

APPLICATION OF LIQUID SCINTILLATION SPECTROMETERS
TO RADIOCARBON DATING

Henry A. Polach

The Australian National University
Radiocarbon Dating Laboratory
Canberra

Abstract

Low-level countrate characteristics of liquid scintillation spectrometers are evaluated, specifically in relation to radiocarbon dating. The ^{14}C age determination precision (and limits of determinable ages) are evaluated in terms of a *Relative Factor of Merit* and sample size. A statistical analysis of reproducibility of age determinations and background stability is given. It will be shown that *unmodified commercially available* liquid scintillation spectrometers can produce ^{14}C age determinations of high precision, and that L.S. equipment performance is not the limiting factor in the evaluation of validity of ^{14}C ages.

Introduction

The early application of the liquid scintillation counting technique to radiocarbon dating was primarily motivated by the desire to develop this technique for use as a research tool in archaeology. The first account of its application is given by Arnold in 1954 (1) and reminiscences of the early and now historical efforts were presented at the Liquid Scintillation Counting conference held in 1957 at the North Western University (2). In his summary of the mildly successful results, Arnold (3) concluded that the only thing that could be said with certainty about the future of liquid scintillation counting, as applied to radiocarbon dating, was that it awaited an elegant solution of the chemical synthesis problem for the conversion of specimen carbon

to suitable organic liquids which preferably should be scintillation solvents.

The application of benzene for this purpose had its conception in the early work of many researchers and accounts of evolution of ideas and progress made can be found in the work of Tamers (4), Noakes (5) and Polach (6). The reader interested in chemistry of the benzene synthesis and purity of the final product is referred to these papers. This paper will deal particularly with the evaluation of L.S. spectrometer equipment performance, bearing in mind the specific requirements of the ^{14}C dating method. Counting vial design considerations are not discussed here: although this is important in low-level counting, the matter is discussed elsewhere (4), (12), (14).

Low-level countrate characteristics of L.S. spectrometers

Modern commercially available spectrometers using two alkali quartz faced photocathodes, selected for high quantum efficiency and low thermal noise and working on the coincidence pulse summation principle, have a guaranteed ^{14}C detection efficiency of >96% and in this respect alone are directly comparable to gas proportional detectors. The performance of L.S. Spectrometers is commonly expressed as the *Figure of Merit* (E^2/B) where E is % efficiency and B is background in cpm. Manufacturers of spectrometers quote an E^2/B of >450 for ^{14}C above ^3H and >250 for whole of the ^{14}C spectrum for a 20 ml low ^{40}K glass counting vial, filled with 15 ml of toluene. However, the use of E^2/B is inappropriate as an expression of *Merit* for low-countrate determinations, as the background (B) is volume dependent and the % efficiency (E) is not related to the sample volume in the formula used. Loevinger and Berman (7) have introduced the volume dependence of the *Figure of Merit* (M) into their formula, but an even more appropriate approach, particularly suitable for the evaluation of equipment performance related to age calculations, was proposed by Felber (8). One of the components of the Felber expression, $N_0/(N_B)^{1/2}$, (N_0 = Modern dating Reference Standard cpm; N_B = background cpm), is used commonly by all dating laboratories when evaluating equipment performance based on Poisson

distribution of countrate alone.

L.S. - spectrometer evaluation for ^{14}C dating

A radiocarbon age (A) is calculated using the decay equation $A = \tau \ln (N_0/N_S)$ (1)

where τ represents the mean life, taken by agreement to be 8033 years (9), and N_0 represents the counting rates of standard and N_S of sample. The radiocarbon dating modern reference standard is accepted as 95% of the observed activity of the National Bureau of Standards Oxalic acid (.95 NBS Ox). The absolute activity of .95 NBS Ox is given as $13.53 \pm .07 \text{ DPM g}^{-1} \text{ Carbon}^*$ (10) which corresponds to $10.978 \pm .06 \text{ DPM ml}^{-1} \text{ benzene}$.

Of particular interest in radiocarbon dating is the confidence with which we are able to discriminate between samples of similar age. Two natural limits exist:

(i) the age of the youngest sample which can be distinguished from the modern reference standard (A_{min}) and (ii) the age of the oldest sample which can be distinguished from the background (A_{max}). Both are of significance, but to evaluate equipment performance the theoretical maximum detectable age is the most appropriate. From the theory of extreme age calculations (8), Calf and Polach (12, this vol.) give the following equation

$$A_{\text{max}} = 8033 \ln (t/k)^{\frac{1}{2}} + 8033 \ln [N_0/(N_B)^{\frac{1}{2}}] \quad (2)$$

where t = equal time spent counting the sample, standard or background; $k = 18$ for 3σ criterion; $k = 8$ for 2σ criterion**. For a given 'k' and 't', the first term of equation (2) is a constant, the values of which are listed in Table I.

* Karlen et al. (11) report $13.56 \pm .07 \text{ DPM g}^{-1} \text{ Carbon}$. Both determinations are in excellent agreement.

** The 2σ criterion gives a probability of .975 of identifying a countrate greater than background (13).

Table I: Values for $8033 \ln(t/k)^{\frac{1}{2}}$ for $t = 1$ to 4×10^3 minutes and $k = 8$ and 18

Time in minutes	2σ criterion $k = 8$	3σ criterion $k = 18$
1000	19,390	16,100
2000	22,180	18,900
3000	23,800	20,550
4000	24,960	21,700

After substituting the appropriate value for the first term of equation (2), the theoretical maximum age is dependent on the value of $N_0/(N_B)^{\frac{1}{2}}$, which Calf and Polach (12, this vol.) called the *Relative Factor of Merit*.

Relative Factor of Merit and Optimum Sample Size

To estimate the Relative Factor of Merit (F) for any L.S. spectrometer used for dating, N_0 and N_B must be measured at chosen equipment parameters. The important equipment variables are (i) Photomultiplier high voltage, (ii) amplifier gain, (iii) lower and upper discriminator settings (which define the 'limited coincidence window'). The window efficiency E, must be evaluated directly from the observed countrate of N_0 by relating it to the absolute determinations of the standard used for dating. The background N_B must be measured for the same vial design, same solvent, solute mix, and volume as N_0 .

Prior to selection of optimum parameters a series of tests must be carried out and F must be evaluated for a range of background and modern sample pairs of different sizes. An experiment of this kind conducted at ANU using a Beckman LS-200 spectrometer is described.

The modern reference standard and background were counted at fixed high voltage*, and amplifier gain set at 360. The settings of the lower and upper

* The Beckman Spectrometer EHT is fixed by the manufacturer and cannot be readily varied without modifying the equipment.

LIQUID SCINTILLATION COUNTING

discriminators were adjusted to correspond to balance-point operations (14) for a given ^{14}C efficiency window. The observed countrates therefore characterise uniquely and reproducibly the spectrometer's performance at the chosen settings.

To reduce the background of the 20 ml low ^{40}K glass counting vial, used for this series of experiments, to best obtainable values for a given sample size, the glass vial was masked above the level reached by the top of the scintillation liquid*.

The experiment yielded the results list in Table II.

The background of the progressively masked vial was found to be directly related to the sample volume (V), within the range of efficiencies studied, according to the linear equation:

$$\text{cpm}_B = mV + b \quad (3)$$

Where m and b are the regression parameters.

In addition to determinations at .95E, .85E, and .75E, listed in Table II, the $\ln(F)$ for .65E and .55E were also evaluated. They were so similar to those given for the .95E window that they are not tabulated. The results show that the reduction of *limited coincidence* window width, corresponding to lower efficiencies does not give a higher *Relative Factor of Merit*. Indeed, the highest was obtained at .85E.

The net countrates for N_0 were also linearly related to sample size. From the data given in Table II it can be readily shown that $\ln(F)$ is dependent on the regression parameters of the linear equations for N_B and N_0 in the following manner:

$$\ln(F) = \ln(m_2V) - \frac{1}{2} \ln(m_1V + b) \quad (4)$$

where m_1 and b are slope and intercept for N_B versus V, and m_2 is slope for N_0 . From this it is clear that rate of increase of F diminishes as V increases, as Table III illustrates for 0.85E data.

Values of A_{max} in Table III indicate the relative gain from the ^{14}C point of view when sample size is increased. An increase from 1 to 10 ml raises A_{max}

* Black paper, aluminium foil or black matt paint are suitable.

Table II: Evaluation of Beckman L.S. Spectrometer performance for radiocarbon dating.

V	.95E			.85E			.75E		
	N_B^*	N_O	$\ln(F)$	N_B	N_O	$\ln(F)$	N_B	N_O	$\ln(F)$
1	5.4	10.4	1.50	2.9	9.33	1.7	2.6 ⁺	8.2 ⁺	1.63
2	7.0	20.9	2.07	3.8	18.7	2.26	3.4 ⁺	16.5 ⁺	2.19
5	11.5 ⁺	52.1 ⁺	2.73	6.4 ⁺	46.7 ⁺	2.91	5.6 ⁺	41.2 ⁺	2.86
10	19.0	104.3	3.17	10.8	93.3	3.35	9.4 ⁺	82.3 ⁺	3.29
15	26.5 ⁺	156.4	3.41	15.2 ⁺	140.0	3.58	13.2 ⁺	123.5 ⁺	3.53
20	34.0	208.6	3.58	19.6	186.6	3.74	17.0	164.7	3.63

V = ml sample benzene with dry scintillant weighed in

Efficiency calculated using .95 of the *observed* countrate modern oxalic standard whose .95 of absolute activity is $10.978 \pm .06$ DPM ml⁻¹ C₆H₆

F = Relative Factor of Merit = $N_O / (N_B)^{\frac{1}{2}}$

* Linear equations relating sample volume to background in shielded vials were found to be:

$$\text{cpm (.95E)} = 1.5 V + 4.0$$

$$\text{cpm (.85E)} = 0.88 V + 2.0 \text{ (USED IN TABLE 3)}$$

$$\text{cpm (.75E)} = 0.755 V + 1.85$$

$$\text{cpm (.65E)} = 0.58 V + 1.75$$

$$\text{cpm (.55E)} = 0.48 V + 1.6$$

+ values determined by measurement throughout the range of .75E on N_B and N_O . Correlation coefficient $r = >0.99$ for the regression equation for this data. Other data (i.e. .95, .85, .65, and .55 E) could therefore be soundly inter- and extra- polated from measured values at 5 and 15 ml benzene.

LIQUID SCINTILLATION COUNTING

Table III: Evaluation of *Merit* of counting samples of increasing sizes for radiocarbon dating. 0.85E, Beckman L.S.-200, calculated from values given in Table II.

V	ln(F) (Calc')	Amax (years)
1	1.70	37,490
2	2.26	41,990
5	2.91	47,210
10	3.35	50,680
15	3.58	52,560
20	3.74	53,850
50	4.23	57,790
100	4.59	60,660

[In Table III the following values were used:

$m_1 = 0.88$; $b = 2.0$; $m_2 = 9.33$; ($k = 8$; $t = 3000$; i.e. 1st term of eq. (2) = 23,800).]

Table IV: Sample sizes submitted for dating.

% of FULL REQUIREMENT*	2	2-5	6-10	11-50	51-99	100	200	500	Total
No. of samples	8	9	33	206	167	164	164	25	774
% of samples (Rounded off)	1	1	4	27	22	21	21	3	100

* % FULL REQUIREMENT BASED ON 3.5g Carbon = 100% yielding ca. 4 ml C₆H₆ counting sample.

from 37.5 Ky to 50.7 Ky, while a further increase to 100 ml only raises A_{max} further to 60.7 Ky.

We can conclude that counting sample volumes from 5 to 10 ml at ca. 85% efficiency would give the best return for our labours. This opinion is reinforced by the range of actual sample sizes submitted for dating to the ANU laboratory over the past 3 years (Table IV).

The results indicate that ca. 45% of samples submitted for dating are more than adequate for 4 ml benzene counting, 49% are just adequate and 6% were inadequate. Only 25% of samples submitted could have been applied to 10 ml benzene counting. This strongly supports the choice of the 5 ml counting vial (4,14).

Long term performance of L.S. spectrometers

Few radiocarbon dating laboratories have published data on long term stability of their counting equipment. Whilst background and reproducibility tests are available for L.S. spectrometers [e.g. (4,5)] and the results given are very satisfactory, only one detailed case study is available to me, and hence I propose to analyse the performance of the L.S. counting equipment of the ANU ^{14}C dating laboratory.

The equipment, a Beckman LS-200, was set up early in 1968. Lacking experience, we chose on an intuitive basis to work at ca. 70% efficiency (relative to .95 NBS Ox), with a sample size of 4 ml benzene, to which we added 1 ml of toluene in which PPO and POPOP were dissolved at concentrations corresponding to 5g/l and 0.05g/l of final solvent (14). Operating at balance-point, with $\frac{1}{4}$ " masking placed on the periphery of the tubes (12, this vol.) the following results were achieved: $N_0 = 30.77$ cpm; $N_B = 5.5$ cpm; $F = 13.1$ with $A_{max} = 42,400$ years ($k = 18$; $t = 4000$ Min). Tests on stability then carried out made us state that: 'the degree of stability is 200 times greater than observed or anticipated chemical quench variations, and 10 times greater than observed equipment-induced countrate variations' (14). Now, after 4 years of continuous operation, we can examine how well the equipment really behaved, but before we do so, some points as to counting procedures must be made clear.

LIQUID SCINTILLATION COUNTING

Eleven vials are placed within the automatic charger in the following order: S₁ S₂ S₃ S₄ B₁ S₅ S₆ S₇ S₈ H B₂, where S₁₋₈ are sample counting vials, B₁₋₂ are flame sealed backgrounds and H is flame sealed ¹⁴C spiked 'hot' standard of 800 cpm. The vials are cycled at 20 minute intervals, with the exception of hot standard, which gives 2000 counts in ca. 2.5 minutes and is then cycled out. When the relationship of individual background of each counting vial to the mean background value of the two sealed background vials is established, the ¹⁴C modern reference standard (NBS Ox) is counted in our standard sample vials, and its relationship to the 'hot' standard is calculated. The cycling method thus provides quasi-simultaneous background and modern countrate checks, as well as automatic short term checks on stability. Long term reproducibility checks of the spectrometer are also made easier as the data output is stored on punch tape. Cycling operations commenced in March 1968 and continued until January 1970; the equipment was then moved to its present position and cycling operations recommenced June 1970 and continue without change of operating parameters today. To evaluate performance of the equipment for low-level counting, the reproducibility of age determinations and the stability of background has to be analysed.

¹⁴C Counting: reproducibility of age determinations

We had a choice to analyse either the reproducibility of the Oxalic reference standard measurements, the 'hot' sealed ¹⁴C standard, or the reproducibility of duplicate age determinations.

The oxalic standard, for reasons of isotopic fractionation (15, 16), is not satisfactorily reproducible and should not be used for purposes of equipment performance evaluation. To analyse the 'hot' would be interesting but it is arguable that is irrelevant to R.C. dating as we are dealing with activities 20x higher than are actually attributed to the modern reference standard. We therefore chose to analyse the reproducibility of duplicate age determinations.

From the start of L.S. operation in 1968 until 1972, when all duplicate measurements were analysed, 67 sample pair comparisons were available for analysis. These consisted of 39 inter-lab. cross checks and 28 other cross checks which were duplicates of our own measurements. All repeat age determinations were carried out on portions of the same sample. All duplicate measurements carried out at the ANU lab. are listed, none were knowingly omitted. The analysis was carried out on results as reported to sample submitters, (for full details, code numbers and ages \pm errors, see Polach (15)) Results are presented in Table V.

To better evaluate equipment performance, we subdivided the duplicate determinations into two groups: those carried out between other laboratories and ANU (Table V, group A), and ANU-duplicates of our own determinations (Table V group B). It is apparent that the broadness of distribution (ca. 11% more values lie between 1 and 2 S.D. and ca. 6% more beyond the 2 S.D. limit) is entirely confined to group A, the inter-laboratory cross check age determinations, whilst ANU-duplicates of our own determinations, group B, are almost ideally distributed around the mean.

We can therefore conclude that other factors than equipment performance influenced the distribution of international cross checks and that based on ANU-duplicates alone, the equipment performance was as good as could be expected (14).

^{14}C Counting: reproducibility of background

Whilst the long term stability for ^{14}C countrates for samples submitted for dating is shown to be excellent, it would be wrong to assume that background counting is just as stable. Indeed, the spectra for ^{14}C sample activity and corresponding background are vastly different (the background counts increase continuously towards the lower energy region) and operating at the ^{14}C balance-point, with demonstrated stability of ^{14}C counts, does not imply that background

Table V: Analysis of pair comparisons of duplicate ^{14}C age determinations.

WITHIN ± S.D.	INTER LAB X-CHECKS B				ANU-DUPLICATES B			
	ACTUAL		IDEAL		ACTUAL		IDEAL	
	FREQ.	%	FREQ.	%	FREQ.	%	FREQ.	%
0-1	20	51.3	26.8	68.3	19	68.0	19.2	68.3
1-2	15	38.5	10.6	27.2	8	28.5	7.6	27.2
2-3	4	10.2	1.6	4.2	1	3.5	1.2	4.2
SUM OF PAIRS	39	100	39	99.7	28	100	28	99.7

would exhibit the same degree of stability* In selecting operating parameters the background stability has therefore to be carefully evaluated, as in low-level counting age determinations a high statistically reproducible background is acceptable, whilst a low changing background would spell disaster.

An analysis of the continuous 20 minute output for our flame sealed background vial No. 5 (B₁) forming part of our background record B-001 to B-258 (i.e. June 1970 to August 1972) has now been performed, and is presented in Table VIa, b, c. All data as punched on tape were analysed and none for any reason whatsoever were rejected. We could not have wished for better results.

Measurement errors and ¹⁴C dating errors

We have been concerned with the error of measurement based on L.S. spectrometer performance (also of concern is the laboratory error due to variation in purity of benzene discussed in this volume (17)). It is appropriate however to recognise that these errors today form the minor and diminishing component in establishing the true ¹⁴C age of the sample. More important in ¹⁴C dating are errors resulting from the age of the material at time of deposition, the chemistry of the sample and the chemistry of the environment in which the sample lay buried or exposed, the variations in concentration of radiocarbon due to past variation in production rate and/or variations due to equilibration and distribution of radiocarbon within its storage reservoirs.

All of these, in the ¹⁴C dating experience, are the most significant ones and are subject to continuous studies. An excellent review is given by Neustupny (18).

* We were able to test that if ¹⁴C operations were carried out with very much reduced high voltage when ³H efficiencies equalled zero, that backgrounds were very low, but extremely unstable.

LIQUID SCINTILLATION COUNTING

Table VI: Analysis of Background Readings

VIa) Main Characteristics

TOTAL TIME = 123,000 MINUTES POISSON DEVIATION = 10.59
 TOTAL COUNT = 689,372 GAUSSIAN DEVIATION = 10.70
 MEAN CPM = 5.6047 CHI SQ = 6286 with 6150 DF

VIb) Percentile Distribution of 20 min Counts Round Mean

+ -S.D.	20 MIN. COUNT LIMITS	No REC.	%
+ 4	154.45	12	0.19
+ 3	143.85	130	2.11
+ 2	133.27	856	13.92
+ 1	122.68	1952	31.74

MEAN = 112.09 ± 10.59 COUNTS; No REC = 6150

- 1	101.50	2234	36.32
- 2	90.92	849	13.80
- 3	80.33	108	1.76
- 4	69.74	9	0.15

VIc) Distribution Summary

SIGMA LIMITS	ACTUAL %	IDEAL %
WITHIN 1 SIGMA	68.1	68.3
1 to 2 SIGMA	27.7	27.2
2 to 3 SIGMA	3.9	4.2
3 - 4 SIGMA	.34	.3
BEYOND 4 SIGMA	NIL	

Nevertheless, and quite correctly, much detailed attention continues to be given to evaluation of accuracy of measurement based on equipment performance. Studies as presented by Geyh (19), introducing the concept of *limiting accuracy* which is primarily determined by the instability of electronic measuring equipment and secondarily by the purity of synthesised gas or liquid as prepared for counting, lead to the introduction of *longest justifiable counting time*. Studies such as carried out by Polach and others [e.g. (20,21,22)] introduced the reporting of *pertinent statistical data* allowing the evaluation of results that hitherto could be reported only as 'greater than' ages; further introduced the concept of running *background blanks* in studies of age determinations close to the limit of countrate detection in the presence of suspected contamination as well as counting a number of *chemical fractions* of the same sample rather than prolonging the counting time of individual age determinations to achieve greater validity and precision. Equally significant is the concept of the *reduced activity* (sample activity/background equivalent activity) plot offered by Currie (23) as a means of planning dating activities and rapidly assessing the capabilities of any specific age determination equipment and procedure.

Notwithstanding the limitations imposed by the above statement, I am nevertheless presenting here a plot of ages and errors showing their dependence on sample size and counting time alone (Fig.1), as the limitation imposed by these remain determinable, whilst the previously mentioned limitations are subject to interpretation and are the basis of the contributions which a radiocarbon dater can make to chronological investigations.

The family of curves presented in Fig. 1 are based on the performance of the Beckman LS-200 spectrometer on which all ANU routine dating operations have been carried out since 1968. The errors are based on 3000 minutes countrate determinations, chosen because for critical measurements, 3000 minutes counting time is indicative of the maximum time we generally spend counting a single sample. The fundamental basis for error assessment, in this diagram, is the theoretical

LIQUID SCINTILLATION COUNTING

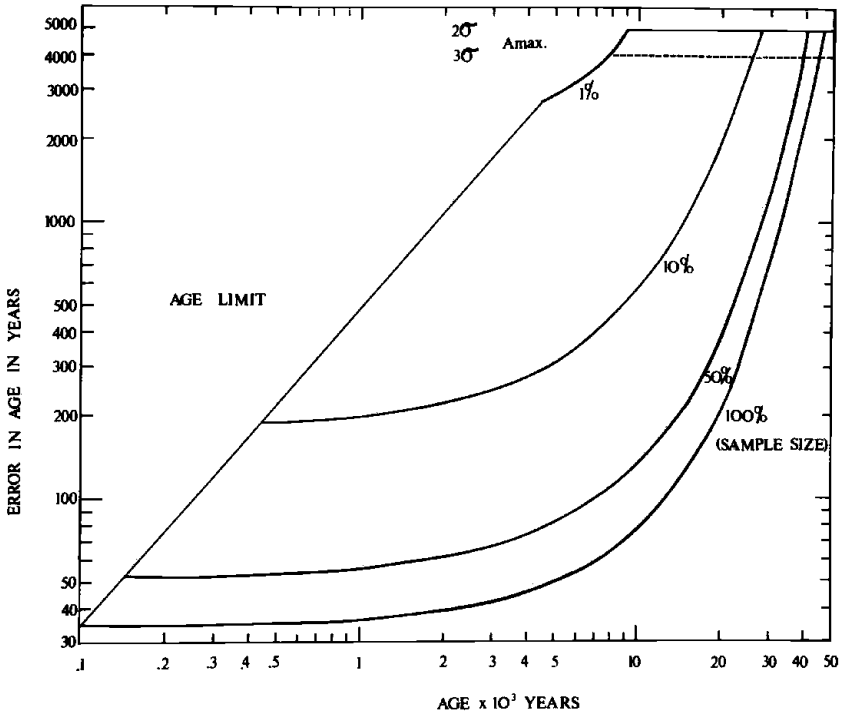


Figure 1: Precision of age determination is dependent on sample size, age and counting time. (Counting time = 3000 Min; 3.5 g carbon = 100% Age limits are imposed by the 2σ and 3σ detection criteria).

Poisson variation of countrates. Fig. 1 becomes more significant if we remember the distribution of sample sizes as submitted to the ANU ^{14}C dating laboratory over the past 3 years (Table IV).

An analysis of sample ages (Table VII) reported by the ANU lab. in the last 3 years of its dating activity indicates that 45% fall within the age limits of 1-10 thousand years, and that beyond this the demand on our laboratory is equally great for younger and older samples.

Referring back to Fig. 1 we can see that the performance of the equipment meets the demand made upon it adequately: the ability to discriminate minimum ages is extremely good; the ability to discriminate maximum ages is adequate; the minimum sample size that can be counted with acceptable errors is ca. 250mg carbon.

Conclusions

We have established that commercially available liquid scintillation spectrometers will in the hands of ^{14}C dating experts give a highly satisfactory long term performance. The ability to determine ^{14}C ages within the range of 100 to 30,000 years with maximum precision conforms well with the average demand made upon the method. Extension of precise dating beyond 30,000 years is limited by the relationship of the signal to noise ration of L.S. spectrometers. In order to achieve higher equipment resolution near the maximum age limit, an increase in sample size alone is not appropriate. Aware of the limitations imposed by the average sample size submitted for ^{14}C dating, we recommend a 5 to 10 ml counting vial as most appropriate. This coupled with the use of vial material with a high *Figure of Merit* and selection of best operating parameters to reduce background (12,24, this vol.) makes the usage of liquid scintillation spectrometers for dating purposes very attractive. The quotation taken from Arnold and used in our introduction therefore no longer applies. We no longer await the

LIQUID SCINTILLATION COUNTING

Table VII: Sample ages evaluated over the last 3 years of activity in the ANU ^{14}C dating laboratory.

Age limits $\times 10^3$ y.	<.5	.5-1	1-10	10-20	20-30	>30	Total
No. of determin.	70	49	260	61	74	66	580
%	12.0	8.4	44.9	10.5	12.8	11.4	100

elegant solution to our problems' as is so vividly demonstrated by the fact that the majority of newly established ^{14}C dating laboratories have adopted the liquid scintillation counting technique.

Acknowledgements

I wish to thank Professors John C. Jaeger, Jack Golson and Donald Walker, The Australian National University, who throughout the past years have encouraged and supported the activities of the ANU ^{14}C dating laboratory. Particular thanks go to my colleague, Dr. John Chappell, ANU, as he contributed so much through discussion and critical reading of this manuscript, and to the staff of this laboratory, John Gower, John Head and Maureen Powell whose continuous effort made this work possible.

References

1. J.R. Arnold, *Science* 119, 155 (1954).
2. C.A. Bell, Jr. and F.N. Hayes, Ed., *Liquid Scintillation Counting*, Proc. of the Northwestern University, August 1957. London: Pergamon Press, (1958).
3. J.R. Arnold *in* *Liquid Scintillation Counting*, p.129 (Carlos G. Bell, Jr. and F. Newton Hayes, Ed.) London: Pergamon Press (1958).

4. M.A. Tamers *in* Radiocarbon and Tritium Dating, Proc. 6th Internatl. Conf., Pullman, Washington, p. 53 (1965).
5. J.E. Noakes, S.M. Kim and J.J. Stipp *in* Radiocarbon and Tritium Dating, Proc. 6th Internatl. Conf., Pullman, Washington, p. 68 (1965).
6. H.A. Polach and J.J. Stipp, J. Appl. Radiation and Isotopes, 18, 359 (1967).
7. R. Loevinger and M. Berman, Nucleonics, 9, 26 (1960).
8. H. Felber, Report of the Austrian Ac. of Sc., 170:2, 85 (1962).
9. H. Godwin, Nature, 195 : 4845, 984 (1962)
10. Int. Commiss. Rad. Units and Measurements, *in* Measurement of Low-Level Activity, ICRU Report 22, p. 47 (1972).
11. I. Karlen, I.U. Olsson, P. Kallberg and S. Killicci, Arkiv Geofysik, 4, 465 (1964).
12. G.E. Calf and H.A. Polach *in* Liquid Scintillation Counting: Recent Developments. (Philip E. Stanley and Bruce A. Scoggins, Ed.) New York: Academic Press (this volume).
13. W.J. Kaufman, A.Nir, G. Parks and R.M. Hours *in* Tritium in the Physical and Biological Sciences, IAEA, Vienna, p. 250 (1962).
14. H.A. Polach, Atomic Energy in Australia, 12:3. 21 (1969).
15. H.A. Polach *in* 8th Internatl. Conf. on Radiocarbon Dating Proceedings, Lower Hutt, New Zealand, 688 (1972).
16. H.A. Polach and H.A. Krueger, 8th Internatl. Conf. on Radiocarbon Dating Proceedings, Lower Hutt, New Zealand, 718 (1972).

LIQUID SCINTILLATION COUNTING

17. I. Fraser, H.A. Polach, R.B. Temple and R. Gillespie *in* Liquid Scintillation Counting: Recent Developments (Philip E. Stanley and Bruce A. Scoggins, Ed.) New York : Academic Press. (this volume).
18. E. Neustupny *in* Radiocarbon Variations and Absolute Chronology, (Ingrid U. Olsson, Ed.) Stockholm: Almqvist and Wiksell, p. 23 (1970).
19. M.A. Geyh *in* Radiocarbon and Tritium Dating, 6th Internatl. Conf., Pullman, Washington, 29-35 (1965).
20. H.A. Polach, J. Chappell and J.F. Lovering, Radiocarbon, 11:2, 245 (1969).
21. I. McDougall, H.A. Polach and J.J. Stipp, Geochem. Cosmochim. Acta. 33, 1485 (1969).
22. J. Chappell and H.A. Polach, Quaternary Research, 2:4, 244 (1972).
23. L.A. Currie *in* 8th Internatl. Conf. on Radiocarbon Dating, Lower Hutt, New Zealand, 598-611 (1972).
24. P.E. Hartley and V.E. Church *in* Liquid Scintillation Counting: Recent Developments. (Philip E. Stanley and Bruce A. Scoggins, Ed.) New York : Academic Press (this volume).

