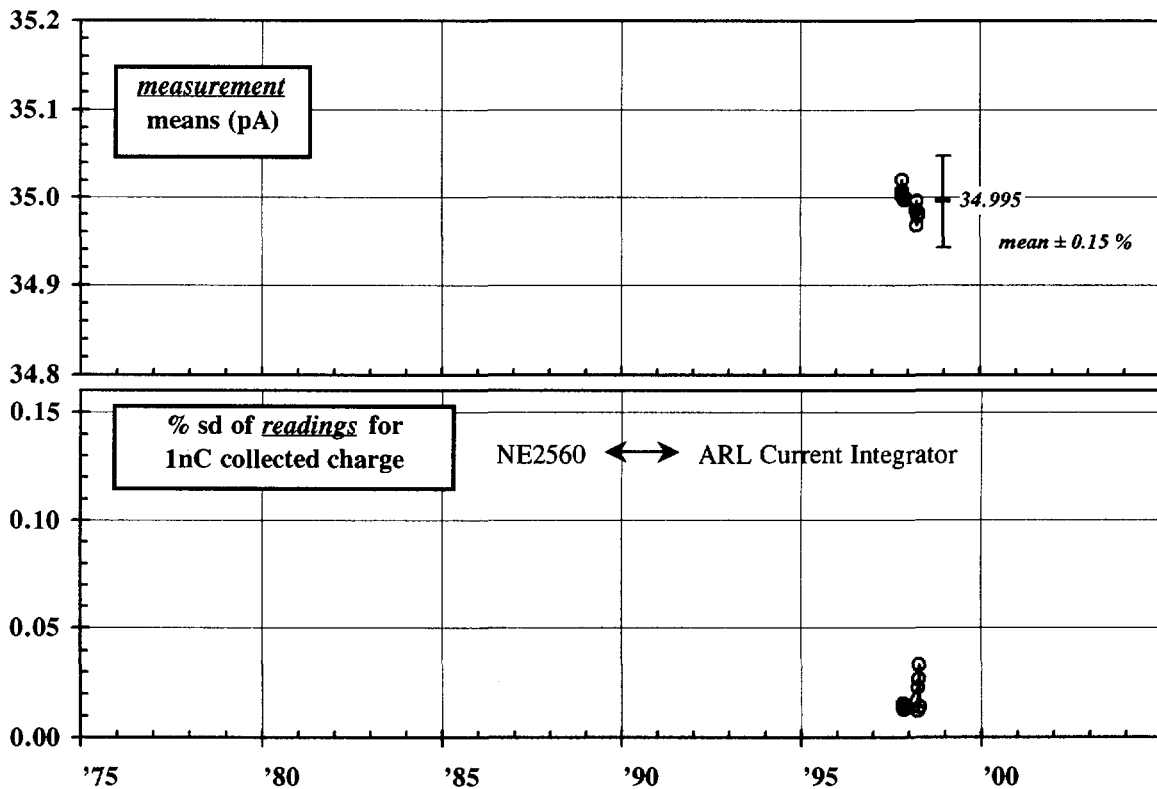
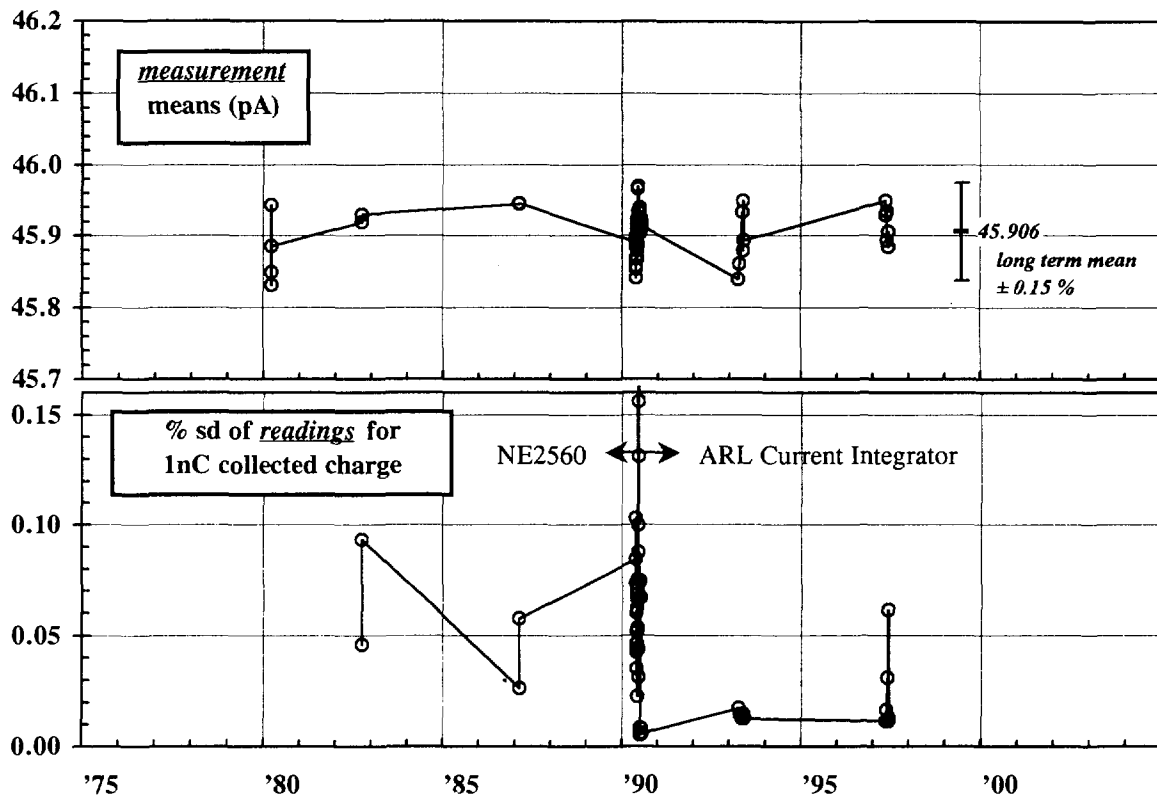
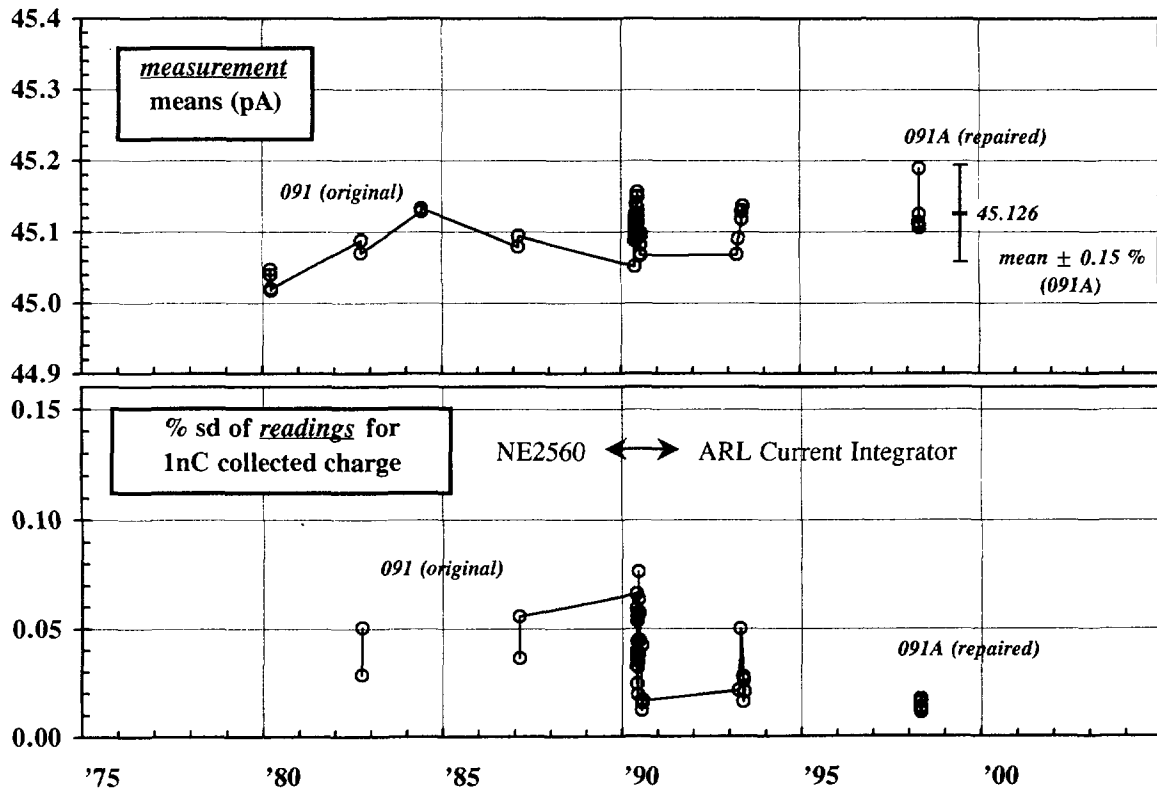
Figure 5.  $^{90}\text{Sr}$  Ref. Source Results; ARL NE2611A #150Figure 6.  $^{90}\text{Sr}$  Ref. Source Results; ARL NE2611A #152

Figure 7.  $^{90}\text{Sr}$  Ref. Source Results; ANSTO NE2561 #058Figure 8.  $^{90}\text{Sr}$  Ref. Source Results; ANSTO NE2561 #091 / 091A

A corrected test current of 123.104 pA was supplied by NE2611A chamber number 150 with its build-up cap in place, in a wooden phantom, in the horizontal beam from the ARL <sup>60</sup>Co source. This test current has been corrected to normal ambient conditions (NTPH) of 20 °C, 101.325 kPa and 50% relative humidity and to 1200h AET on 11/5/98, the date of the first measurement.

The combined leakage and radiation background current was measured by an overnight charge accumulation with the polarizing voltage connected. A reading of -0.50 nC was shown after the measurement, equivalent to a current of -8.9 fA. This is only 0.007% (70 ppm) of the test current, and has been ignored.

Several sets of measurements were made by reading the K35040 after identical incremental exposures (*ie* without resetting the electrometer to zero between readings) to investigate the effect of the incremental charging time on the results of a linear regression analysis. The true accumulated charge was fitted to the indicated charge (corrected as above to NTPH and 1200h AET on 11/5/98). This investigation was suggested in the previous report<sup>(1)</sup>.

The results showed a marked dependence on the incremental charging time as shown in Table 4, where the intercept (A) and slope (B) are the linear regression coefficients in:

$$\{\text{True Charge}\} = A + B \cdot \{\text{Indicated Charge}\} \quad (1)$$

**Table 4**  
**Keithley 35040 Calibration Using Incremental Exposures**

*accumulated charge not reset to zero between readings*

Incremental Exposure		A <sub>20</sub> <sup>a</sup>	B <sub>20</sub> <sup>a</sup>	A <sub>200</sub> <sup>a</sup>	B <sub>200</sub> <sup>a</sup>
Time, s	Charge, nC				
5.011	0.6169	0.010	1.0183		
10.011	1.2324	-0.007	1.0077		
20.011	2.4634	0.002	1.0014		
40.011	4.9255	0.003	0.9997	0.02	0.9998
80.011	9.8497			0.02	0.9987
160.011	19.6980			0.02	0.9983

<sup>a</sup> the subscripts <sub>20</sub> and <sub>200</sub> indicate the full scale range in nC.

While the “intercept” results (A) are not significantly different from zero, there is a bias in the “slope” results (B) at small incremental exposure times and charges. Note that the present test current ( $\approx$  123 pA) is 2 to 3 times that used in the previous calibration in 1997<sup>(1)</sup>.

In order to avoid the observed bias in the incremental exposure method, two or three sets of readings were taken on each of three ranges, resetting the K35040 to zero between each reading. This “separate exposures” method is identical to the manner of use of the instrument in normal practice and so truly reflects the deviation of the indications from the true charge. The disadvantage of this method is the much longer time taken for the calibrations. As it was

considered possible that the results obtained may still depend on the test current, the measurements on each range were repeated at a range of typical ionization chamber currents. The results are shown in Table 5.

**Table 5**  
**Keithley 35040 Calibration Using Separate Exposures**

*accumulated charge reset to zero between readings*

Keithley 35040 Range, nC	Test Current, pA	Additive correction, nC		Gain correction factor		Residuals, $\pm$ nC <sup>b</sup>
		A	$\pm se$ <sup>a</sup>	B	$\pm se$ <sup>a</sup>	
<b>-2.0000</b>	-57.2837	0.0047	0.0004	0.9975	0.0003	0.0005
	-25.8542	0.0012	0.0005	0.9966	0.0005	0.0007
	<b>mean</b>	<b>0.0030</b>	<b>0.0012</b>	<b>0.9971</b>	<b>0.0003</b>	<b>0.0006</b>
<b>-20.000</b>	-123.1036	0.016	0.001	0.9974	0.0001	0.006
	-57.2837	0.010	0.002	0.9967	0.0001	0.004
	-25.8542	-0.003	0.002	0.9978	0.0002	0.003
	<b>mean</b>	<b>0.008</b>	<b>0.006</b>	<b>0.9973</b>	<b>0.0004</b>	<b>0.004</b>
<b>-200.00</b>	-123.1036	0.00	0.02	0.9978	0.0002	0.01
	-57.2837	0.01	0.03	0.9972	0.0002	0.06
	-25.8542	0.03	0.03	0.9969	0.0002	0.04
	<b>mean</b>	<b>0.01</b>	<b>0.01</b>	<b>0.9973</b>	<b>0.0003</b>	<b>0.04</b>

<sup>a</sup> standard error from the regression analysis for each test current,  $\frac{1}{3}$  of the range of values for the means.

<sup>b</sup> observed range of the regression residuals for each test current.

While there may appear to be marginally significant correlations between the regression coefficients and the test current, the results for the three ranges show no consistent pattern. The variations in the gain correction factor B are in all cases less than 0.06% from the mean values. The mean values have been adopted.

The regression parameters may be interpreted for future comparison with the manufacturer's specification [ $\pm(0.2\% + 2$  counts) for 1 year over the typical ambient temperature range] as in the following example.

On the -200.00 nC range, Table 5 shows a mean value for  $A_{200}$  of  $(+0.01 \pm 0.01)$  nC, which represents  $(+1 \pm 1)$  counts. According to the manufacturer's specification, in 1 year the value of  $A_{200}$  should therefore be  $(+1 \pm 2)$  counts.

The mean value for  $B_{200}$  is given as  $0.9973 \pm 0.0003$ . This shows that the gain error is currently  $(+0.27 \pm 0.03)\%$ . When the calibration is repeated in 1 year, the gain error should therefore be within the range  $(+0.27 \pm 0.2)\%$  according to the manufacturer's specification.

The regression residuals for the -200.00 nC range fall within a mean range of  $\pm 0.04$  nC or

$\pm 4$  counts. This means that the regression line is within  $\pm 4$  counts of the data points. This may represent either noise in the data or an actual differential non-linearity in the electrometer response. An indication of which conclusion is more appropriate may be drawn from the form of the residual plots. As these plots show no consistent patterns at the various test currents used, we conclude that the residuals result from the reproducibility of the data points, so the residuals have been interpreted as uncertainty in the results.

The mean results from Table 5 are summarized in Table 6 for each range tested. One third of the range of residuals shown in Table 5 has been added in quadrature to the standard error shown for the additive correction A in Table 5, to give the overall uncertainty for A shown in Table 6.

**Table 6**  
**Keithley 35040 Mean Calibration Results**

Range, nC	Additive correction, A			Gain correction factor, B		
	value, nC	uncertainty nC	value in counts	value	uncertainty	% gain correction
-2.0000	0.0030	0.0012	30 $\pm$ 12	0.9971	0.0003	-0.29 $\pm$ 0.03
-20.000	0.008	0.007	8 $\pm$ 7	0.9973	0.0004	-0.27 $\pm$ 0.04
-200.00	0.01	0.02	1 $\pm$ 2	0.9973	0.0003	-0.27 $\pm$ 0.03

### 3.1 Comparison with previous results

These results are comparable with the previously determined values for the -200.00 nC range (A =  $-0.01 \pm 0.01$ , B =  $0.9976 \pm 0.0006$ ), which were found using cumulative exposures<sup>(1)</sup>.

The previous values for the -20.000 nC range (A =  $+0.004 \pm 0.002$ , B =  $0.9988 \pm 0.0006$ ), which were also found using cumulative exposures, were apparently biased by the shorter exposure times used for that range.

While these results indicate that the calibration coefficients for the K35040 electrometer have not changed significantly since the previous calibration in May 1997, the calibration procedure has been improved to avoid biased results. It is therefore recommended that the K35040 electrometer should be recalibrated at ARL in twelve months. Earlier recalibration will be needed if quality assurance measurements with the <sup>90</sup>Sr reference sources show consistent changes exceeding 0.2% for ALL the ANSTO secondary standard ionization chambers.

## 4. IONIZATION CHAMBER CALIBRATION FACTORS

### 4.1 The calibration factors for exposure, $N_x$ and air kerma, $N_k$

The secondary standard ionization chambers were calibrated in air for exposure and air kerma with their individual build-up caps in place. The calibration factor for exposure is given by:



$$N_x = \dot{X} / {}_aI_s \quad (2)$$

where  $\dot{X}$  is the exposure rate at the centre of the ionization chamber, measured with the Australian primary standard of exposure/air kerma as described previously<sup>(1)</sup>. The corrected secondary standard ionization chamber currents in air  ${}_aI_s$  were measured with the ARL Current Integrator<sup>(1)</sup>.

The centres of the chambers were placed within 1 mm of the air reference distance from the source effective centre ( ${}_ad_{ref}=993.00$  mm). Distance measurements were made with a micrometer and the measured currents were corrected to  ${}_ad_{ref}$  using the inverse square law.

Note that exposure may be expressed in the pre-SI unit, the roentgen (R), which is equal to 0.258 mC/kg. The corresponding calibration factor is usually given as R/nC. In SI units, the exposure calibration factor is (C/kg) / C, which is often arcanelly expressed as kg<sup>-1</sup> or mg<sup>-1</sup>.

The calibration factor for air kerma is derived by calculation from  $N_x$ :

$$N_k = N_x \cdot (W/e) / (1-\bar{g}) \quad (3)$$

where  $W$  is the energy required to create an ion pair in dry air,  $e$  is the electronic charge and  $\bar{g}$  is the fraction of energy converted into bremsstrahlung. The values of  $W/e$  and  $\bar{g}$  for <sup>60</sup>Co radiation currently accepted by the Consultative Committee for Ionizing Radiations (CCRI) of the International Bureau of Weights and Measures (BIPM) are 33.97 J/C and 0.0032 respectively<sup>(2,3)</sup>. Thus:

$$\{\text{air kerma in mGy}\} = \{\text{exposure in R}\} \times \{0.258 \times 33.97 / 0.9968 = 8.7924\} \quad (4)$$

#### 4.2 The calibration factor for absorbed dose to graphite, $N_c$

The calibration factors in terms of absorbed dose to graphite are given by:

$$N_c = \dot{D}_c / {}_gI_s \quad (5)$$

where  $\dot{D}_c$  is the absorbed dose rate in solid graphite, measured by the graphite calorimeter and  ${}_gI_s$  is the corrected current from the secondary standard ionization chamber in the graphite phantom, measured with the ARL Current Integrator<sup>(1)</sup>.

The ionization chambers were placed in the graphite phantom, with their centres within 1 mm of the graphite reference distance ( ${}_gd_{ref} = 650.56$  mm) and also within 1 mm of the graphite reference depth ( ${}_gz_{ref} = 30.98$  mm). Distance measurements were made with a micrometer and the measured currents were corrected to  ${}_gd_{ref}$  using the inverse square law and to  ${}_gz_{ref}$  using measured broad beam attenuation data.

#### 4.3 The calibration factor for absorbed dose to water, ${}_{dr}N_w$

The absorbed dose to water calibration factors  ${}_{dr}N_w$  were found by the “dose ratio” method<sup>(1)</sup>:

$${}_{dr}N_w = {}_{dr}\dot{D}_w / {}_wI_s \quad (6)$$

$${}_{dr}\dot{D}_w = \dot{D}_c \cdot (\bar{\mu}_{en}/\rho)_c^w \cdot \beta_c^w / (R_c^w)^2 \cdot {}_wk_{air} \cdot {}_wk_{wall} \cdot {}_wk_{pfst} \quad (7)$$

where:

- $\dot{D}_c$  is the absorbed dose rate measured by the graphite calorimeter,
- $(\bar{\mu}_{en}/\rho)_c^w$  is the ratio of the mean mass energy absorption coefficients for water and graphite (averaged over the photon radiation energy spectra at the reference depths in the two phantoms),
- $\beta_c^w$  is the ratio of the quotients ( $\beta = D/K$ ) of absorbed dose and collision kerma in water and graphite,
- $R_c^w$  is the ratio  $R_w / R_c$  of the reference distances from the effective centre of the source to the centre of the ionization chamber in the water phantom and to the centre of the graphite calorimeter core,
- ${}_wk_{air}$  is the correction for air attenuation in the different air paths to the two phantoms,
- ${}_wk_{wall}$  allows for the different attenuation of the front wall of the water phantom compared with water,
- ${}_wk_{pfst}$  corrects for failure to fully satisfy the requirements of the photon fluence scaling theorem and
- ${}_wI_s$  is the corrected current from the secondary standard ionization chamber in the water phantom.

The values of the factors in equation (7) are shown in Table 7. These were discussed in reference (1).

The ionization chambers were placed one at a time in the water phantom, with their centres within 1 mm of the water reference distance from the effective centre of the source ( ${}_wd_{ref} = 1050.00$  mm; SSD = 1000.00 mm, depth = 50.00 mm). The water depth was adjusted before each measurement using a perspex gauge and a computerized motion control system to  $50.00 \pm 0.05$  mm. Distance measurements were then made with a micrometer and the measured currents were corrected to  ${}_wd_{ref}$  using the inverse square law. No correction was made for the variation of the effective water depth with temperature, as this only amounts to  $\pm 0.01\%$  between 17 °C and 23 °C, the range of temperatures observed in the ARL water phantom.

**Table 7**  
**Factors for Converting Absorbed Dose from Graphite to Water**

$(\bar{\mu}_{en}/\rho)_c^w$	1.1125
$\beta_c^w$	1.0003
$R_c^w$	1.6140
${}_w k_{air}$	0.9972
${}_w k_{wall}$	0.9988
${}_w k_{pfst}$	0.9992

#### 4.4 Recombination correction

The recombination correction for incomplete charge collection was re-evaluated using NE2561 chamber number 091A. The chamber was placed in a wooden phantom with a build-up cap in place, at three distances from the ARL  $^{60}\text{Co}$  source, to obtain ionization currents of approximately -124 pA, -57 pA and -26 pA. These measurements were made concurrently with the electrometer calibration described in section 3, using the same experimental arrangements. The recombination correction was found in each case by linear extrapolation of  $I^{-1}$  vs  $V^{-1}$  to  $V^{-1}=0$ . This method was found in previous work at ARL<sup>(1)</sup> to provide a better model of the data for these chambers than the more traditional  $I^{-1}$  vs  $V^{-2}$  extrapolation. A recent publication<sup>(4)</sup> suggests that extrapolation of  $I^{-1}$  vs  $V^{-2}$  does not adequately account for all the mechanisms of recombination that occur in an ionization chamber; a method based on a least squares fit to a three parameter model is suggested. This will be investigated in future work. Results of the recombination measurements are shown in Table 8.

These results show no significant correlation with the test current. They are close to the value reported by the BIPM<sup>(5)</sup>. As all the chambers are of similar physical construction, the mean value of  $1.0014 \pm 0.0001$  has been adopted here for all the ionization chambers.

#### 4.5 Exposure, air kerma and absorbed dose calibration factors for $^{60}\text{Co}$

The secondary standard ionization chambers were calibrated in the three  $^{60}\text{Co}$  geometries (air, graphite and water) as described previously<sup>(1)</sup>. The results have been consolidated into a single mean current for each chamber in each geometry and corrected to a common reference date (29/4/98). Calibration factors have been determined in each case as described above from the true exposure, air kerma and absorbed dose rates found using the primary standards. The calibration conditions are shown in Table 9. Also shown in Table 9 are the values that have been used on this occasion for the saturation correction (as described above) and for the phantom actual depth to reference depth, radial non-uniformity and waterproof sheath corrections. The last three corrections are unchanged from those given in the previous report<sup>(1)</sup>.

**Table 8**  
**Recombination Measurements**

*reference conditions: 20 °C, 101.325 kPa, 50% RH,  
1200h AET on the date of measurement, <sup>60</sup>Co T<sub>1/2</sub>, 1925.5 days*

Approx. distance mm	Date of Measurement	Polarizing Voltage, V	Ionization current			k <sub>s</sub>	se <sup>b</sup>
			Mean, pA	% sd	n <sup>a</sup>		
587	14/5/98	-202.6	-124.067	0.010	30	1.00148	0.00013
		-135.4	-123.994	0.008	30		
		-67.3	-123.716	0.018	60		
830	14/5/98	-203.2	-57.276	0.012	40	1.00132	0.00010
		-135.7	-57.231	0.015	30		
		-67.3	-57.117	0.015	40		
1174	18/5/98	-212.9	-25.8994	0.025	50	1.00145	0.00008
		-142.1	-25.8782	0.020	25		
		-71.1	-25.8227	0.020	120		

<sup>a</sup> the number of readings in the measurement.

<sup>b</sup> derived from the relative standard error of the intercept ( $\Gamma^{-1}$  for  $V^{-1}=0$ ) in the linear regression analysis.

**Table 9**  
**<sup>60</sup>Co Calibration Conditions**

*reference conditions: central axis, d<sub>ref</sub>, z<sub>ref</sub> 1200h AET on 29/4/98, <sup>60</sup>Co T<sub>1/2</sub>, 1925.5 days*

Medium and Calibration Quantity	Air		Absorbed dose	
	Exposure	Air kerma	Graphite	Water <sup>a</sup>
1 True rate, mR/s or mGy/s	514.32	4.5221	9.5012	4.0394
2 Reference distance d <sub>ref</sub> , mm	993.00		650.56	1050.00
3 Phantom reference depth z <sub>ref</sub> , mm	na		30.98	50.00
4 Square field size, mm x mm	100 x 100		65 x 65	105 x 105
5 Saturation correction, k <sub>s</sub>	1.0014			
6 Phantom depth correction, k <sub>z</sub>	na		0.9947	1.0000
7 Radial non-uniformity correction, k <sub>rn</sub>	1.0000		1.0006	1.0000
8 Waterproof sheath correction, k <sub>sh</sub>	na			1.0003

<sup>a</sup> absorbed dose rate to water evaluated by the dose ratio method<sup>(1)</sup>.

Note that in Table 9:

- Row 1 gives the true rates of exposure, air kerma, absorbed dose to graphite and absorbed dose to water, on the radiation beam central axis, at the reference distance  $d_{ref}$  shown in row 2, and (for absorbed dose) at the phantom reference depth  $z_{ref}$  shown in row 3, corrected to 1200h AET on 29/4/98 (the reference date for this report). These figures are based on the mean responses of the primary standards, including all determinations that have been made with the present  $^{60}\text{Co}$  source. They therefore represent the current best estimates of the true rates.
- Row 4 shows the approximate field size of the ARL  $^{60}\text{Co}$  calibration facility, which has a fixed square collimator producing a conical square beam.

Table 10 shows the mean corrected negative ionization currents  $I_s$  for the secondary standard ionization chambers under the indicated reference conditions, where  $I_s$  is given by:

$$I_s = I_m \cdot k_t \cdot k_T \cdot k_P \cdot k_H \cdot k_d \cdot k_s \cdot k_z \cdot k_{rn} \cdot k_{sh} \quad (8)$$

in which	$I_m$	is the measured current,
	$k_t$	is the decay correction,
	$k_T$	is the ambient temperature correction,
	$k_P$	is the ambient pressure correction,
	$k_H$	is the ambient humidity correction,
	$k_d$	is the distance correction,
	$k_s$	is the saturation correction,
	$k_z$	is the phantom depth correction,
	$k_{rn}$	is the beam radial non-uniformity correction and
	$k_{sh}$	is the waterproof sheath correction.

Note that the prefixes <sub>a</sub>, <sub>w</sub> and <sub>g</sub> are used with the symbol  $I_s$  to denote the corrected current when the chamber is used in air, water and graphite respectively.

The decay and ambient corrections  $k_t$ ,  $k_T$ ,  $k_P$  and  $k_H$  were applied as usual by the ARL Current Integrator computer. The distance correction  $k_d$  was evaluated separately for the measurements made on any particular day, using a micrometer to measure the actual source to detector distance in each case. The values of  $k_s$ ,  $k_z$ ,  $k_{rn}$  and  $k_{sh}$  are shown in Table 9.

**Table 10**  
**Mean Corrected Negative Ionization Currents (pA)**

*reference conditions: 20 °C, 101.325 kPa, 50% RH,*  
*central axis,  $d_{ref}$   $z_{ref}$  1200h AET on 29/4/98,  $^{60}\text{Co } T_{1/2}$  1925.5 d,  $^{90}\text{Sr } T_{1/2}$  10516 d*

Chamber				$^{60}\text{Co}$ - medium			Owners $^{90}\text{Sr}$ Reference Source
Owner	Type	Serial	Date	Air	Graphite	Water	
ANSTO	2561	091A	5/98	48.164 (16)	104.642 (21)	39.490 (9)	29.028 (20)
ARL	2561	070	5/98	48.127 (12)	104.598 (14)	39.456 (18)	23.064 (4)
		194A	4/98	50.299 (34)	109.316 (55)	41.231 (30)	23.928 (7)
		238A	12/97	na	na	39.236 (16)	23.012 (0.3)
		328	4/98	47.725 (22)	103.655 (36)	39.139 (23)	22.047 (7)
	2611A	150	12/97	47.707 (17)	na	39.087 (25)	23.004 (5)
			4/98	47.693 (28)	103.696 (62)	39.092 (27)	22.989 (6)
		152	12/97	47.516 (5)	na	38.951 (8)	22.513 (1)
			4/98	47.481 (13)	103.284 (57)	38.945 (20)	22.499 (5)

Note that in Table 10:

Chambers 150 and 152 were first calibrated in December 1997. Number 238A was also calibrated in December 1997. Chambers 150, 152, 194A and 328 were calibrated in April 1998, and chambers 091A and 070 in May 1998.

The figures in parentheses represent the observed standard deviations (in fA) of the mean currents measured on different dates.

The currents for the  $^{60}\text{Co}$  beams have been corrected to infinite polarizing voltage to account for ion recombination effects. The nominal polarizing voltage used for all measurements was -210 V.

The  $^{90}\text{Sr}$  reference source currents shown in the right hand column were measured using the reference source belonging to the owner of each chamber. The  $^{90}\text{Sr}$  results have not been corrected for ion recombination effects.

The calibration factors for each chamber, obtained from Tables 9 and 10, are shown in Table 11. The relative uncertainties shown in the bottom row of Table 11 have been discussed previously<sup>(1)</sup>.

**Table 11**  
**<sup>60</sup>Co Calibration Factors of ANSTO and ARL**  
**Secondary Standard Ionization Chambers**

*reference conditions: 20 °C, 101.325 kPa, 50% RH,*  
*measured charge corrected for recombination*

Medium and Calibration Quantity				Air		Absorbed Dose	
				Exposure	Air kerma	Graphite	Water
Ionization Chamber				$N_x$	$N_k$	$N_c$	$_{dr}N_w$ <sup>a</sup>
Owner	Type	Serial	Date	R/nC	mGy/nC	mGy/nC	mGy/nC
ANSTO	2561	091A	5/98	10.679	93.89	90.80	102.29
ARL	2561	070	5/98	10.687	93.96	90.84	102.38
		194A	4/98	10.225	89.90	86.92	97.97
		238A	12/97	na	na	na	102.95
		328	4/98	10.777	94.75	91.66	103.21
	2611A	150	12/97	10.781	94.79	na	103.34
			4/98	10.784	94.82	91.63	103.33
		152	12/97	10.824	95.17	na	103.70
			4/98	10.832	95.24	91.99	103.72
Relative uncertainty, %				0.36	0.31	0.18	0.19

<sup>a</sup> based on absorbed dose rate to water evaluated by the dose ratio method<sup>(1)</sup>.

#### 4.6 Comparison with previous results

The new calibration factors for each ionization chamber with a recent history of calibrations at ARL are compared with the previous values in Table 12. Chamber number 091A (originally number 091) was repaired in 1997 and chambers 150 and 152 were purchased in 1997, so earlier calibration data for these chambers are either not relevant or not available. The 1997 values are taken from the previous report<sup>(1)</sup>.

**Table 12**  
Comparison with Previous <sup>60</sup>Co Calibration Factors

Serial Number	Date	$N_x$ R/nC	$N_k$ mGy/nC	$N_c$ mGy/nC	$_{dr}N_w$ mGy/nC
070	1998	10.687	93.96	90.84	102.38
	1997	10.668	93.79	90.73	102.25
	% change	+0.18	+0.18	+0.12	+0.13
194A	1998	10.225	89.90	86.91	97.97
	1997	10.202	89.70	86.78	97.77
	% change	+0.23	+0.22	+0.15	+0.20
238A	1998	na	na	na	102.95
	1997	10.736	94.40	91.34	102.91
	% change	na	na	na	+0.04
328	1998	10.777	94.75	91.66	103.21
	1997	10.756	94.57	91.46	103.06
	% change	+0.20	+0.19	+0.22	+0.15
Mean % change		+0.20	+0.20	+0.16	+0.13

Note that the recombination correction has been re-evaluated from approximately 1.0018 to 1.0014. This has changed the corrected ionization chamber currents by -0.04 %, which changes the calibration factors by +0.04 %. Allowing for this change, none of the ionization chamber calibration factors has changed by more than 0.16 %. This is comparable with the long term variation of the <sup>90</sup>Sr reference source results, and is not considered to be significant, even though there is some apparent correlation between the four ionization chambers. Note also that these variations are less than the uncertainties of the primary standards.



## 5. SUMMARY AND CONCLUSIONS

The continued stability of the Australian secondary standards of exposure/air kerma and absorbed dose has been demonstrated. Data from ARL records of previous calibrations have been collated for the  $^{90}\text{Sr}$  reference source responses of the two ANSTO NE2561 chambers numbers 058 and 091. These chambers have thus been shown to have comparable stability to the ARL chambers.

The ANSTO reference electrometer has been recalibrated using an improved technique to avoid biased results at short incremental exposure times. The calibration has not changed significantly since May 1997. The electrometer should be re-calibrated at ARL in 1999. Earlier recalibration will be needed if quality assurance measurements with the  $^{90}\text{Sr}$  reference sources show consistent changes exceeding 0.2% for ALL the ANSTO secondary standard ionization chambers.

The recombination correction for the 325 mm<sup>3</sup> ionization chambers has been re-evaluated and now agrees more closely with the findings of other laboratories. The new results were found using a more restricted range of polarizing potentials. Further investigations will be undertaken using a recently published empirical model.

New calibration factors have been reported for several of the ionization chambers including the repaired ANSTO chamber number 091A and all of the ARL 325 mm<sup>3</sup> ionization chambers. These calibration factors have not changed significantly since 1997 in the case of the four chambers previously calibrated. Every secondary standard ionization chamber of both ANSTO and ARL should be recalibrated at intervals not exceeding five years. Chambers with a calibration history of less than 10 years should be recalibrated at least every three years.

**APPENDIX****Calibration Data for Supporting Standards**

The primary standards maintained at ARL are supported by numerous secondary and tertiary measurement standards, for a range of quantities. To ensure the validity of the ARL primary standards, these supporting standards must be traceable to the corresponding Australian primary standards maintained by the National Measurement Laboratory (NML) of the Commonwealth Scientific and Industrial Research Organization (CSIRO). The ARL supporting standards are summarized in Table A.1, and their most recent calibration data are given in Tables A.2 (Electrical Standards) and A.3 (Meteorological Standards). Equipment used to make ionization current measurements and to correct these measurements is calibrated periodically against the supporting standards. The most recent calibrations of the components of the ARL Current Integrator and of the other equipment used to make the measurements reported here are shown in Table A.4.

**Table A.1**  
**ARL Supporting Standards**

Quantity	Quality or Range	Standards maintained (number)
time (frequency)	quartz oscillators	Telstra time signals used (0)
<b>Electrical Standards - see Table A.2</b>		
voltage	dc	Weston standard cells (3) <sup>a</sup>
capacitance	1 kHz	standard air capacitors (5)
resistance	low voltage dc	standard resistors (11)
<b>Meteorological Standards - see Table A.3</b>		
temperature	ambient (15 to 30 °C)	mercury in glass thermometers (8) platinum resistance thermometer (1)
pressure	ambient	Kew mercury barometer (1)
relative humidity	ambient	aspirated whirling hygrometer (1)

<sup>a</sup> One cell was damaged in September 1997 by faulty equipment.

**Table A.2**  
**Current Certified Values of ARL Electrical Standards**

Type	Serial number	Certificate number	Date	Valid to	Value	±LSD	Unit
<b>VOLTAGE</b> Elmeasco standard cell enclosure calibrated by NML.							
700A-04	340.1	RM1647	9/12/96	Nov 98	1.018 156 80	(35)	V
	340.2				1.018 158 40		
	340.3				1.018 159 00		
	340.4				1.018 154 10 <sup>a</sup>		
<b>CAPACITANCE</b> General Radio standard air capacitors calibrated at 1 kHz by NML.							
1403-K	6707	RM1831	4/4/97	Mar 02	1.000 62	(60)	pF
1403-G	6837	RM1832			10.000 7		
1403-D	6732	RM2053	24/6/98	Jun 03	100.026 90	(15)	
1404-A	1887	RM2051			1000.049	(2)	
1404-A	2181	RM2052			1000.051		
<b>RESISTANCE</b> Guildline(G) William(W) or Keithley(K) calibrated at dc by NML.							
G 9330	55323	RM2049	2/7/98	Jun 03	0.999 984 4	(3)	Ω
	54306	RM1838	24/4/97	Apr 99	9.999 995	(2)	
	55230	RM2050	2/7/98	Jun 03	100.001 250	(25)	
W 1k	5015	RM1839	24/4/97	Apr 99	999.789 80	(25)	
G 9330	54534	RM1380	2/8/94	Apr 97 <sup>b</sup>	10.000 173 0	(23)	kΩ
	55111	RM1840	24/4/97	Apr 99	100.006 76	(6)	
	54726	RM1413	6/10/94	Sep 96 <sup>b</sup>	999.978 2	(15)	
		54946	RM1841	24/4/97	Apr 99	10.000 174	(10)
K 100M	RM1414	RM1414	6/10/94	Sep 96 <sup>b</sup>	100.17	(8)	GΩ
K 10G	RM1415	RM1784	23/12/96	Dec 98	9.920	(29)	
K 100G	RM1785	RM1785			99.10	(65)	

<sup>a</sup> standard cell number 4 was damaged in September 1997 by faulty equipment. This value is no longer valid.

<sup>b</sup> these standard resistors are scheduled for re-calibration in 1998.

**Table A.3**  
**Current Certified Values of ARL Meteorological Standards**

Type	Serial number	Certificate number	Date	Valid to	Value or correction	u/c	Unit
<b>TEMPERATURE</b> Dobbies mercury-in-glass thermometers calibrated by Dobbies.							
-1/1 and 15/30	B7419	34162 / B5850	8/12/78	not stated	+0.01	0.02	°C
	B7423	44760 / B7103	8/12/83		-0.01		
	R2282	36638 / B6182	24/7/80		-0.03		
	R2284	36639 / B6182			-0.03		
	S/6019	57816 / B8577	29/6/89		-0.02	0.03	
	S/6022	57819 / B8577			-0.02		
	3907	47835 / B7350	18/9/84		-0.01	0.02	
	3908	47836 / B7350			0.00		
Rosemount platinum resistance thermometer calibrated by NML.							
162N100A	3318	RS27895	13/3/97	Mar 02	$R_0:99.908\Omega$	0.01	°C
<b>PRESSURE</b> Franklin Hg barometer calibrated by Bureau of Meteorology.							
Kew	1169	not numbered	Sep 94	not stated	-20	1.5	Pa
<b>REL. HUMIDITY</b> uncalibrated aspirated (whirling) hygrometer							
<p>This influence quantity is insufficiently important to merit traceability. The effect of changes in the relative humidity on the response of an ionization chamber is less than 0.1% for relative humidity between 10% and 90%. Uncalibrated commercial hygrometers are reliable to <math>\pm 5\%</math> RH which represents an uncertainty in the ionization chamber current of only 0.01%. This uncertainty has been taken into account in the overall uncertainty<sup>(1)</sup> of the calibration factors reported here.</p>							

**Table A.4**  
**Calibration Data for the ARL Current Integrator**

Item	Procedure	Date	Result			
<b>TIME</b>						
hp86 computer #2550A50975 clock oscillator	calibrated against Telstra time signals	Jun 98	correction = $+9 \pm 0$ ppm			
Current Integrator timer hp5316A #2052A00467	verified against corrected hp86 #2550A50975	Jul 98	error = $+1 \pm 1$ ppm			
<b>VOLTAGE</b>						
dc voltage standard	standardized <sup>a</sup>	Jun 98	error < 10 ppm			
Current Integrator DMM K199/1992 #467251	linear regression: True = a + b.Reading	Jul 98	fsd	a, $\mu$ V	b	
			3V	-3	0.999 99	
			30V	+190	1.000 34	
<b>CAPACITANCE</b>						
capacitance bridge	standardized at 1kHz <sup>a</sup>	Jun 97	error < 100 ppm			
Current Integrator C <sub>ref</sub> (box number 2959). Polystyrene capacitors in a Keithley model 3011 shielded switch. <sup>b</sup>	calibrated at a range of frequencies and extrapolated to 10 Hz	Jun 97	capacitor #1	57.07	pF	
			capacitor #2	204.57		
			capacitor #3	502.26		
			capacitor #5	1995.26		
<b>TEMPERATURE</b>						
<sup>90</sup> Sr:	08 Co Ref	YSI thermistors calibrated at ambient temperature	Feb 98	correction	-0.12	°C
Air:	01 Co Air		Feb 98		-0.08	
Graphite:	00 RBH system		Mar 98		0.00	
Water:	04 Co H <sub>2</sub> O		Mar 98		-0.02	
<b>PRESSURE</b>						
capacitance manometer	calibrated	daily	correction	-30 to -60	Pa	

<sup>a</sup> Standardized means tested and adjusted to ensure tracability to national standards.

<sup>b</sup> Switch position #4 is a short-circuit for offset voltage measurements.

**GLOSSARY**

*Note that all acronyms have been expressed in English.*

AET	Australian Eastern Time = GMT + 10 hours.
ANSTO	Australian Nuclear Science and Technology Organisation
ARL	Australian Radiation Laboratory
BIPM	International Bureau of Weights and Measures
CCRI	Consultative Committee for Ionizing Radiations
CSIRO	Commonwealth Scientific and Industrial Research Organisation
NML	National Measurement Laboratory (CSIRO)
NTPH	Normal Temperature, Pressure & Relative Humidity (20°C, 101.325 kPa, 50 %)
NRC	National Research Council (Canada)

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