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Acceptance Testing of the TASL Radon Dosimetry System

Brendan Tate and Stephen Long

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by

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We would also like to thank the staff at Track Analysis Systems Ltd for assistance with the many facets of commissioning a new TASL system.

Executive Summary

ARPANSA has purchased TASL (Track Analysis Systems Ltd) Radon dosimetry systems for the automated reading of nuclear track-etch plaques used in radon dosimetry measurements. ARPANSA has operated an in-house developed program for radon dosimetry for many years. This program has involved human readers and more recently an automated system. Both of these methods have proven to be time intensive and prone to higher than acceptable uncertainties. It is believed that the TASL system will provide a more robust solution that will be simpler to operate and provide more consistently accurate results.

The system was tested by preparing a linearly graded exposure regime, where plaques were exposed to a approximately constant radon atmosphere for successively longer periods, from four hours up to ten days. The exposures were measured using ARPANSA's calibrated radon exposure system. The plaques were then processed using the TASL system and a comparison between the ARPANSA measurements and the TASL system was performed. The TASL system returned measurements that were 80.4% of that expected. The calibration factor of the TASL system was then altered to account for this disprecancy. A second set of three exposures was then performed, and the results added to the previous data to check that the new calibration factor was valid. Plaques were then allowed to rest for several weeks and then read a further time to check repeatability of measurements.

An uncertainty analysis was then performed to determine the characteristic limits of the TASL system. Using the Currie method the critical limit (L_C) and the detection limit (L_D) were determined to be 487 and 980 Bq.day.m^{-3} respectively. The minimum reportable level of the system was found to be 825 Bq.day.m^{-3}.

The TASL system has been found to operate well within the specifications advertised, and is very efficient and operator friendly. It will provide a very adequate alternative to the in-house designed radon dosimetry system currently in use by the Personal Radiation Monitoring Service.

1. Introduction

1.1 Objective and Scope

ARPANSA has purchased a TASL (Track Analysis Systems Ltd) Radon dosimetry system for the automated reading of nuclear track-etch plaques used in radon dosimetry measurements. ARPANSA has operated an in-house developed program for radon dosimetry for many years. This program has involved human readers and more recently an automated system. Both of these methods have proved to be time intensive and prone to error. It is believed that the TASL system will provide a more robust solution that will be simpler to operate and provide more consistently accurate results. The introductory measurements designed to test the suitability of the TASL system for the Personal Radiation Monitoring Service (PRMS), the operating limits and accuracy of the system are detailed in this report.

1.2 Radon

Radon is a colourless and odourless gas, and is part of the radioactive decay series of uranium-238, uranium-235 and thorium-232. These decay series lead to two main isotopes, radon-222 (commonly known as radon) and radon-220 (commonly known as thoron). Both isotopes undergo alpha decay, with half lives of 3.82 days and 55.6 seconds, respectively. Human exposure to radon is mostly due to radon-222 and its short lived progeny. Due to its short half-life, radon-220 is considered to be less important in ambient air. Radon is largely regarded as the second highest cause of lung cancer in humans, behind smoking, and is the primary cause of lung cancer in non-smokers (WHO, 2009).

Human exposure to radon primarily falls into two categories, in dwellings (as members of the public) or in the workplace (as occupational exposure).

Uranium exists in trace amounts in rocks and soils, and therefore radon is present in the earth's atmosphere due to emanation from these sources. Radon concentrations in outdoor air are very low, but can rise substantially when trapped and able to accumulate indoors. Elevated levels of radon have been observed in areas such as the UK, Scandinavia and the USA (NRC, 1999). A number of factors can influence these levels, including construction materials, ventilation, soil porosity and uranium content of the soil.

1.3 ARPANSA Radon Calibration Facility

ARPANSA has maintained a radon calibration facility since the establishment of the Australian Radiation Laboratory (ARL) Yallambie premises in the late 1970s. The original ARL radon chambers were designed to calibrate ARL's radon measurement equipment. In the mid 1980s the laboratory was designated as the Pacific Region Radon Reference Facility for the Organisation for Economic Cooperation and Development - Nuclear Energy (OECD/NEA) International Intercalibration and Intercomparison (III) Program. The facility was upgraded at this time to be suitable for the requirements of the intercomparison program. Around this time there was a growing international awareness that exposure to radon and its progeny was not only a problem experienced by the uranium mining and milling industry. The International Atomic Energy Agency (IAEA) and Commission of the European Communities began a 5-year coordinated research program (CRP) on radon in the human environment. The program consisted of projects involving more than 50 countries and concluded in 1994. During the CRP, the III Program was replaced by the IAEA International Radon Metrology Program (IRMP). The ARL radon laboratory was at this point designated as a Reference Laboratory and Coordinating Laboratory for the IRMP. As a result of this affiliation, the original chamber was upgraded to its existing format in 1996. The current version of the facility, now operated by ARPANSA has been operational since this time.

The ARPANSA radon calibration facility (referred to as the 'radon chamber', or just 'the chamber') is comprised of three connected rooms with a total volume of 24.8 m^3. These rooms are the radon chamber, environmental conditioning room and entry passageway. The radon chamber itself has a volume of 16.5 m^3. The chamber is supplied with radon from various discrete sources (uranium ore, Pylon[1] radium sources and ARL radium sources) housed in sealable drums. Various radon concentrations can be achieved from background to greater than 20 $kBq.m^{-3}$ by using different combinations of sources and the use of inlet and outlet fans.

The radon calibration facility chamber environment is controlled by a combination of air conditioner/heater (Daikin DCS303A51) and humidifier systems which are designed to maintain the temperature and relative humidity in a relatively narrow, controllable band. As the overall facility is not designed to be air-tight, the chamber remains at ambient atmospheric pressure.

1.4 Radon Measurement

1.4.1 Radon Determination, ATMOS 12 DPX

The ARPANSA radon chamber uses as its primary method of determining radon concentration an ATMOS 12 DPX (referred to as an 'Atmos') portable radon meter (pictured in Figure 1.1). The instrument is made by GammaData Instruments AB, from Uppsala, Sweden. The instrument uses a pulse-counting ionisation chamber for the determination of radon concentration in air. It also stores energy spectrum information as well as time-based radon concentration. Radon concentrations are saved at 10 minute intervals and the device can store up to four weeks (28 days) of data in its internal memory. ARPANSA owns three Atmos units, two of which (serial numbers ATM266 and ATM272) were used in this measurement program.

The radon concentration in the chamber is measured by a radon monitor calibrated to a traceable standard at three different concentrations, 1, 3 and 10 $kBq.m^{-3}$. Until 2014, the calibrations were performed by Physikalisch-Technische Bundesanstalt (PTB) 'The National Metrology Institute of Germany' in Braunschweig, Germany. Since the closure of PTB's radon calibration facility in 2014, this task has been handled by Bundesamt für Strahlenschutz (BfS) – 'The Federal Office for Radiation Protection' in Berlin, Germany.

[1] Pylon Electronics Inc., Ottawa, Canada.

Figure 1.1: Atmos12 DPx used for measuring radon exposures

1.4.2 *Passive Measurement – CR-39 Plaques*

Radon is most often measured in homes and workplaces using passive-style monitors called solid-state nuclear track detector (SSNTD) systems. These monitors commonly use the material polyallyl diglycol carbonate (PADC) as their basis for measurement. PADC is formed using the monomer diethyleneglycol bis allylcarbonate (ADC) (pictured in Figure 1.2) along with diisopropyl peroxydicarbonate (IPP) as an initiator for polymerisation. PADC is a clear, colourless material with the empirical formula $C_{12}H_{18}O_7$, known more commonly as CR-39 ('Columbia Resin number 39'). Any radionuclides that undergo alpha decay in the vicinity of the material leave small damage tracks in the plastic. These tracks can be enlarged by a chemical etching process that allows them to be observed under a microscope. CR-39 detectors housed in an appropriate container that allows radon to diffuse in, but does not allow dust and other contaminants to enter can be left in the field for up to 12 months. Very low concentrations of radon (approx. < 10 Bq/m^3) can be measured in this fashion.

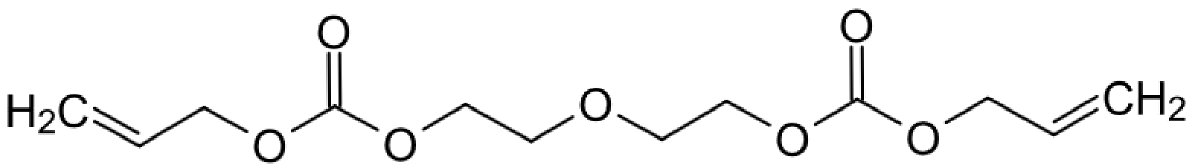

Figure 1.2: The monomer structure of ADC used in the formation of CR-39.

1.4.3 *Existing PRMS System*

The ARPANSA PRMS uses monitors designed in-house for passive radon measurement in homes and workplaces. The rectangular detectors are supported on a foam rubber disc held in place by a plastic sleeve, encased in small white polypropylene plastic jar (also referred to as a pot), designed and built by PRMS and ARPANSA's workshop (see Figure 1.2). The pot allows air to diffuse in through a small gap between the screw lid and the jar. Any radon that diffuses into the jar will undergo radioactive decay, with the resulting alpha particles leaving damage tracks in the CR-39 plaque. The monitor also includes a TLD monitor for gamma-radiation measurement (not pictured). The monitor housings are designed for multiple uses, with only a new CR-39 plaque required on each placement. This system has been operated for many years, and was used during ARL's radon in homes survey in 1990.

Until 2010, the measurement system involved human operators counting tracks on the plaques using a microscope. In 2008, human readers were replaced by an in-house developed automated reading system called SANTECS (Semi-Automated Nuclear Track Etch Counting System). The system was designed with the aim to be simpler to use and more efficient than human readers. This has not necessarily proven to be the case. It has been found that the SANTECS reader is prone to underestimate radon readings when larger than expected artefacts or marks appear on the plaques. These artefacts can be scratches on the plaque, or other similar marks introduced by the etching process. The appearance of these marks is not handled well by the image processing software, and causes the entire plaque to be underexposed when read. This means that actual radon tracks are washed out and not recorded as such by the software. The plaque then needs to be read again using a modified reading area that does not include the large mark in the area of interest. Once read, the value for this modified area then needs to be 'scaled-up' to an equivalent reading for a full-sized measurement area before the next step of the calculations can be performed. The set up and calculations for this modified region are entirely manual, and can be very time consuming compared to the automated reading process. This is especially true if multiple plaques in a batch exhibit artefacts of this type. The positioning of plaques on the scanner platen is also critical. Optical Interference patterns are a common occurrence if the plaques contact the glass platen too closely. It is not recommended to try and reset a single plaque on the platen in this instance, but rather reposition the entire batch of plaques on the platen if this occurs, which is again quite time consuming.

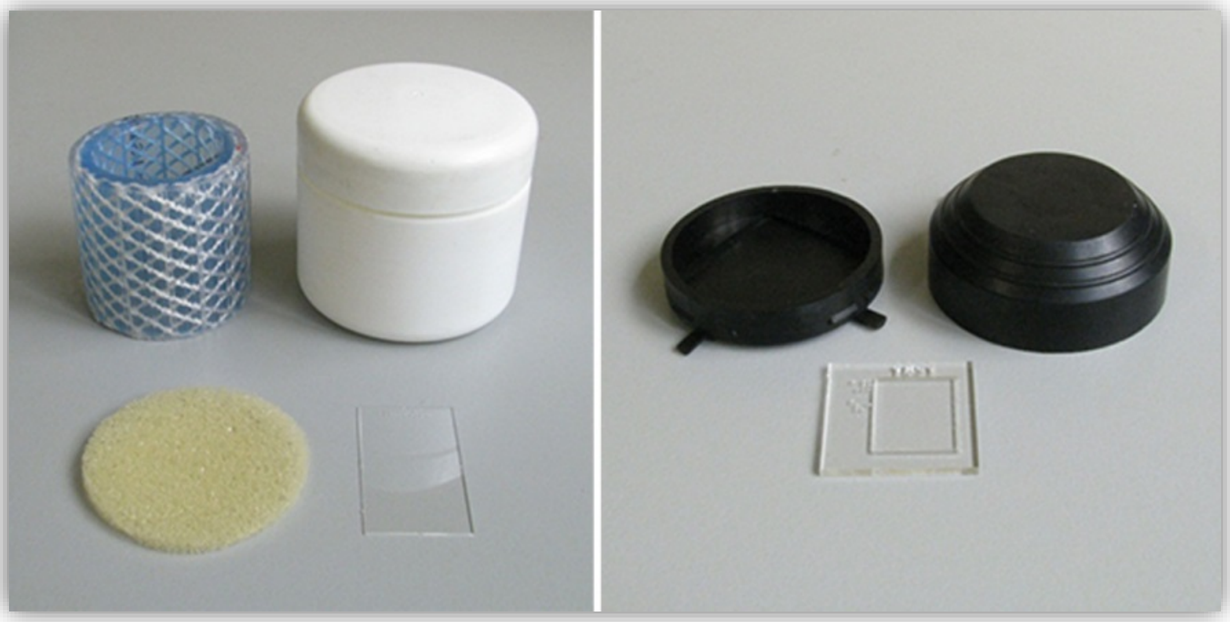

Figure 1.2 Composition of ARPANSA PRMS radon monitor (left) vs TASL 'radosure' radon monitor (right)

The CR-39 sheets used for both human readers and in SANTECS are of a proprietary brand known as Pershore, and were originally sourced from Page Moulding Ltd in the United Kingdom. They are expected to be stored in a nitrogen atmosphere, at room temperature. This is designed to keep them isolated from possible radon background contamination. SANTECS plaques are 35mm x 20mm and 0.5mm thick. Historically using human readers, the total area scanned is 0.36 cm^2, comprised of 20 separate areas, each of 0.018 cm^2. The SANTECS reader scans approximately 80% of the plaque, an area of 560mm^2, or 5.6 cm^2. Each plaque has a pre-etched serial number at the top. The area surrounding and including the serial number is not readable. Since 2015 Track Analysis Systems Ltd (TASL) have supplied plaques made from their proprietary TASTRACK material, cut to the specifications required to fit the SANTECS monitor housings.

After exposure, the plaques are etched for six hours in a 6.25 M potassium hydroxide (KOH) solution heated to 70 °C (Brown et.al. 2011) before they can be read.

1.5 TASL Radon and Neutron dosimetry system

Track Analysis Systems Ltd (TASL) provide a self-contained system which includes all equipment necessary to etch, scan and analyse TASL's CR-39 nuclear track detectors (using a proprietary highly purified variety of CR-39 called TASTRAK). This system was purchased by ARPANSA as a long-term replacement for the existing in-house developed system and the SANTECS. The components of the TASL scanning system are pictured in place at ARPANSA in Figure 1.3.

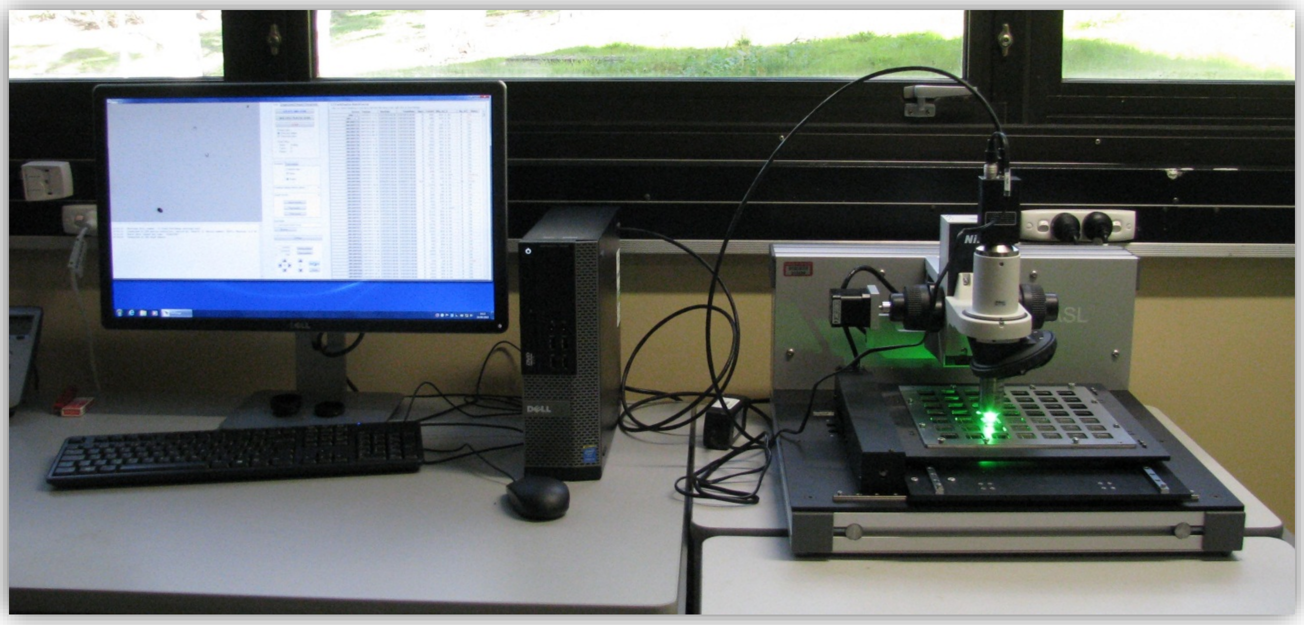

Figure 1.3: TASL radon plaque scanning system in place at ARPANSA

The TASL system is quoted to be capable of reading one tray (containing 49 plaques) per hour. This assumes a reading time of 30 to 80 seconds per plaque. A close-up of the microscope in operation scanning plaques in their mounting frame is shown in Figure 1.4. The system features a custom-fitted Nikon optical microscope, capable of three-axis motorised control. The image generated is viewed using a monochrome 24fps CCD imaging system. A close-up of an etched plaque featuring alpha particle tracks as pictured by the imaging system is shown in Figure 1.5.

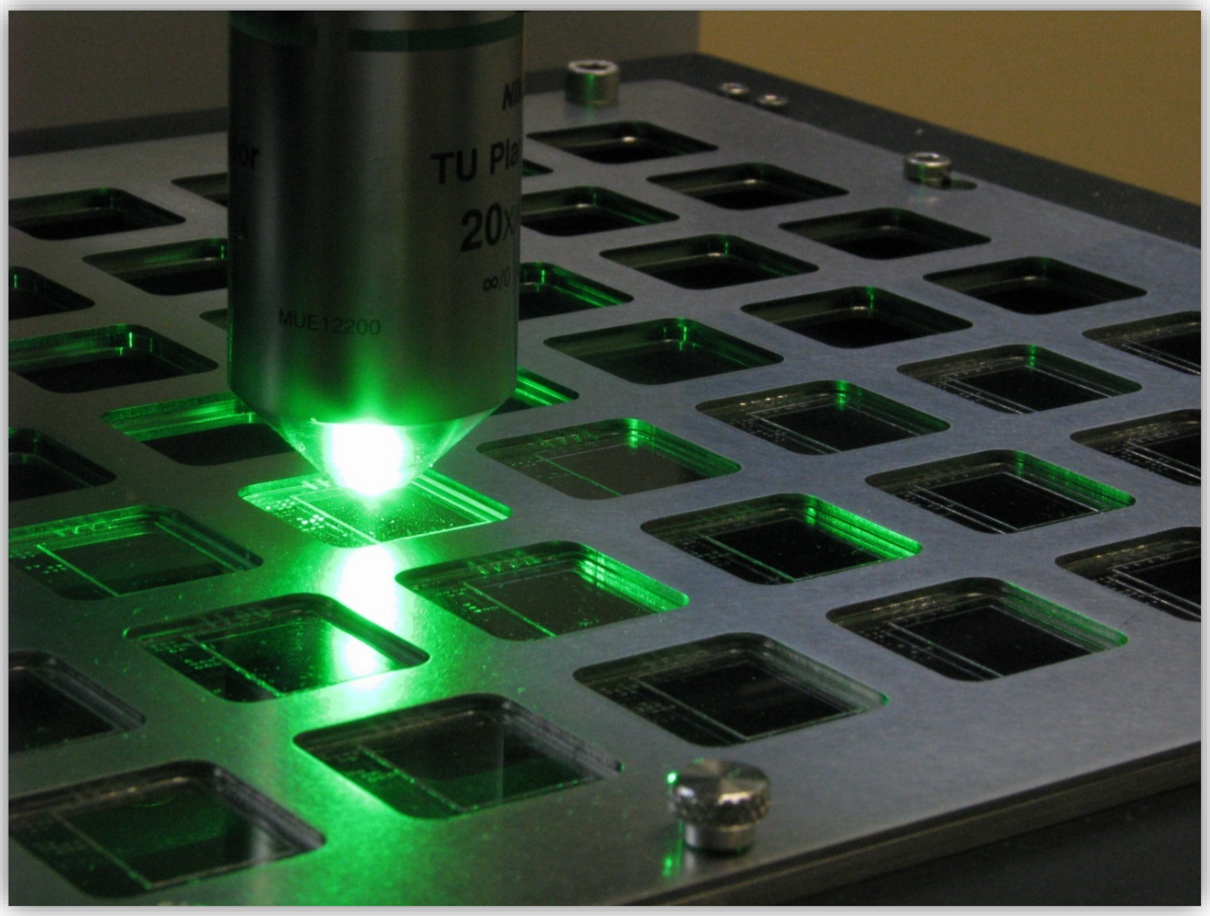

Figure 1.4: Close-up view of TASL scanning microscope in operation

TASL specifies that TASTRACK plaques are etched in a process that requires immersion in a 6.25 M NaOH solution, kept at 98°C for one hour for radon plaques. This solution is constantly stirred during the duration of the process. At the end of the etch, the plaques are rinsed with a 5% solution of Acetic Acid, CH_3COOH. This process is described in detail in the TASL*IMAGE* manual (TASL, 2015). The TASL etching system consists of a bath that can immerse one TASL supplied rack at a time. Each of these racks can hold six mounting trays allowing up to 294 radon plaques to be etched in one batch. The total time required for etching is approximately three hours, not allowing for the time required to completely dry the plaques following the rinsing stages of the etch. When being stored, TASL's specifications require that the CR-39 sheets are kept sealed in supplied static free plastic envelopes, in a freezer (with a standard temperature of approximately -18°C).

The plaques supplied by TASL are squares of area 625 mm^2 (25mm x 25mm). The plaque has a readable area of 221 mm^2 (13mm x 17mm). Also included on the plaque are a pre-etched serial number and corresponding dot code. The dot code is read by the TASL instrumentation to verify the serial number of the plaque during the analysis process.

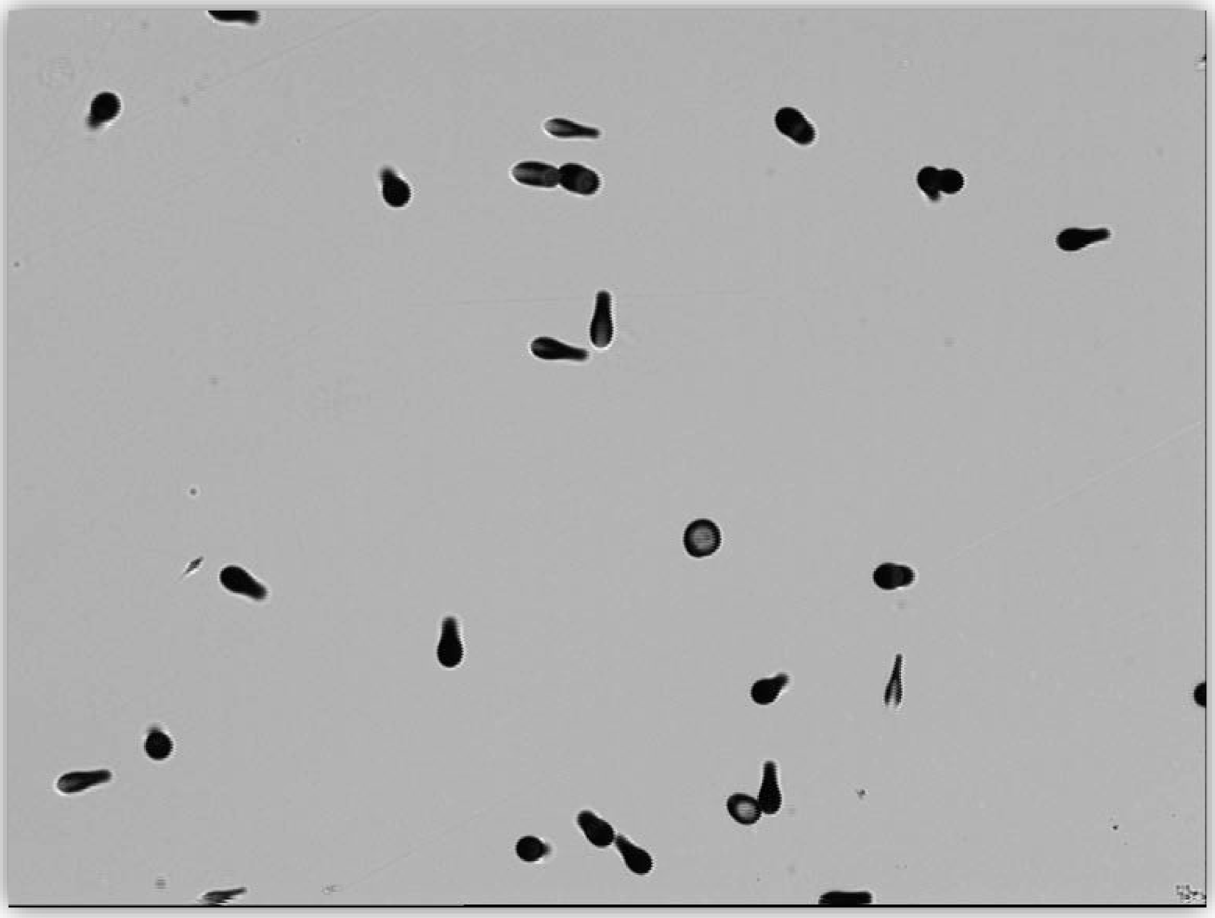

Figure 1.5: TASLImage microscope view of alpha particle tracks (image © TASL, UK)

1.5.1 Track Density Comparisons

ARPANSA has employed two methods of counting radon plaques, human readers and automated counters.

The plaque sizes and areas read differ markedly between the human and automated readers, and also between the two automated readers themselves. The differences in these systems are summarised in Table 1.0. The human reader counts tracks in 30 separate areas, chosen at random. These only add up to 0.4% of the total plaque area, whilst the SANTECS automated system reads 80% of the plaque area. The area excluded from measurement includes the region set aside for the pre-etched plaque serial number. The TASL system has a designated readable measurement area, the automated reader reads 100% of this area. The readable area of SANTECS plaques is greater than twice that of the TASL plaques, 560 mm^2 vs 221 mm^2.

Table 1.0: Comparisons of reading characteristics for three ARPANSA-based systems

	Tracks cm^{-2} per $Bq.d.m^{-3}$	Plaque Area mm^2 (mm x mm)	Area read mm^2	Total counts[a]
Human PRMS Readers[b]	0.085	700 (35x20)	30x0.1 = 3	90-120
SANTECS automated counter	0.053	700 (35x20)	560	10500
TASL automated counter	0.064	221 (13x17)	221	5600

a. Examples for an exposure in the range 35 – 45 kBq.d.m^{-3}

b. Each plaque read by two operators

From a sensitivity point of view, reading equivalent exposures human readers still provide the best option, reading at 0.085 tracks.cm^{-2} per Bq.d.m^{-3}. However, due to the fact that humans read a small fraction of tracks compared to the automated systems, there is a higher overall uncertainty. Of the two automated systems, the TASL reader reads 0.0112 more tracks.cm^{-2} per Bq.d.m^{-3} than the SANTECS reader, which is a 21% improvement.

1.5.2 Current PRMS radon methodology

The PRMS SANTECS uses a very simplified methodology to convert from tracks.cm^{-2} to radon concentration. The system uses an Epson V700 Photo flatbed scanner to take high-resolution images of the plaques. A Perspex rack is used to evenly space up to 20 plaques on the scanner for each batch. Custom designed macros for Image-Pro Plus software are used to examine each image, identify appropriate marks as alpha tracks and calculate the tracks.cm^{-2} for each plaque.

For each set of measurements, a set of blank plaques is exposed to a known radon atmosphere (40 kBq.day.m^{-3}), these are referred to as 'standards'. A corresponding set of plaques from the same CR-39 sheet is kept unexposed in a radon-free nitrogen atmosphere; these are referred to as 'blanks'. Both these sets of plaques are then combined with the field exposed plaques and are etched, imaged and processed using SANTECS in a single batch.

Once processed, the results obtained for the blanks are then averaged to obtain a minimum 'background' exposure value. This is given the nominal value of zero Bq.day.m^{-3}. The standards are then averaged to obtain a second exposure value. The values obtained from SANTECS for these plaques are then used to create a linear conversion model from tracks.cm^{-2} to Bq.day.m^{-3}. The results obtained for the field exposed plaques (in tracks.cm^{-2}) are then fitted to the model and radon exposures for each plaque are calculated. These procedures are detailed in the ARPANSA quality system manual RNL-SOP-010.

1.5.3 TASL radon methodology

The TASL system is designed to be wholly automatic, with minimal intervention required from the user during plaque processing. The plaques are locked into stainless steel trays for the etching process, and these trays are then transferred to the optical system for measurement. There is no need to alter the position of plaques once locked in place in the tray. The system calculates its doses using a pre-calculated track density (in tracks.cm^{-2}) to exposure (in kBq.h.m^{-3}) ratio. The track density is calculated using an algorithm that uses a range of parameters relating to the characteristics of a track. This algorithm deciphers genuine radon alpha tracks from background noise and other defects introduced during the exposure and etching process. The software also has a range of error codes so that any spurious results can be quickly identified and investigated. The resulting track density is converted to exposure using the pre-defined ratio. This calibration ratio is set to coincide with conditions at TASLs home laboratory in Bristol, UK. The calibration factor is able to be set by the user if the default is unsuitable for their conditions. The method used to set the calibration factor for use at the Yallambie premises is detailed in Section 4.1. The supplied TASL*IMAGE* software outputs data for track density and exposure. If the exposure period is input by the user during processing, TASL*IMAGE* also calculates the average radon concentration for each plaque.

Contrary to the method employed by SANTECS, there is no requirement to include blanks or to do standard exposures as part of the calculation process. However, ARPANSA will continue to perform these functions as part of the normal procedure for processing radon monitors since the inclusion of blanks and standards can be used to improve the track detection algorithm. This will result in better overall performance of the system. The TASL*IMAGE* software also has options to apply corrections for polonium-214 plate out excess and fading. Fading is defined as the loss of sensitivity that occurs during long exposures. The ideal timing for radon exposures appears to be between one and three months, although with these corrections applied, exposures of up to a year are able to be measured with confidence.

2. Performance Tests

The performance of the TASL system was assessed by constructing a set of plaques subjected to a wide range of radon exposures. From these measurements the linearity and the calibration factor of the system was to be determined. Repeatability of measurements was assessed by re-measurement of these plaques at later dates.

2.1 Exposure Regime

A total of 92 TASL radon monitors were exposed in ARPANSA's radon chamber to a radon atmosphere for various periods over ten days. A set eight of plaques was removed approximately every 24 hours over this period, with an initial group of four monitors exposed for four hours, and another group of eight exposed for eight hours. The average radon concentration in the chamber over this period was 5600 Bq.m^{-3} (5.6 kBq.m^{-3}), giving exposures in the range of 0.94 kBq.day.m^{-3} to 56 kBq.day.m^{-3} (see Table 2.1 and Figure 2.1). The Atmos ATM272 was used to record the radon concentration for the duration of this exposure. By keeping the chamber at an approximately constant concentration during the total regime, a linearly graduated set of average exposures was obtained.

Table 2.1: 1st Batch Plaque Exposure Details

Date Removed	Average Rn	Exposure duration	Rn Exposure	Measured TASL
	kBq.m^{-3}	day	kBq.day.m^{-3}	kBq.day.m^{-3}
2/06/2015	5.62	0.17	0.94	0.38
2/06/2015	5.53	0.32	1.75	1.00
3/06/2015	5.57	0.99	5.53	3.86
4/06/2015	5.57	2.00	11.12	8.67
5/06/2015	5.53	3.00	16.58	12.68
6/06/2015	5.54	4.03	22.33	17.10
7/06/2015	5.58	5.03	28.05	21.92
8/06/2015	5.57	6.03	33.59	25.91
9/06/2015	5.56	7.02	39.07	30.20
10/06/2015	5.57	8.00	44.50	36.71
11/06/2015	5.59	9.02	50.39	39.78
12/06/2015	5.60	10.04	56.25	47.53

Note: All atmos exposures have an uncertainty of ≈20% which indicates a 95% confidence interval.

The data for the first exposure group as described above is plotted in Figure 2.1. This plot shows the exposure delivered, as measured by the Atmos ATM272 over the ten day exposure period. The data shown has had a linear trendline fitted, with an R^2 value of 1, emphasising the strong linear relationship of the exposure with time.

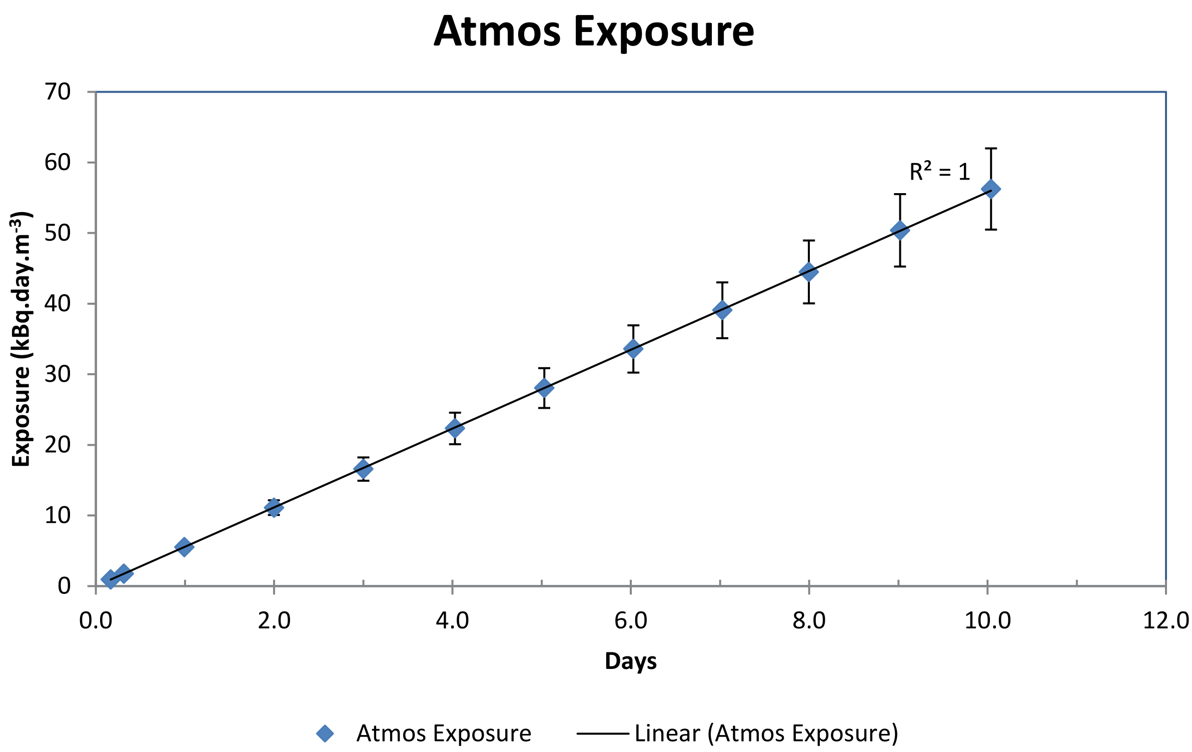

Figure 2.1: Delivered radon exposure vs. time, as measured by Atmos ATM 272 for first exposure group

2.2 TASL Linearity

The 92 plaques from the first exposure group were then processed using the TASL measurement system. Each batch of eight plaques (or four in the first case) was averaged to give a single value for each exposure. These values are plotted in Figure 2.2. A linear trendline was fitted to this data. This data also shows a strong linear fit, the trendline fitted has an R^2 value of 0.9953. The trendline is also able to account for the uncertainty ranges for all the measurements except for the values recorded at six and ten days of exposure.

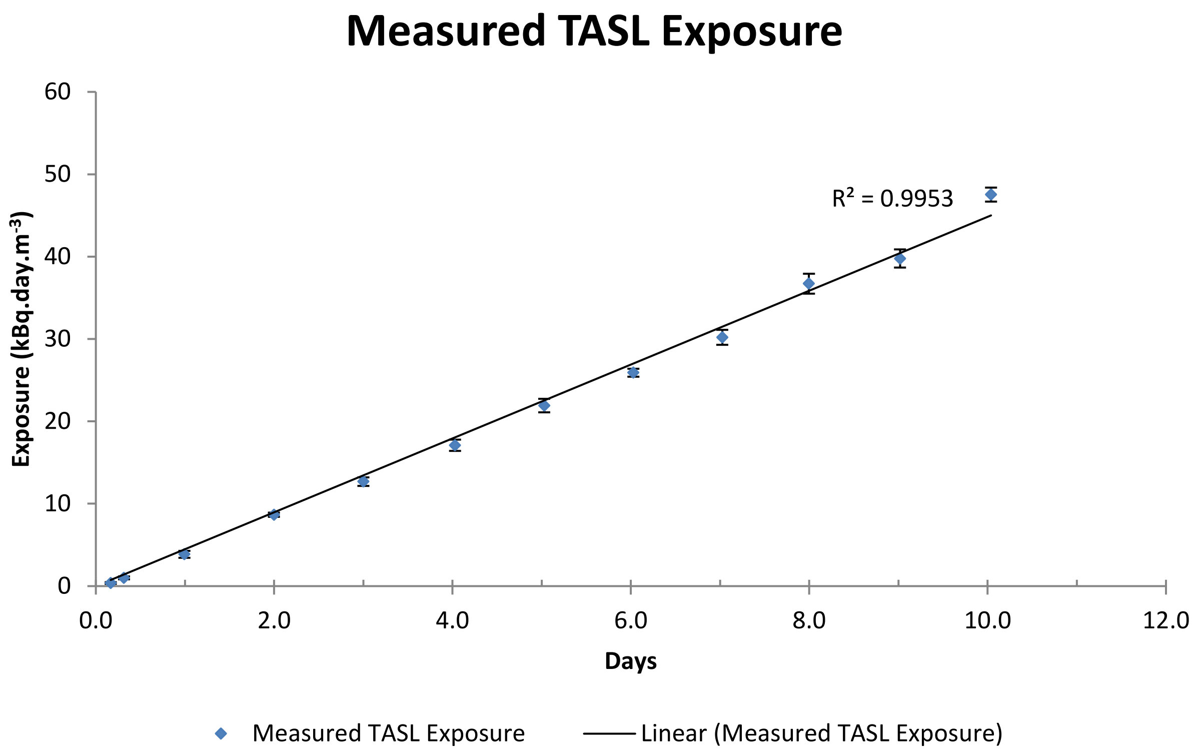

Figure 2.2: Radon exposure vs. time, as measured by the TASL system, for first exposure group

2.3 Calibration Factor

To determine if the default calibration factor supplied with the TASL system applied to ARPANSA's measurements, a suitable comparison method had to be devised.

The calibration factor is described in the TASL*IMAGE* manual (p95) as the conversion factor between tracks.cm^{-2} and Bq.m^{-3}.h. If desired, it can be altered by the user in the TASL*IMAGE* software on the 'radon settings' page. For the system supplied by TASL the factor is given as 0.53. To determine if this setting applied to ARPANSA's lab conditions, the Atmos exposure values were plotted against the measured TASL exposure values (Figure 2.3). This curve showed a strong linear response, with a gradient of 0.804, or measurements that were 80.4% of the expected values. This discrepancy indicates that the pre-determined calibration factor was not appropriate for ARPANSA's laboratory conditions and would need to be adjusted.

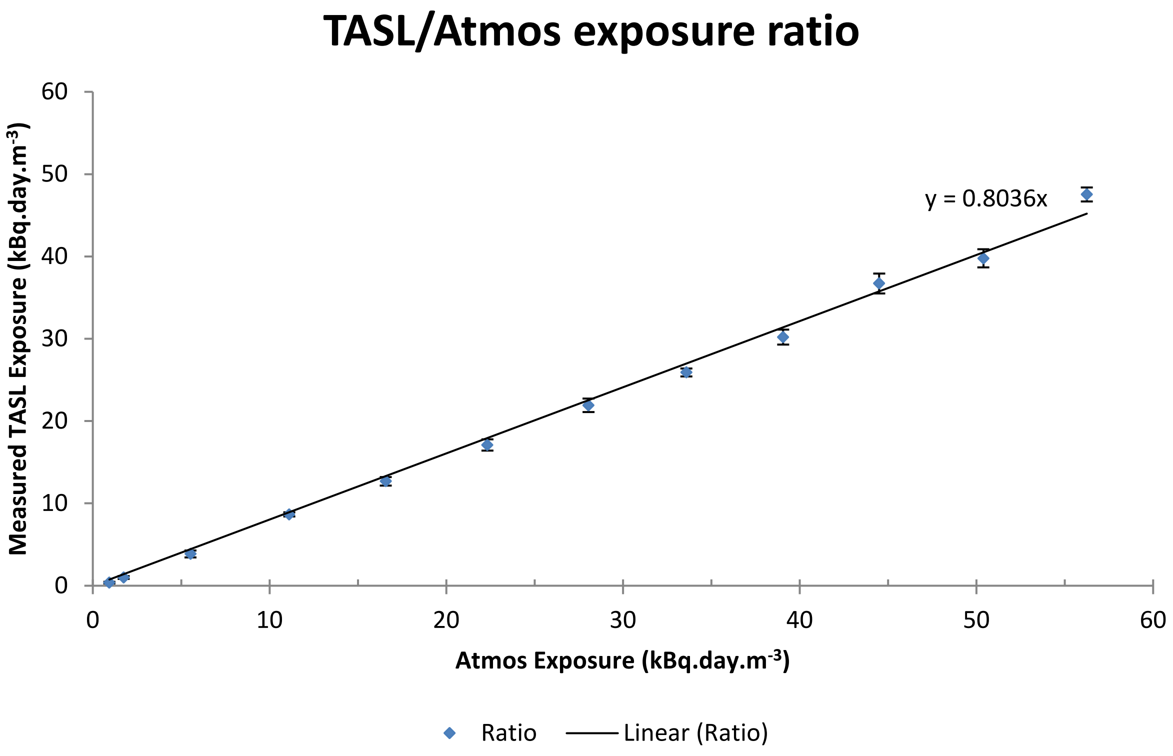

Figure 2.3: Measured TASL radon exposure vs. measured Atmos ATM266 exposure

To determine the new calibration factor, it was decided to use only the most linear portion of the response curve. It was decided to use only values from 10 to 40 kBq.day.m^{-3}, as this appears to be the best operating range of the TASL system. This required the removal of both the lowest three exposure data points, and the highest three exposure data points. This left six data points which were nearly completely linear in response. From this plot, the gradient of the curve was determined to be 0.773.

An alternate view is shown in Figure 2.4, where the ratio of measured to delivered exposure is plotted against delivered exposure. The gradient of the previous plot is shown in this view as a bold line. This plot gives a clearer indication that exposures in the lower range (below 5 kBq.day.m^{-3}) give numbers that are inconsistent with those calculated for the higher exposures. It also clearly shows some small variability in the highest three values, which gave more reason for them to be excluded from the calculation of the altered calibration factor.

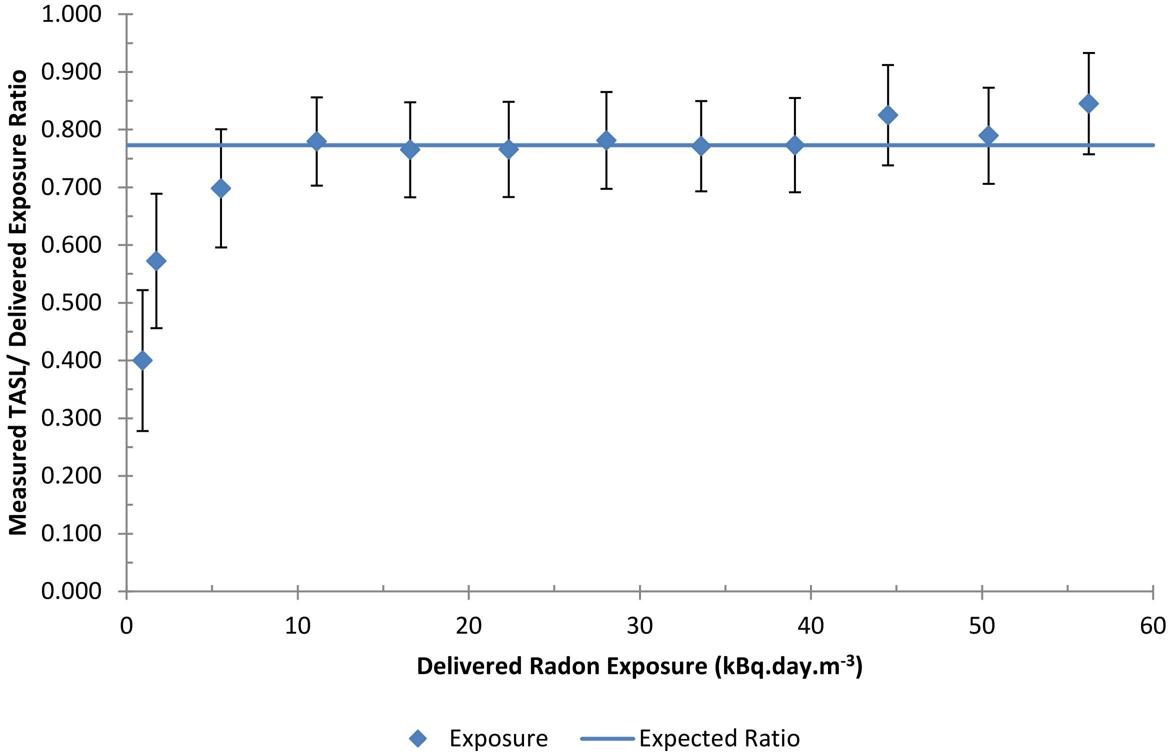

Figure 2.4: Ratio of TASL/Atmos vs. delivered exposure

2.4 Calculation of Modified Calibration Factor

The supplied TASL calibration factor is 0.53. This value is pre-built into the TASL*IMAGE* software but can be altered by the user if so desired. The number supplied by TASL represents the calibration and environmental conditions at the TASL reference laboratory. TASL expects that different laboratories with differing environments may need to use slightly altered calibration factors. Using the method suggested by TASL, the new 'ARPANSA' calibration factor was determined to be 0.530/0.773=0.6856. The new reference number was transferred to the TASL*IMAGE* program and all further exposures and calculations performed in this study will use this new calibration factor.

2.5 Repeatability

The original set of ten exposures was scanned again approximately three weeks after the first scans. This was a test to see how the measurements varied, comparing a 'pristine' set of plaques, measured very soon after the etching process, to a set of plaques that that have been allowed to 'degrade' in an office environment over several weeks. The TASL*IMAGE* software has options to apply corrections for Po-214 plateout excess and Fading. Fading is defined as the loss of sensitivity that occurs during long exposures. Both of these settings were left turned on. The plaques were first cleaned with alcohol wipes to remove surface dust and marks before being scanned. Under the microscope the plaques themselves now appeared quite different, with extra marks and surface defects. Upon scanning however, the results were very similar to the original scans. The TASL system appeared mostly unaffected by the extra artefacts and was able to resolve that these were not alpha tracks. The linear fit to these points gave a gradient of 1.008, a small enough difference to the original numbers to be considered non-relevant. The bold line on Figure 2.5 denotes a one-to-one ratio.

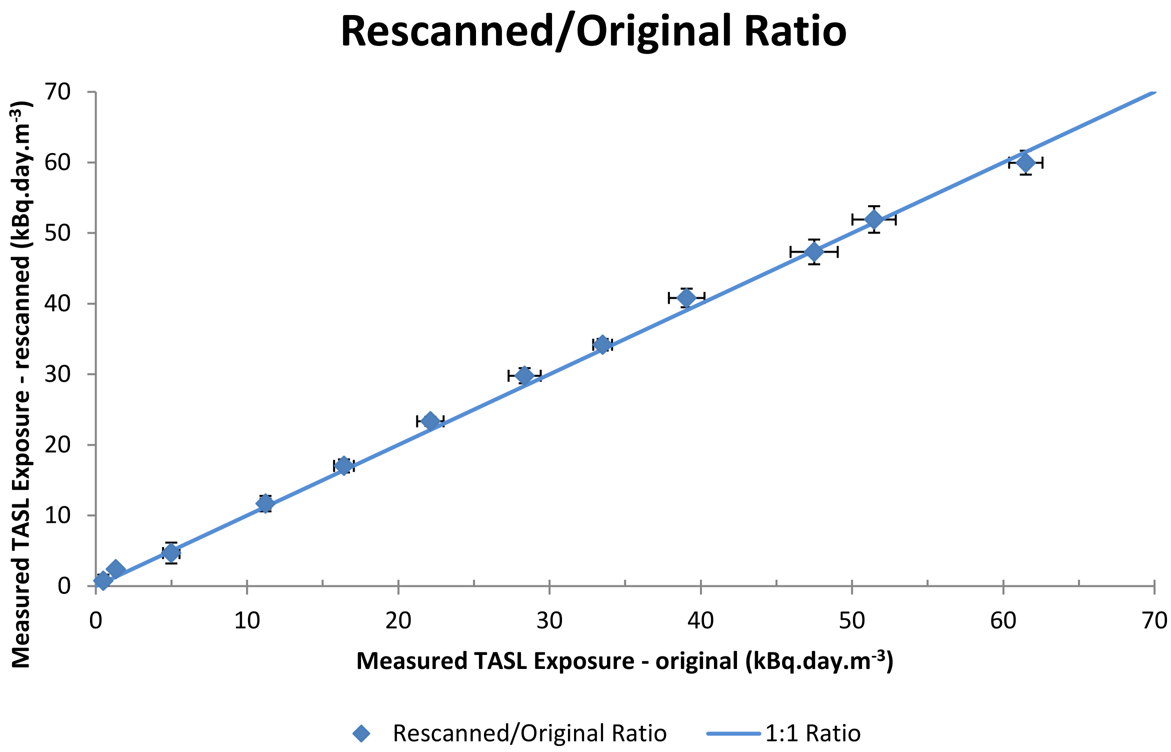

Figure 2.5: The ratio of rescanned to original measured TASL radon exposures

2.6 Second Exposure Results

After recalibration, a second exposure was undertaken aimed to give three more data points evenly spaced amongst the previous exposure values. A total of 18 monitors were exposed, with six exposed to each level. The chamber was set to hold an approximately constant concentration of 5.9 kBq.m^{-3} for six days. Atmos ATM266 was used measure this exposure. The exposure values obtained are shown in table 2.2.

Table 2.2: 2nd Batch Plaque exposure details

Date Removed	Average Rn	Exposure Time	Rn Exposure	Measured TASL
	kBq.m^{-3}	days	kBq.day.m^{-3}	kBq.day.m^{-3}
22/07/2015	5.87	1.17	6.85	7.38
24/07/2015	5.91	3.23	18.86	19.92
27/07/2015	5.93	6.00	35.59	37.79

These results show an extremely close linear fit, although the measured TASL exposures are slightly higher than what would have been expected from the previous set of exposures. These values do however fall within the expected uncertainty limits previously determined.

3. Addition of Modified Calibration Factor

3.1 Recalculation of results

The results of the first and second exposures have then been combined in Figure 3.1, using the new ARPANSA calibration factor to complete the calculations. All values (with the exception of the two lowest value of less than 5 kBq.day.m^{-3}) have uncertainty ranges that are within the bounds of the linear fit.

As with the previous batch, it shows very good consistency above the 5 kBq.day.m^{-3} values. Any measured exposure values below this amount though are quite variable in this case, and should not be considered to be accurate.

The lowest measured values, corresponding to exposures of less than 5 kBq.day.m^{-3} show a wide variation in readings and when averaged do not agree well with the delivered radon exposure. Once above the 5 kBq.day.m^{-3} value, the calculated ratios settle in to a pattern that is very consistent, with uncertainty ranges that cover the required measured: delivered exposure ratio of 1:1. This variation of results at low exposures can be explained by diffusion times, and is addressed in Section 3.2.

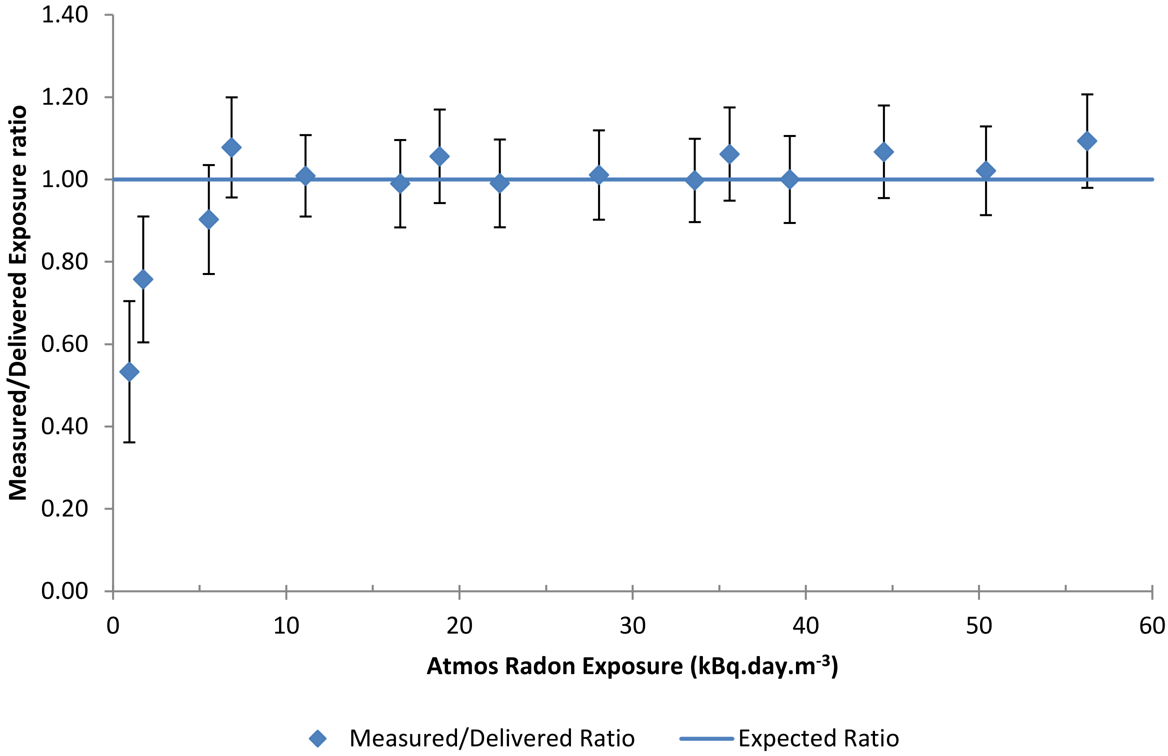

Figure 3.1: Measured/Delivered exposure ratios using recalculated calibration factor

3.2 Diffusion Issues

During the first exposure regime, three points were exposed to less than 6 kBq.day.m^{-3}. It was supposed that the best way to achieve these results was to expose these plaques to a relatively high radon concentration for short amounts of time. In this case, these were 4, 8 and 24 hours respectively. None of the values obtained fit any of the linear relationships expected and determined from the other measurements.

A review of the procedures used revealed that insufficient attention had been paid to the effect of the enclosure on the exposures. The TASL 'Radosure' enclosures enable radon to diffuse into the enclosure but prevent dust from entering. This means that, for some time, the radon concentration within the enclosure is less than that of the atmosphere within the chamber. Therefore, the exposure measured by the plaque is less than expected after the designated exposure time.

Analysis of these data indicates that the diffusion half-time for the enclosure is approximately 90 minutes. This means that the radon concentration within the enclosure reaches equilibrium with the external atmosphere after approximately 12 hours. Once equilibrium has been reached, the relative difference between the expected and measured exposure decreases. After approximately 48 hours, the difference between expected and measured exposure is negligible.

The radon also takes time to diffuse out of the enclosure after the being placed in a lower radon atmosphere. This means that the plaque continues to be exposed to a higher concentration of radon. If the plaque is left within the enclosure for at least 12 hours after exposure to higher levels of radon the additional exposure as the radon diffuses out of the container is equal to the reduced exposure as the radon diffused into the enclosure.

It is critical that the plaque not be removed from the enclosure less than 12 hours after exposure to elevated levels of radon.

4. Characteristic Limits

4.1 Environmental levels and system performance

The global indoor average radon concentration is considered to be 39 $Bq.m^{-3}$ (WHO, 2009). According to ARL's 1990 radon in homes survey, the average Australian indoor concentration is approximately 11 $Bq.m^{-3}$, which is considered to be very low compared to most other countries. These background values are two orders of magnitude lower than the levels to which the monitors are exposed in the radon chamber. Given the nominal sensitivity of the TASL plaques is 0.064 $tracks.cm^{-2}$ per $Bq.d.m^{-3}$, exposure to such levels would produce less than ten tracks per week of exposure. As other process (e.g. cosmic rays, physical damage, etc.) can also generate a small number of tracks, there will be limits to the levels of radon exposure for which the system can provide meaningful results.

To ensure that the TASL system can provide meaningful measurements of radon exposure, three questions need to be asked:

1. Is the system capable of measuring such low levels?
2. Is there a contribution from radon exposure among the tracks measured?
3. Which range of true values may be reasonably attributed to the radon exposure given the measured results?

These three questions are answered by determining following three values, respectively: the decision threshold or critical limit; detection limit; and the limits of the confidence interval. These three values are referred to as characteristic limits, which are widely used in nuclear radiation measurement techniques.

4.2 Currie Method

4.2.1 L_C and L_D Calculations, Minimum Reportable Exposure

The methodology first outlined by Currie (Currie, 1968) will be used to determine the critical limit (L_C) and detection limit (L_D). The critical limit is the number of net counts below which the level of exposure to radon cannot be confidently determined. The detection limit is the smallest exposure to radon that can be confidently determined by the measurement.

Currie defines the critical limit (L_C) and the detection limit (L_D) as follows:

$$L_D = L_C + k_\beta \sigma_D$$
$$L_C = k_\alpha \sigma_0$$

The following values can be used at low concentrations:

$\sigma_0 = \sigma_D = \sigma_B$= 7.1 $kBq.h.m^{-3}$ (or 296 $Bq.day.m^{-3}$) [from TASL*IMAGE* manual, page 104]

$\alpha = \beta$ = 5%, k = 1.645

Currie's equations can now be simplified to:

$L_C = k\sigma_B$
$L_D = k^2 + 2L_C$

This then gives the characteristic limits of the TASL system as:

The critical limit, L_C = 1.645 x 296 = **487** Bq.day.m^{-3}
The detection limit, $L_D = 1.645^2$ + (2 x 487) = **980** Bq.day.m^{-3}

Therefore, the system cannot be used to measure radon exposures below 500 Bq.day.m^{-3} and may not produce a meaningful measurement for exposures less than 1000 Bq.day.m^{-3}.

4.3 Minimum Reportable Level

The TASL system calculates the measurement uncertainty and hence, the confidence interval for the measurement, assuming Gaussian statistics. However, such symmetric distributions are not appropriate for measurements near the detection limit. The international standard, ISO11929, requires that, in such cases, the confidence interval be calculated using Bayesian statistics.

The introduction of an additional calculation of the confidence interval using Bayesian statistics for measurements would introduce significant complication to the reporting of results. A more pragmatic approach is to only report results where Gaussian statistics apply. That is, for measurements below the exposure level above which Gaussian statistics are adequate, are reported only as being less than a certain value, called the Minimum Reportable Value. Such an approach obviates the complications inherent in calculating and reporting confidence intervals based on Bayesian statistics.

It can be shown that Gaussian statistics are adequate for measurements with a relative uncertainty less than 40%. So the Minimum Reportable Value is that exposure level for which the relative uncertainty is 40%.

The relative uncertainty for each of the 110 monitors measured in the program is shown in Figure 4.1. Interpolation of this data indicates that the exposure which would have a relative uncertainty of 40%, shown as the brown line on the plot, is approximately 825 Bq.day.m^{-3}, (or approximately 20 kBq.hr.m^{-3}).

It is recommended that measured exposure levels below 825 Bq.day.m^{-3} be reported as less than the detection limit (e.g. less than 1000 Bq.day.m^{-3}).

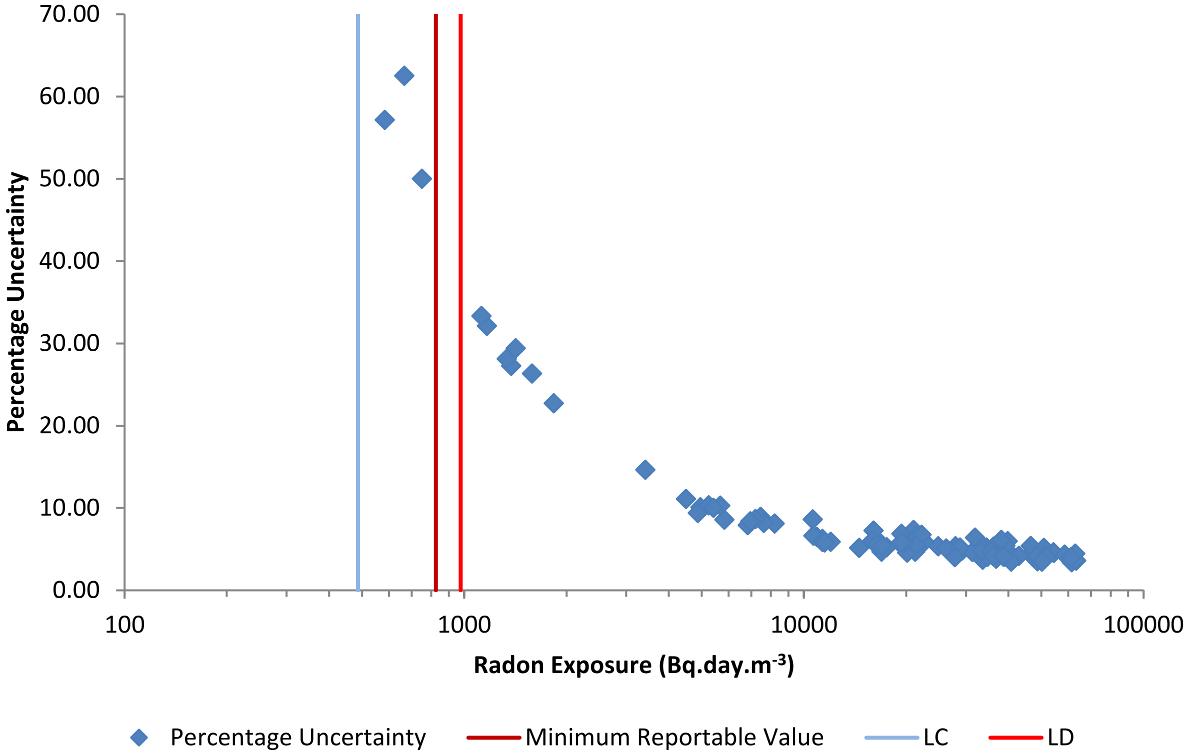

Figure 4.1 Percentage Uncertainty analysis

4.4 Background Exposure, Minimum Placement times

Monitors placed in homes, workplaces or in the environment need to return acceptable measurements of radon concentrations. To ensure these results are believable, there are minimum times these monitors need to be in place to measure results above expected background levels with confidence. Some examples of minimum placement time for monitors can now be determined from the preceding determination of the systems' characteristic limits. At the Australian indoor average level, monitors would need to be placed for 90 days to guarantee an exposure above the detection limit, and 45 days to exceed the critical limit. If the measured values were closer to the global average of 39 Bq.m^{-3}, the detection limit would be exceeded in 26 days, and the critical limit in 13 days.

5. Conclusions

The TASL system has been found to operate well within the specifications advertised, and is very efficient and operator friendly. It requires far less person hours to operate and maintain than the current in-house designed radon dosimetry system currently in use by PRMS, and will provide a very able alternative to this system.

The supplied default calibration ratio of 0.53 was found to be not valid, and returned exposure values that were 80.4% of that expected. This required that the calibration factor be recalculated, and was modified to be 0.69. Successive measurements showed that the new calibration factor was valid for continued use.

An analysis of the characteristic limits of the system found that the critical limit (L_C) of the system is 500 Bq.day.m^{-3}, and the detection limit (L_D, or the minimum reportable exposure) of the system is 1000 Bq.day.m^{-3}. At the Australian indoor average level of 11 Bq.m^{-3}, the characteristic limits for the TASL system require that monitors would need to be exposed for 90 days to guarantee an exposure above the detection limit, and 45 days to exceed the critical limit. This period is within the recommended three month placement currently used by PRMS for radon track-etch monitors.

It is recommended that PRMS replace the current SANTECS method for the analysis of radon track-etch monitors with the TASL system as soon as practicable.

6. References

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