Limits for Qualitative Detection and Quantitative Determination

A visiting professor at NIST once pointed out that our measurement professionals are given a difficult task by some of our customers. In a (macroscopically) continuum universe, we are asked to perform measurements with tools and techniques of finite precision and in the end to produce digital answers, preferably binary: yes or no, safe or unsafe, above or below the regulatory limit. A common triple question arises in the measurement of environmental radioactivity, atmospheric ozone, gold in rock, or the efficacy of a flu treatment: Is the signal there? What is the chance that we will detect it? How big is it?

Until Lloyd Currie's paper *Limits for Qualitative Detection and Quantitative Determination: Application to Radiochemistry* [1] was published, there was enough inconsistency in the definition of "detection limit" to conceal a great deal of disagreement. In just over seven pages, this tightly written communication established a high level of uniformity in answering these questions. The paper contains fundamental information that has made it influential far beyond its size, and it is rich enough to be discussed actively in e-mail newsgroups over 30 years later. This is surely one of the most often cited publications in analytical chemistry. The *Science Citation Index* lists 1280 published references to this paper—so far.

Currie asks and answers a disarmingly simple question: What do we mean by the detection limit of a measurement process? He found that the literature "revealed a plethora of mathematical expressions and widely-ranging terminology." The same terms have been used to denote both the amount that can be detected and the amount that can be measured, which are very different quantities. Statistical justification for some common recipes has been absent or incorrect.

To show graphically how serious the problem was (and is), he used literature definitions to compare detection limits, defined by eight common recipes, or rules of thumb, for a simple measurement: counting a radioactive source for 10 minutes with a detector that is 10 % efficient and has a background of 20 counts per minute. Currie then arranged the values of the detection limit in serial order, and found that the range of these definitions spans a factor of nearly 1000. His Figure 1, reproduced here, clearly showed the need for a consistent, statistically and physically defensible, definition of this common term.
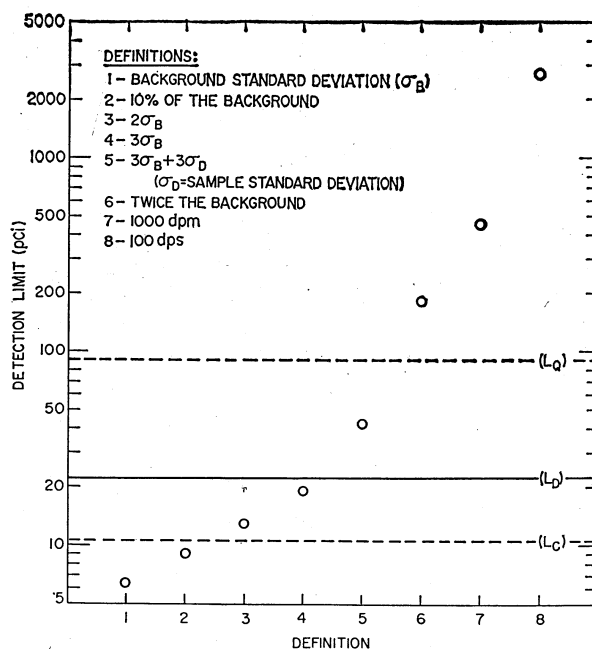

Fig.1. "Ordered" detection limits—literature definitions. The detection limit for a specific radioactivity measurement process is plotted in increasing order, according to commonly-used alternative definitions. L_C, L_D, and L_Q are the critical level, detection level, and determination limit as derived in the text.

Currie then defined measures of detectability, firmly based on the statistical theory of hypothesis testing. He began by defining the concepts of qualitative and quantitative analysis limits. Three limiting levels were defined:

- The critical level L_C, the signal level above which an observed instrument response may be reliably recognized as "detected."

- The detection limit L_D, the true net signal level that may be expected a priori to lead to detection.

- The determination limit L_Q, the signal level above which a quantitative measurement can be performed with a stated relative uncertainty.

Numerical values of these levels depend on four criteria, most importantly the standard deviation σ_0 of the blank, or background. By choosing a probability α (error of the first kind) for falsely deciding that the

signal is present when in fact it is not, the critical level L_C is calculable. Choosing a probability β (error of the second kind) for deciding that the signal is absent when it is in fact present permits the detection limit L_D to be calculated. Finally, specifying the maximum tolerable statistical error in a quantitative measurement allows the determination limit L_Q to be computed. "The levels L_C, L_D, and L_Q are determined entirely by the error-structure of the measurement process, the risks, α and β, and the maximum acceptable relative standard deviation for quantitative analysis. L_C is used to test an experimental result, whereas L_D and L_Q refer to the capabilities of [the] measurement process itself."

Currie then gives recipes for calculating these quantities, for the conventional assumptions of a normal distribution; 5 % errors of the first and second kind; the uncertainty of the blank independent of the signal level; and quantitation at 10 % or better. His Table I has been reprinted in many textbooks and operating manuals:

Table I: "Working" Expressions for L_C, L_D, and L_Q*

	L_C	L_D	L_Q
Paired observations	2.33 σ_B	4.65 σ_B	14.1 σ_B
"Well-known" blank	1.64 σ_B	3.29 σ_B	10 σ_B

*Assumptions: α = β = 0.05; $k_Q = 10$; $\sigma = \sigma_0$ = constant

For radioactivity or a similar counting measurement, where the data are digital and the distribution Poisson-Normal, the equations are particularly simple; for example, if the background is exactly zero with no uncertainty, then $L_C = 0$ counts, $L_D \approx 2.71$, and $L_Q = 100$. In agreement with experience, this means that any observed count will be evidence of a non-zero signal, and 100 counts gives a standard uncertainty of $\sqrt{100}/(100) = 10$ %. A more rigorous formulation for L_D, for extreme low-level counting, using the exact Poisson distribution, was given by Currie in 1972. Here, $L_D = 3.00$ replaces the Poisson-Normal approximation of 2.71 counts [2].

To make his 1968 paper still more concrete, three specific illustrations of analytical procedures were given, with worked-out equations for the three quantities: spectrophotometry, radioactivity, and a complex case of activation analysis.

This seminal paper has been elaborated in many contexts (e.g., [3]) and has led to an American Chemical Society symposium on the topic [4]. Currie's formulation was so convincing that it has been universally incorporated in many rules of practice governing measurement procedures, international standards [5],

regulations [6], and software. The culmination of Currie's early work was seen in the adoption of a harmonized international position (ISO-IUPAC) on the nomenclature, concepts, and formulation of detection, decision, and determination limits [7]. The IUPAC position has been further embedded in the new edition of its definitive guide for analytical chemistry [8]. Few scientific papers have been so definitive and decisive, or so clearly set the standards of subsequent discourse. This work is central to the NBS/NIST role in measurement science.

Lloyd A. Currie attended the Massachusetts Institute of Technology and then received his Ph.D. in 1955 at the University of Chicago under Willard Libby. After serving on the faculty at Pennsylvania State University, he came to the National Bureau of Standards in 1962. In addition to chemometrics, his specialty has been atmospheric radioactivity, especially ^{37}Ar and ^{14}C. His research group pioneered the application of micro-radiocarbon measurements for the discrimination of anthropogenic and natural carbonaceous pollutants. He has held visiting faculty appointments at the Universities of Bern and Gent, and was a Commerce Science Fellow in the U.S. House of Representatives Science Committee and the office of Congressman Mike McCormack. He has served as a consultant or advisory panel member for NASA, NSF, IAEA, IUPAC, and other organizations. Currie is a Fellow of the American Institute of Chemists, holds Department of Commerce Gold and Silver Medals, and was named a NIST Fellow in 1994.

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