CHAPTER 4

SOURCES OF BIAS IN IN-SITU MONITORING SYSTEMS

Chapter 4 Highlights

Sampling System Problems — In-Situ Gas CEMS and Opacity Monitors

Problem		Corrective Actions	Page Refs
Name	**Description**		
Point Monitors			
Blinding	Precipitate on the filter seals the probe tip from the flue gas.	Clean or replace filter.	4-4
Faulty Audit Gas Injection	Improper flow rate of calibration gases results in biased concentrations in probe cavity.	Adjust flow, carefully following calibration procedures.	4-4
Temperature Distortions	If temperature sensors are not working properly, errors can result in emission values.	Calculate correction. Adjust or replace sensor.	4-5
Path Monitors			
Internal Calibration Cell Defects	Errors are introduced when internal calibration cell leaks or its gas decomposes.	Check daily cal chart for jumps or drift. Replace cell.	4-5–4-7
Gas Cell Temperature Problem	Bias results if the temperature of the gas cell and flue gas differ greatly.	Correct mathematically. Install cell in "zero pipe" or outside stack in heated area.	4-9
Flow-Through Calibration Gas Availability	Protocol 1 gases often not available at required concentrations.	Use only if certified gases are available. Redesign system - use longer cell.	4-7–4-10
Transmissometers (Opacity Monitors)			
Improper System Design	Poor design produces both bias and inconsistencies with visual observations.	Redesign.	4-10
Dirty Windows	Build-up on windows produces bias.	Auto-correct.	4-10
Interferences	Water droplets and high NO_2 distort measurements.	Calculate correction.	4-10

CHAPTER 4

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4.1 INTRODUCTION

In-situ systems are used to monitor pollutant gases, O_2, CO_2, flue gas velocity, and flue gas opacity. These instruments monitor the flue gas "in-situ," in the stack without extraction. In-situ gas monitors were developed in response to maintenance difficulties and availability problems associated with source-level extractive systems. However, in-situ monitoring does not relieve the user of monitoring problems. Different types of measurement errors and biases can occur, such as those associated with flue gas stratification (discussed in Chapter 2).

In-situ monitors can be classified into two basic categories, point and path. Point monitors measure at a single point in the stack (strictly speaking, a short path generally 5–10 cm in length). Path monitors measure from one side of the stack or duct to the other. There are several options within these two categories, as listed in Table 4–1.

Table 4–1. Types of In-Situ CEM Systems

Pollutant/Diluent Gases	Velocity (Volumetric Flow)	Opacity
Point	Point Single point Multiple probe Averaging probe Probe arrays	
Path Single Pass Double Pass	Path Two pass Multi-pass	Path Single pass Double pass

Path monitors can be of either single-pass or double-pass design. Single-pass gas concentration monitors typically project a beam of light across the stack to a detector. Single-pass systems, once popular for gas monitoring in the 1970s, are no longer widely marketed due to difficulties associated with their calibration. The double-pass systems return the light beam from the opposite side of the stack back to a detector in the transceiver assembly, which also houses the projection lamp. Double-pass systems can be calibrated by a number of techniques and a new generation of these systems is being applied to a variety of sources.

A variety of point and path methods have been developed for monitoring flue gas velocity, the different approaches representing attempts to overcome problems associated with velocity stratification. In cases of uniform, fully developed flow, the simplest approach is to measure at one or two points in the stack. If the flow pattern changes frequently, multiple probes or averaging probes can be applied. In the worst cases, an array of sensors can be installed to monitor at Reference Method 1 traverse points. The ultrasonic path monitors use two transducers to pass sound pulses with the flow and against the flow. In multi-pass systems, more than two transducers can be used to grid the cross-section further.

One of the major problems associated with gas path monitoring systems and all velocity monitoring systems is that methods for **independently** checking system calibration are limited. In contrast to extractive and point in-situ gas monitoring systems, where independently certified gas can be easily routed into the system, path monitors for measuring gases must add special flow-through calibration cells. Velocity monitors all use internal calibration methods that are not referenced to independent, certified standards. These instruments may use a "reference" sound pulse, a "reference" voltage, or a "reference" pressure, but these "references" are generated by the instrument and in most cases are only electrical checks and do not check the sensing element itself. Ultimately, the only completely independent method for detecting bias in these systems is performing a RATA.

4.2 BIAS IN IN-SITU POLLUTANT AND DILUENT GAS MONITORS

4.2.1 Point Monitors

Point in-situ gas monitors are subject to a number of specific problems and biases. These problems tend to be unique to the measurement method, but several general observations can be made. First, consider a typical in-situ point monitor as shown in Figure 4–1.

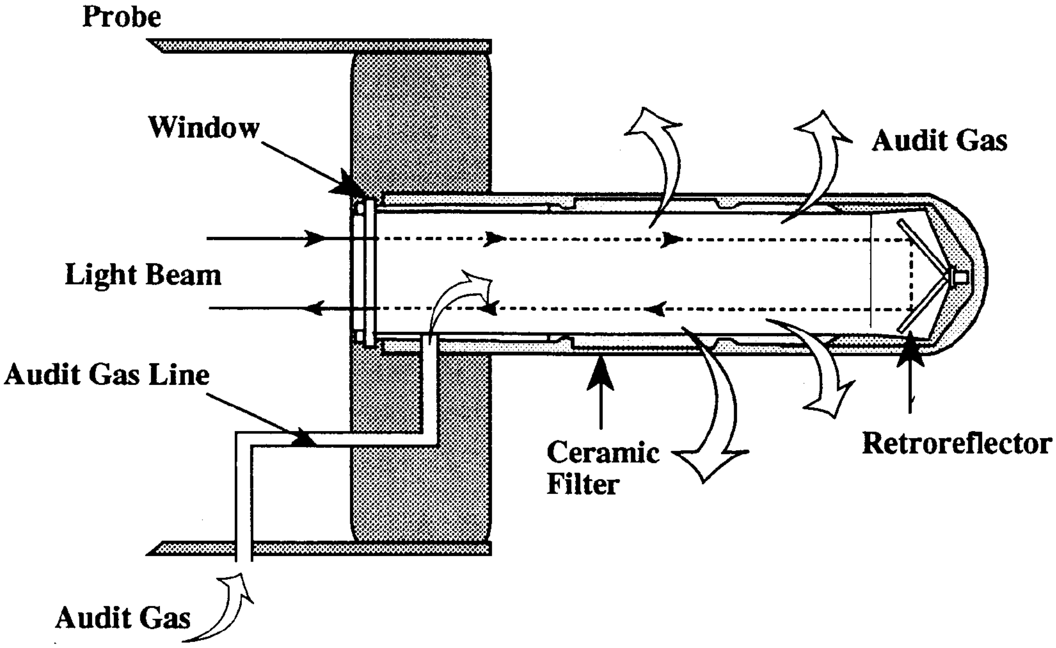

Figure 4–1. A Typical In-Situ Point Monitor for Measuring Gas Concentration

A typical system consists of a measurement cavity that incorporates a gas sensor or a cavity in which light absorption can take place. A ceramic filter prevents particulate matter from entering the cavity, and a deflection bar limits impaction of particulate matter directly onto the filter to minimize plugging of the filter pores. A gas injection port allows calibration gas to enter the cavity, and, when at a pressure greater than the absolute stack pressure, flushes the flue gas out of the cavity. At an "appropriate" pressure, the calibration of the system can be checked.

There are several generic problems that can arise in these systems:

Stratification. Since the monitor is sampling at a point, gas stratification can result in a misrepresentation of the total flue gas concentration, as discussed in Chapter 2. Although measurements can be conducted at a "representative" point, that point must be consistently representative through changing plant operating conditions. It is sometimes difficult to obtain a probe of a length that will position the sensor at a representative measurement point. In-situ probes come in standard lengths and a probe might have to be customized for the application. Structural factors limit probe length; if the probe is too long, it may sag or oscillate in the moving gas stream, either of which can lead to catastrophic failure.

Blinding. In dirty gas streams, particulate matter can impact on the ceramic filter and plug the filter pores. For systems installed after wet scrubbers, a scrubber upset may cause scrubber liquor to become entrained in the flue gas. The dissolved solids may then precipitate on the filter and in the filter pores, essentially sealing the probe tip from the flue gas. This problem will generally be recognized when a greatly increased period of time is necessary for the monitor to read the flue gas concentrations after a zero or upscale gas injection. The response time of the instrument is, of course, greatly increased.

Audit Gas Injection. Although flue gas can be flushed out of the measurement cavity, if the calibration gas flow rate is too high, the gas in the cavity will be pressurized. This pressurization will lead to a higher calibration gas concentration reading than true and a bias in the system if it is recalibrated based on that value. Conversely, if the flow rate of the zero gas or calibration gas is too low, all of the flue gas will not be flushed from the probe cavity and a bias will again result. If the audit gas flows in too fast, it also may not come up to the stack temperature by the time it is being sensed by the monitoring system, causing another error. These biases can be minimized by following calibration procedures carefully. Reynolds (1989) gives detailed methods for conducting such calibrations.

Temperature Measurement. In-situ measurements are made at stack temperature. Because of this, a thermocouple or resistance thermometer is normally incorporated in the system so that the gas density variations can be accounted for in the concentration measurements. In some cases, temperature measurements are necessary to correct for temperature-dependent spectral absorption characteristics. The nature of these corrections is dependent on the measurement technique, where errors in these corrections may have a substantial impact on measurement bias.

The temperature sensor should be checked periodically; however, because the temperature corrections are performed using absolute temperatures, small inaccuracies may not contribute significantly to measurement error. For large variations in temperature, particularly between unit shut-down and operation, significant measurement problems may occur if the system is calibrated initially at lower temperatures. For optimum performance, in-situ monitor calibration checks and calibration adjustments should always be conducted at operating temperatures.

4.2.2 Line Averaged Measurements

Path in-situ gas monitors perform a line average measurement. Although this type of measurement may give a better correspondence to the three-point average of the reference method, there is no guarantee that the line average concentration is representative of the cross-section area average. In circular stacks, if a line average is used to represent an area-averaged concentration, the gas concentrations near the center of the stack will weight the average unrepresentatively—they will bias the result.

When the gas concentration or velocity profile is stratified, bias can be corrected, as discussed in Chapter 2, by determining the profiles and establishing proper weighting factors or by developing an algorithm based upon the measurement line and the profile. Again, mathematical corrections of this kind are dependent upon the stability of the profiles under different plant operating conditions.

It should be noted that a frequent claim for path in-situ systems is that because more points are measured, the data are more representative; an averaged value is obtained and therefore the results are more accurate. This may or may not be true—the only way to test the validity of such claims is to perform a stratification study and evaluate the profiles with respect to the proposed measurement path.

4.2.3 Internal Calibration Techniques

A new generation of double-pass in-situ gas monitors avoids calibration problems associated with single-pass units. In these new systems, a measuring light beam is returned from the opposite side of the stack using a retroreflector, so that the transceiver assembly will house the "active" optical and electronic components such as the lamp, detector, and spectral filters. A system calibration is normally performed by moving a mirror, inside the transceiver, into the path of the light beam so that the light does not enter the stack but reflects directly back to the detector. This procedure should give a "pseudo-zero" value that can check the performance of the transceiver assembly. Although the pseudo-zero value may not correspond exactly to a "true" stack zero measurement, it can be correlated with it. This method has been accepted for many years in transmissometer systems and is equally valid in gas monitoring path systems.

To obtain an upscale calibration value, a gas cell containing a known amount of the measured gas or an optical filter can be moved into the light path when the zero mirror is in place. Absorption of light energy by the pollutant molecules in the calibration cell causes the light intensity to decrease at the detector and gives a corresponding upscale calibration reading (Figure 4–2).

As discussed in the next section, such internal gas calibration cells do not meet Part 75 criteria for daily calibration checks because the cell gases are not Protocol 1 gases and usually have concentrations higher than those specified by Part 75. Nevertheless, they are essential for keeping these systems "in tune."

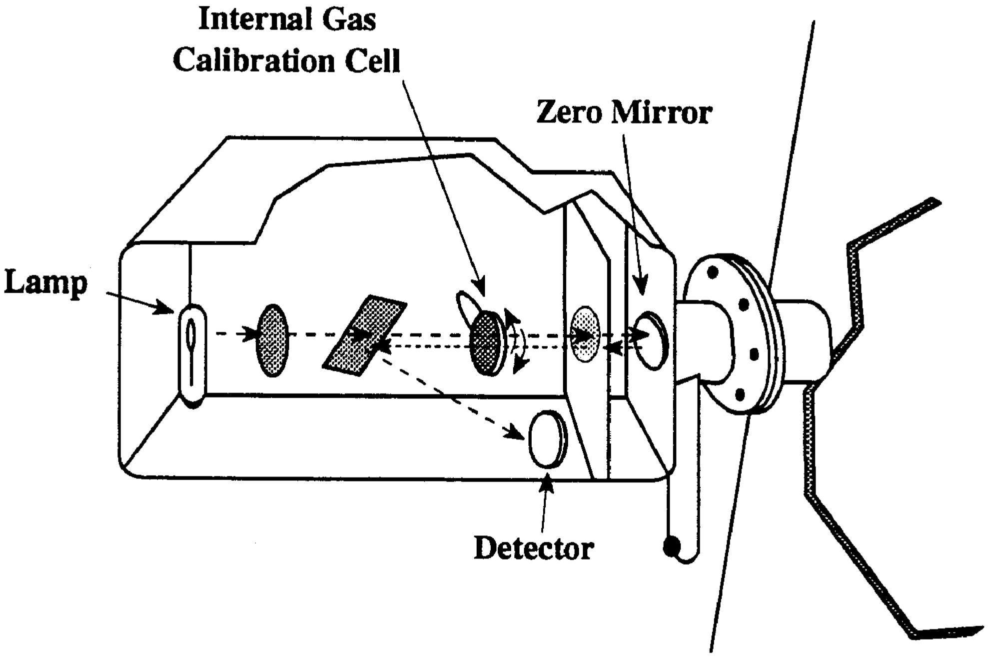

Figure 4–2. An Internal Gas Calibration Cell in a Path In-Situ Monitor

Biases can occur in this calibration method if the internal calibration cell leaks or if the gas inside the cell decomposes. In such situations, calibration adjustment would then be made based on a faulty internal standard and the data would not be representative. These problems can be identified from a calibration QC chart on which the daily calibration responses are tracked. A noticeable jump in drift values or continuously increasing drift values may indicate changes in the calibration cell gas concentration. More commonly, however, RATAs give the first indication that a problem has developed. A failed RATA tends to bring immediate attention to the problem.

Sealed gas cells are made by the instrument manufacturer, but there are currently no third parties that independently certify gas cell concentrations. Although the cells can be checked relatively easily in a spectroscopic laboratory, no programs or protocols have been established to provide certified cell concentration values. This dependence on the instrument manufacturer's values prevents the gas cell calibration technique from being a truly independent audit method.

One single-pass unit performs internal calibration checks using reference spectra. This technique is effective, but even further removed from being an independent check than are the sealed gas cells used in other systems. It is a numerical check based on data stored in the computer memory and does not rely directly on the installed system to perform a reference measurement.

4.2.4 Flow-Through Gas Cell Calibration Techniques

Despite the relative convenience of using internal calibration techniques in path monitoring systems, these methods do not meet performance specification and audit requirements of the U.S. Federal government. In fact, it is specifically stated in Part 75 (U.S. EPA, 1993):

> "Design and equip each pollutant concentration and CO_2 or O_2 monitor with a calibration gas injection port that allows a check of the entire measurement system when calibration gases are introduced.....For in-situ type monitors, the calibration must check against the injected gas for the performance of all active electronic and optical components (e.g., transmitter, receiver, analyzer)."

Because of this requirement, flow-through gas cells are now being incorporated into path monitoring systems (Figure 4–3).

The use of flow-through gas cells does provide a valid means of independently checking the monitor performance. However, in current practice, the cells constitute merely an "add-on," applied to satisfy the EPA requirements for cylinder gas audits and calibration error tests. In most instruments of this type, the actual calibration checks are still conducted using the internal filters, sealed gas cells, or reference spectra. The flow-through gas cell is an extra check that is not integral to the instrument operation. This is in contrast to the use of calibration gases in extractive system analyzers (Chapter 6), where the instruments **are** referenced to the zero and calibration gases.

Several additional problems surface in the use of flow-through gas cells in path in-situ systems. If the gas cell is relatively short with respect to the stack diameter (the measurement path), a high concentration calibration gas must be used. For a cell length on the order of a few centimeters, the gas flowed through the cell may have to be at percent level concentrations to elicit a response.

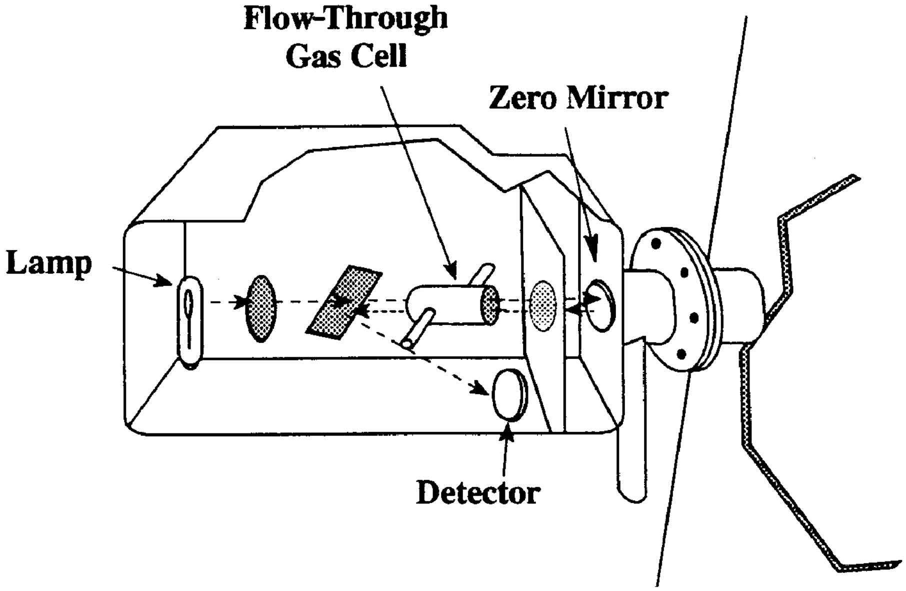

Figure 4–3. Flow-Through Gas Cell for Path In-Situ Monitor Certified Gas Calibrations

This necessity can be seen by considering the "optical depth" of both the stack and the flow-through cell. For path-integrated concentration measurements, the optical depth is defined as the product of the gas concentration, c_s, and the measurement path, d_m, or:

$$\text{Optical Depth} = c_s \times d_m$$

where the measurement path is the distance that the light beam traverses through the flue gas.

Consider, then, if a double-pass path monitor is installed on a 5-m diameter stack having an SO_2 concentration of 1000 ppm, the optical depth will be 2 x 1000 x 5 = 10,000 ppm-m. If the transceiver of the monitor is installed with a 5-cm long flow-through gas cell and the zero mirror is put into place, an SO_2 concentration of 10% would be required in the cell to obtain a cell optical depth of 10,000 ppm-m:

$$\text{Stack Optical Depth} = \text{Cell Optical Depth}$$

$$10{,}000\ \text{ppm-m} = c_s \times 2 \times 0.05\ \text{m}$$

$$c_s = \frac{10{,}000}{0.1} = 100{,}000\ \text{ppm} = 10\%$$

Conceptually, to reduce the light attenuation by molecular absorption, the number of molecules seen across the stack must be "squeezed" into the cell to obtain a similar instrument response. Required audit and calibration gases would therefore also be at percent level concentrations.

In the CEM quality assurance requirements of Appendix F to 40 CFR 60 and the calibration error requirements of Appendices A and B to 40 CFR 75, cylinder gases traceable to the U.S. National Institute of Standards and Technology (NIST) are required. Specifically "Protocol 1" gases must be used. A problem exists in that Protocol 1 gases at these percent level concentrations are not available. Using other gases not referenced to a national standard is not allowed under the regulations, because it would cause uncertainty in the audit measurement. However, new protocols have been prepared that address this issue (Mitchell, 1993). Note also that since the instruments perform their own internal calibration checks, an incorrect audit gas may not necessarily introduce bias into the system. The instrument could still read correctly, but then might not meet the calibration or audit specifications. Bias would, however, be introduced if adjustments were made with respect to the incorrect gas concentration.

Another issue associated with flow-through cells is that of temperature. The spectral absorption properties of molecules are dependent upon temperature. Therefore, if the flow-through gas cell temperature is appreciably different from the flue gas temperature, a bias in the measurement will be introduced. This bias can be corrected mathematically if the flue gas temperature is measured, and normally constitutes an element of the monitor's programming, where applicable.

Calibration gas problems in path monitoring systems can also be resolved by installing a "zero-pipe" across the stack (Figure 4–4).

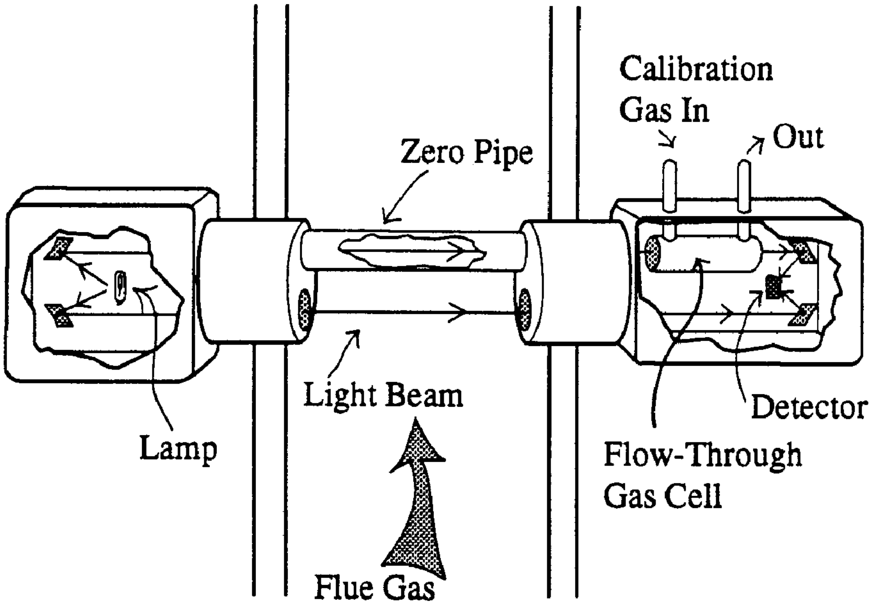

Figure 4–4. Zero-Pipe Configuration

In this technique, the pipe provides an optical path that can be made free of stack gas. The pipe is flushed with clean air when it is desired to check the zero and calibration of the system. A flow-through calibration cell can be incorporated in the pipe so that the calibration gas will be at stack temperature, or the cell can be installed outside of the stack and heated.

The design allows the length of the cell to be adjusted, to meet calibration gas concentration limitations. Calibration gas is normally not flushed through the zero-pipe itself because of the excessive gas volumes required. There are limitations in using this technique because the installation may be difficult, long pipes may sag, and corrosion may be a problem in wet, acidic environments.

4.3 BIAS IN TRANSMISSOMETERS

Transmissometers (opacity monitors) measure the flue gas parameter, opacity. It is intended in U.S. regulations that the flue gas opacity be related to opacity as observed by visual emissions (VE) observers, through the application of Reference Method 9. This requirement has placed design specifications as well as performance specifications on opacity monitoring instruments. Poorly designed opacity monitors, faulty installations, improper calibration, and faulty maintenance can result in inaccurate opacity monitoring data that do not correspond to VE observations.

A thorough discussion of bias in transmissometers is well documented elsewhere (Jahnke, 1984; Plaisance and Peeler, 1988). The reader should refer to these documents to enhance QA plans for opacity monitoring programs.

Briefly, bias can enter opacity measurements by way of the following:

- Improper System Design
    — Incorrect spectral response
    — Angle of projection greater than 3°
    — Angle of view greater than 3°
    — Nonuniform beam cross-sectional intensity

- Dirty Windows (uncorrected)

- Improper Installation - Particulate stratification

- Interference by Water Droplets
  Possible Interference by High NO_2 Concentrations (Lindau, 1991)

Most of these problems are adequately addressed in modern transmissometer systems. In fact, transmissometers are the most developed of the CEM system instrumentation, commonly having availabilities greater than 98%.

4.4 SUMMARY

Errors of measurement specific to the different types of in-situ monitoring systems are summarized in the table on page 4–1. Systematic errors that can be corrected by calculations or adjustments are identified. Generic sources of bias such as location and stratification and stack area calculations have not been included in the table, but have been discussed in detail in the text.

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4.6 ADDITIONAL READING

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