Domestic Radon Monitoring with Electrets – Practical Experiences of Large-Scale Use

A R Denman¹, C J Groves-Kirkby¹, P S Phillips², R G M Crockett³, A Woolridge²

¹Medical Physics Department, Northampton General Hospital, Northampton NN1 5BD, UK
E-Mail: chris.groves-kirkby@ngh.nhs.uk

²University College Northampton, Boughton Green Road, Northampton NN2 7AL, UK

Abstract. The electret quantifies radon concentration by attracting charged daughter-products within a sampling chamber of known volume, filtered to prevent ingress of particulate progeny from the environment, the consequent voltage discharge being proportional to the radon concentration. In addition to responding to radon, electrets respond to ions produced in the chamber by penetrating radiation, dominated by terrestrial γ-radiation, and, arguably, are influenced by humidity. We report here results from a batch of 50 electrets, deployed for periods ranging from one to eight weeks during an extended assessment of domestic radon in Northamptonshire, England. Overall, device responsivity was comparable with results obtained from recently-calibrated continuously-monitoring equipment. Analysis of electret voltage history indicated mean voltage decay during manufacturers’ QA assessment of 0.059 ± 0.026 V·day⁻¹. This increased to -0.114 ± 0.073 V·day⁻¹ during storage to first use, and further increased to 0.204 ± 0.49 V·day⁻¹ during inter-deployment storage. Applying this correction to data from 7-day deployments showed that at a mean radon concentration of 500 Bq·m⁻³, the perturbation was of the order of 3%; at 80 Bq·m⁻³ it was 22%. At low radon levels, the ionising radiation background is significant and the findings are qualitatively compatible with the origin of the voltage drop during storage being attributable to γ-radiation. At the accepted mean UK background level of 0.08 μSv·h⁻¹, a measured radon concentration of 100 Bq·m⁻³ corresponds to an actual level of 75 Bq·m⁻³. At a measured level of 50 Bq·m⁻³, γ-background contributes 25 Bq·m⁻³; at 20 Bq·m⁻³ γ-background dominates the measurement entirely.

1. Introduction

Radon is a colourless, odourless and inert radioactive gas, occurring in a wide range of rocks and soils, together with building materials incorporating or manufactured from these, as a radioactive decay product of uranium ²³⁵U. Radon concentrates in the built environment, the most significant isotope, ²²²Rn, decaying by α-emission (half-life 3.8 days) to ²¹⁸Po and thence to ²¹⁴Po, themselves both α-emitters. These species remain suspended in air adsorbed on to aerosol particles and, on inhalation, can damage the sensitive inner lining of the lung, increasing the risk of lung cancer. Radon progeny are currently believed [1] to provide the majority of the dose to the respiratory system, and a number of case-control studies [2], including studies in domestic properties in South-West England [3], have shown an increased risk of lung cancer in occupants. For UK dwellings, the mean radon concentration is around 20 Bq·m⁻³, compared to 4 Bq·m⁻³ in outside air, but levels up to 10,000 Bq·m⁻³ have been found in domestic housing. Recognizing this variability and the high levels encountered under certain geological/geographic conditions, the UK National Radiological Protection Board (NRPB) recommended [4] the establishment of an Action Level, currently 200 Bq·m⁻³ for domestic properties in the UK, above which occupiers should take steps to reduce radon concentrations. There is therefore a need for simple, sensitive and inexpensive techniques for determining domestic radon levels.

The electret [5], a piece of dielectric exhibiting a quasi-permanent electric charge producing a strong electric field capable of attracting ions, offers one option for this requirement. As long ago as 1955, Marvin [6] suggested that charge reduction on an electret was due to the collection of ions of opposite sign from the surrounding gas, proposing the use of an electret in a closed chamber as a γ-radiation dosimeter. Although not immediately demonstrable, owing to the poor materials then available, the subsequent availability of high permittivity fluoro-polymers led to the emergence of the electret as a reliable electronic component [7], capable of maintaining constant electrostatic fields, even under high temperature and humidity conditions. Teflon electrets were ultimately used [8, 9] to collect and measure ions generated inside an ionization chamber, confirming that the calculated radiation dose agreed well with the actual dose received by the device and demonstrating that the response was essentially independent of temperature and humidity. This approach was extended to radon determination via the α-energy concentration of its decay products, leading [10] to the development of the ‘Electret Passive Environmental ²²²Rn Monitor’ (E-PERM) for short-term radon measurement.
In addition to its intrinsic responsivity to radon gas, the electret appears susceptible to other influences. We report here recent investigations into some of these effects, part of a larger study investigating the applicability of relatively short-term radon determinations to the characterization of mean annual level in residential properties. In this study, radon levels in more than thirty homes situated in close geographical proximity on common geology were monitored for a period of twelve months. During this period, between eight and ten one-week exposures were carried out in each property using electrets, data from which forms the basis of the present study.

2. Experimental Method

A batch of 50 'Short-Term' electrets of nominally identical sensitivity, together with appropriate sampling chambers, was procured. From receipt to first use, and between deployments, electrets were stored, with their protective covers fitted, in a steel cabinet in a cool, thermally stable laboratory environment. Electrets were issued in pairs to homes participating in the study, and were exposed for periods ranging from one week to two months, one in the principal living room and the other in the main bedroom. In most instances, electrets were deployed in parallel with short-term track-etch radon detectors for comparison purposes, a limited number of exposures being also referenced to calibrated Durridge RAD-7 continuous direct-reading equipment. On issue, the voltage on each electret was measured with the dedicated high-impedance voltmeter supplied by the electret manufacturer, using the specified protocol. On receipt following exposure, electret voltage was again measured and the mean radon concentration during the exposure period was calculated using the software tool provided by the manufacturer. At each measurement, system zero was checked and the calibration of the voltmeter confirmed using two permanent reference electrets. No drift was detected in these standards over the period May 2002 to October 2003. To track electret usage, a log was maintained of the date of issue and return of all electrets, together with the electret voltages measured prior to, and on completion of, a field measurement.

3. Results

3.1. Electret Behaviour from Manufacture to First Use

![Graph showing electret voltages before and after QA storage and to time of first use](image)

FIG. 1 Distribution of electret voltages before and after QA storage and to time of first use

FIG. 1 summarizes the distribution of electret voltages reported by the manufacturer before and after the QA assessment, together with values measured in the present study at the time of first use. All distributions are skewed, and there is a general trend for electret voltages to decay with time. For convenience, the behaviour of the electrets will be considered in three phases, the manufacturers’ QA

1 RadElec Inc., 5714-C Industry Lane, Frederick, MD 21704, USA
2 Durridge Company, 7 Railroad Avenue, Bedford, MA 01730, USA
assessment process, in-house storage from receipt to first use, and in-house inter-deployment storage during an extended radon measurement campaign.

3.1.1. Ageing During Manufacturers’ QA Period

The batch of electrets had been stored for a period of approximately 21 weeks and was accompanied by a QA Report tabulating voltages at the commencement and completion of this period. Using this data, the integrated voltage change in storage and the corresponding mean daily voltage change were calculated for each electret, and statistical parameters pertaining to the entire batch were derived. FIG. 2 shows the cumulative fraction of the batch of devices plotted against measured electret voltage for the two states before and after QA assessment, demonstrating the consistent decrease in electret voltage during this procedure. The distribution of voltage changes during the QA assessment process is summarized in FIG. 3.

FIG. 2. Cumulative fraction of electret voltages
closed triangles: before QA assessment crosses: after QA assessment

FIG. 3. Distribution of voltage decay during manufacturers’ assessment

Table I summarizes the outcome of statistical analysis of the QA assessment data. Voltage change in the batch of 50 electrets ranged from -17 V (2.26%) to 0 V, with a mean of -8.3 V (1.11%) and standard deviation of 3.7 V (0.50%). One electret demonstrated zero voltage change during the storage period. Both distributions exhibited significant negative skewness; this decreased from -1.28 to -0.76 during the assessment process, confirming the efficacy of this procedure in electret stabilization.
### Table I. Statistical Analysis of Manufacturers’ QA Data

<table>
<thead>
<tr>
<th></th>
<th>QA Start [V]</th>
<th>QA End [V]</th>
<th>QA Decay [V]</th>
<th>Decay Rate [V·day⁻¹]</th>
<th>QA Decay [%]</th>
<th>Decay Rate [%·day⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>748.9</td>
<td>740.6</td>
<td>-8.3</td>
<td>-0.059</td>
<td>-1.11%</td>
<td>-0.0079%</td>
</tr>
<tr>
<td>Median</td>
<td>750.0</td>
<td>742.5</td>
<td>-8.0</td>
<td>-0.057</td>
<td>-1.05%</td>
<td>-0.0075%</td>
</tr>
<tr>
<td>Mode</td>
<td>749.0</td>
<td>743.0</td>
<td>-7.0</td>
<td>-0.050</td>
<td>-0.935%</td>
<td>-0.0066%</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>9.146</td>
<td>9.996</td>
<td>3.695</td>
<td>0.026</td>
<td>0.495%</td>
<td>0.0035%</td>
</tr>
<tr>
<td>Skewness</td>
<td>-1.28</td>
<td>-0.76</td>
<td>-0.36</td>
<td>-0.36</td>
<td>-0.38</td>
<td>-0.38</td>
</tr>
<tr>
<td>Minimum/Maximum</td>
<td>721/764</td>
<td>715/760</td>
<td>-17/0</td>
<td>-0.12/0.00</td>
<td>-2.26/0.00%</td>
<td>-0.016/0.00%</td>
</tr>
<tr>
<td>95% Confidence Level</td>
<td>2.599</td>
<td>2.841</td>
<td>1.050</td>
<td>0.0074</td>
<td>0.141%</td>
<td>9.97E-6</td>
</tr>
</tbody>
</table>

### 3.1.2. Ageing Following Receipt of Electrets

Not all electrets were introduced into service at the same time. Using the issue logs, dates of first use were established, and electret voltages on placing into first use were determined and analysed.

### Table II. Statistical Analysis of 'Storage to First Use' Data

<table>
<thead>
<tr>
<th>Reading after QA [V]</th>
<th>Reading at first issue [V]</th>
<th>Decay since QA [V]</th>
<th>% Decay since QA [%]</th>
<th>Time to First Use [day]</th>
<th>Decay Rate [V·day⁻¹]</th>
<th>Decay Rate [%·day⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>740.6</td>
<td>729.6</td>
<td>-12.3</td>
<td>-1.66%</td>
<td>130.1</td>
<td>-0.114</td>
</tr>
<tr>
<td>Median</td>
<td>742.5</td>
<td>730.0</td>
<td>-12.5</td>
<td>-1.67%</td>
<td>127.5</td>
<td>-0.092</td>
</tr>
<tr>
<td>Mode</td>
<td>743.0</td>
<td>733.0</td>
<td>-6.0</td>
<td>-1.88%</td>
<td>228.0</td>
<td>-0.066</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>9.996</td>
<td>11.407</td>
<td>6.241</td>
<td>0.85%</td>
<td>72.4</td>
<td>0.073</td>
</tr>
<tr>
<td>Skewness</td>
<td>-0.763</td>
<td>-0.197</td>
<td>-0.747</td>
<td>-0.775</td>
<td>0.0952</td>
<td>-3.312</td>
</tr>
<tr>
<td>Minimum/Maximum</td>
<td>715/760</td>
<td>701/757</td>
<td>-32/-4</td>
<td>-4.378%</td>
<td>47/229</td>
<td>-0.50/-0.02</td>
</tr>
<tr>
<td>95% Confidence Level</td>
<td>2.841</td>
<td>3.176</td>
<td>1.774</td>
<td>0.240%</td>
<td>20.58</td>
<td>0.0206</td>
</tr>
</tbody>
</table>

**FIG. 4. Distribution of voltage decay rates during storage from receipt to first use**

Measured voltages at first use are plotted in FIG. 1 while data for storage time to first use, voltage drop in storage and voltage drop per storage day (to account for the variation in storage times) are
summarized in Table II. The distribution of storage decay rates is shown in FIG. 4. Again, the voltage distribution is negatively skewed, but less so than previously, with skewness value of -3.31. Overall, electret voltages dropped by an average of slightly more than 12 V (1.66%) between receipt and first use, with a standard deviation of 6.25 V (0.85%). Decay rates ranged from a minimum value of 0.03 V·day\(^{-1}\) to a maximum of 0.50 V·day\(^{-1}\), the mean and standard deviation being 0.11 V·day\(^{-1}\) and 0.07 V·day\(^{-1}\) respectively. One device showed an anomalous increase in voltage during storage to first use, and was eliminated from subsequent analysis. Finally, FIG. 5 plots the decay rates during the QA assessment process and the subsequent time-to-first-use storage period on a device-by-device basis, confirming the essentially uncorrelated relationship between these two parameters.

FIG. 5. Correlation between voltage decay rates during QA assessment and during time-to-first-use

3.2. Electret Responsivity in Deployment

As noted, a number of electret-based radon determinations were carried out in parallel with determinations made using other detection systems.

FIG. 6. Correlation of one-week radon measurements using electrets with corresponding averaged hourly-interval sampled real-time measurements (RAD-7)

FIG. 6 plots results from individual one-week electret measurements against the average of the corresponding sets of hourly-interval measurements obtained from the RAD-7 equipment, together with the linear regression relationship. The plot has a slope of unity, confirming that the two
techniques have essentially identical responsivity to radon, with a correlation coefficient of 0.96, indicating a good fit between the two sets of data. However, the plot shows an intercept of around 106 Bq·m$^{-3}$, equivalent to a zero-radon offset of this magnitude. Forcing the regression to pass through the origin, thereby eliminating the offset, results in increased slope of 1.16 and poorer correlation ($R^2 = 0.94$).

### 3.3. Ageing during Repeated Field Deployment

Once detectors were placed in service, their issue was non-systematic and essentially random, since they were returned to a common store between deployments, selected for re-issue in no particular sequence and occasionally transferred between researchers to meet project needs. Using the logged issue and return data, together with voltage measurements at the start and finish of individual deployments, a database of voltage decay behaviour was established. FIG. 7 summarizes the distribution of decay rates during inter-deployment storage, with the principal features of the statistical analysis of the data being shown in Table III.

**FIG. 7. Distribution of decay rates during inter-deployment storage**

Table III. Statistical Analysis of 'Storage between Deployments' Data

<table>
<thead>
<tr>
<th>Storage Time [day]</th>
<th>Decay [V]</th>
<th>Decay/ Rate [V·day$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>31.553</td>
<td>-4.195</td>
</tr>
<tr>
<td>Median</td>
<td>21.00</td>
<td>-2.00</td>
</tr>
<tr>
<td>Mode</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>41.733</td>
<td>8.487</td>
</tr>
<tr>
<td>Skewness</td>
<td>4.986</td>
<td>-5.003</td>
</tr>
<tr>
<td>Minimum : Maximum</td>
<td>1 : 373</td>
<td>-70 : 0</td>
</tr>
<tr>
<td>95% Confidence Level</td>
<td>7.449</td>
<td>1.515</td>
</tr>
</tbody>
</table>

Storage times ranged from 1 to 373 days (mean 31 days), the voltage decay during storage ranging from 0 V to –70 V (mean -4.2 V). The corresponding decay rate ranged from 0.0 V to –3 V·day$^{-1}$ (mean -0.2 V·day$^{-1}$) the distribution being again heavily negatively skewed (skewness -4.30).
4. Discussion

4.1. Accuracy and Precision

As shown in FIG. 6, radon levels returned by electrets during one-week exposures reflect the levels reported by continuously monitoring grab-sample equipment reasonably well. Although unconstrained linear regression indicates the presence of a significant background offset, of the order of 100 Bq·m\(^{-3}\), the observation of numerous individual readings of less than this value suggest that this offset is, in fact, an artefact of mathematical analysis. Forcing the regression to pass through zero suggests that the electrets may be reading approximately 16% high relative to the continuously monitoring equipment used as a reference.

The electret represents the only portable radon detection system where detectors are reusable. As supplied, the devices are charged to a potential of around 750 V, and they are reusable until the potential drops below 200 V. At a radon concentration equal to the Action Level of 200 Bq·m\(^{-3}\), the mid-range voltage drop on an electret of the type used in the present study is of the order of 20 V, and detectors can consequently be used for up to 25 times. Since the voltage measurement system has a resolution of 1 V, and measurement of a radon level requires two such voltage readings, mid-range accuracy for such a determination is ±12.5 Bq·m\(^{-3}\). To a first approximation, accuracy is inversely dependent on exposure time.

4.2. Effects of Voltage Decay

Voltage decay while deployed distorts the indicated radon concentration, the magnitude depending on initial electret voltage, radon level during exposure and exposure time. As shown in Section 3, the mean voltage decay in the absence of radon is of the order of 0.2 V·day\(^{-1}\) giving, for numerical convenience, approximately 1.5 V per week, the normal short-term exposure period. Applying a correction of this magnitude to two sets of recent voltage data obtained from 7-day deployment gives results shown in Table IV. At a mean radon concentration of 500 Bq·m\(^{-3}\), the correction is of the order of 3%, while at the Action Level of 200 Bq·m\(^{-3}\), it has increased to 7.5%. At 80 Bq·m\(^{-3}\), the correction is 22%, a significant perturbation, while for longer exposure periods, the contribution attributable to decay will be greater.

Table IV. Effect of Voltage Drift on Radon Determination Outcome

<table>
<thead>
<tr>
<th>Start Voltage [V]</th>
<th>Finish Voltage [V]</th>
<th>Radon Concentration [Bq·m(^{-3})]</th>
<th>Corrected Finish Voltage [V]</th>
<th>Corrected Radon Concentration [Bq·m(^{-3})]</th>
<th>Decay-Dependent Contribution [Bq·m(^{-3})]</th>
<th>% Decay Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>719</td>
<td>682</td>
<td>510.2</td>
<td>683</td>
<td>495.4</td>
<td>14.8</td>
<td>3.0</td>
</tr>
<tr>
<td>737</td>
<td>721</td>
<td>197.9</td>
<td>722</td>
<td>183.3</td>
<td>14.6</td>
<td>7.4</td>
</tr>
<tr>
<td>714</td>
<td>706</td>
<td>82.0</td>
<td>707</td>
<td>67.3</td>
<td>14.7</td>
<td>21.8</td>
</tr>
</tbody>
</table>

4.3. Non-Radon Decay Influences

4.3.1. Natural Gamma Radiation Background

In addition to responding to ions produced by radon within the sampling chamber, electrets are sensitive to ions produced by penetrating ionising radiation, such as X-rays and γ-radiation, with the latter dominating the non-radon response in the normal domestic environment. Terrestrial γ-radiation originates principally from the radioactive decay of \(^{40}\)K and radio-nuclides in the \(^{238}\)U and \(^{232}\)Th decay series [11]. These are widely distributed in the earth's crust, the dose rate depending on their local concentration. In masonry dwellings, γ-ray exposure arises mainly from the natural radioactivity of the building materials, with relatively little contribution from the exterior. In other, e.g. wooden, buildings, the ground outside is the principal contributor to the γ-ray exposure, although doses may be
reduced owing to the shielding provided by the building. The average dose rate at a height of 1 metre outdoors in the UK was found [12] to be 0.024 µSv·h⁻¹ and the average indoors rate 0.042 µSv·h⁻¹. These indicate an average annual indoor dose in the UK of 350 µSv.

**FIG. 8.** Effect of γ-radiation background on actual radon level as function of 'measured' radon level with background level as parameter.

FIG. 8 shows the effect of making a γ-background to the radon calculation, the effect being conveniently represented by means of a multiplicative correction factor, dependent on both the measured radon level (in units of Bq·m⁻³) and the assumed background (mRad·h⁻¹), and applied to the measured value. At low radon levels, the correction for γ-radiation background is not insignificant and its influence cannot be ignored if reliable quantitative assessment is required. At the assumed mean background of 0.08 µSv·h⁻¹, a measured radon level of 100 Bq·m⁻³ corresponds to an actual level of 75 Bq·m⁻³. At a measured radon level of 50 Bq·m⁻³, the actual radon level comprises just 50% of the measured apparent level, while at a measured level of 20 Bq·m⁻³, γ-background dominates the measurement entirely.

### 4.3.2. Temperature

No formal temperature stability data is provided by the electret manufacturer, but the response of an electret is stated to be essentially independent of ambient temperature. PTFE electrets are polarized under conditions considerably more severe than are experienced in normal use. 'Thick' electrets are prepared by direct application of high voltage at elevated (~150 C) temperature [13], while 'thin' electrets are generated by vacuum triode corona discharge at room temperature, typical conditions being 7kV for 300 s [14], and spontaneous depolarization under the described experimental conditions therefore appears unlikely. This is supported by recent reports of excellent negative-charge stability in PTFE foil at temperatures up to 150 C, leading to the supposition that the current generation of electrets can be regarded as stable over the common environmental range [15].

### 4.3.3. Humidity

The initial report [10] of the independence of electret response to radon ambient relative humidity was supported by a plot of the surface potential of a 2.3 mm thick Teflon electret as function of integrated ²²²Rn dose under conditions of 55% and 95% RH, confirming linear response (correlation coefficient 0.999) over the 100 to 900 volts electret operating range. A comparative study of a number of radon detector types, performed in 1991-92 but not reported until 1999 [16], reported that electrets returned non-reproducible or erroneous results under conditions of high temperature and high humidity. Examination of failed electrets [17] showed that microbial contamination by *vegetative Mycelium hypha*, manifested as the growth of fibres extending from the edge of the electret holder to the electret
surface, could cause detectable charge leakage. Although these observations were communicated to the organizers of the 1992 test, they were not included in the published outcome, although comments were made regarding fungal contamination on the other two classes of sensor included in the test. More recently, electret dosimeters exposed to constant $^{222}\text{Rn}$ levels are reported [18] to exhibit a linear relationship between radon concentration and relative humidity, with measurements at 90% RH showing approximately double the concentrations at 40% RH. The slope of the relationship was ~0.5 Bq.m$^{-3}$.%RH$^{-1}$ over the range 30 - 85% RH.

It is apparent that the role of ambient humidity in the measurement of radon concentration by charged electrets is still unclear and that the mechanisms involved remain to be determined. While elevated humidity might be expected to exacerbate charge tracking around the edges of the electret, the design [19] effectively seals the edges of the dielectric element from the environment. The electret element is enclosed in a metal can contacting both the rear surface of the electret and an annular ring on the front surface (defining the active area), further dismissing any arguments concerning the influence of edge-leakage between the two major surfaces.

4.3.4. Manual Handling

Nearly 1,000 device issues were made during the course of the project, and in most cases, electrets were prepared for exposure and sealed on completion of exposure by relatively unskilled users. Despite this, relatively few failures were encountered. One device developed a negative voltage, attributed to inadvertent touching with a finger, shortly after being placed in service, and another exhibited a large anomalous voltage drop, not reflected in a second device operated in parallel. Overall, however, failure rate was very low, confirming the intrinsic reliability of this type of device. Because of these occasional faulty readings, a high result should always be repeated prior to advising a householder that there is an elevated radon level in the house.

5. Conclusions

A batch of fifty electret dosimeters, procured simultaneously from a common manufacturer, has been operated for more than a year through nearly 1,000 individual deployments. Device responsivity was comparable with results obtained from recently-calibrated continuously-monitoring equipment. Analysis of electret voltage history indicated mean voltage decay during manufacturers’ QA assessment of 0.059 ± 0.026 V·day$^{-1}$. This increased to -0.114 ± 0.073 V·day$^{-1}$ during storage to first use, and further increased to 0.204±0.49 V·day$^{-1}$ during inter-deployment storage. Applying this correction to data from 7-day deployments showed that at a mean radon concentration of 500 Bq.m$^{-3}$, the correction was of the order of 3%; at 80 Bq.m$^{-3}$ it was 22%, a significant perturbation. The findings are compatible with the origin of the voltage drop during storage being attributable to $\gamma$-radiation. At the mean UK background level of background of 0.08 µSv·h$^{-1}$, a measured radon level of 100 Bq.m$^{-3}$ corresponds to an actual level of 75 Bq.m$^{-3}$. At a measured level of 50 Bq.m$^{-3}$, $\gamma$-background contributes 25 Bq.m$^{-3}$; at 20 Bq.m$^{-3}$, $\gamma$-background dominates the measurement entirely.

6. Acknowledgements

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7. References


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