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Effect of liquid scintillating cocktail volume on ^{3}H and ^{14}C measurement parameters using a Quantulus spectrometer

Andrzej Komosa, Katarzyna Ślepecka

Abstract. Results of study on the influence of cocktail volume on such measuring parameters as counting efficiency, standard quench parameter (SQP) and figure of merit (FOM) are described. Nine commercial cocktails were tested using a Quantulus spectrometer. Two kinds of vials (low-diffusion teflon-coated polyethylene (LD-PE) and high-performance glass (HP-G)) and two standard solutions (^{14}C and ^{3}H) were used. Measurements were performed at seven quench levels ensured by carbon tetrachloride addition to the scintillation vials. Various quench sensitivity of the studied cocktails was found. Cocktails based on simple benzene-derived solvents revealed the best quench resistance. In general, increasing cocktail volume caused an increase in the counting efficiency. However, the background increased as well, what resulted in FOM diminishing. Studied cocktails revealed also various responses to volume changes.

Key words: liquid scintillating cocktail • tritium • ^{14}C • Quantulus • counting efficiency • standard quench parameter (SQP) • figure of merit (FOM)

Introduction

Modern spectrometers for radiation measurement which use a liquid scintillation technique are widely applied to determine beta emitting radionuclides, especially those of low energy radiation. Quantulus (Wallac-PerkinElmer) spectrometer, owing to sophisticated electronics (amplitude comparator and anticoincidence systems) being an active system of background reduction, and a passive shielding made of a large mass of lead enables to measure very low activity of beta radiation. For this reason, it is suitable for determining beta emitting radioisotopes occurring in the environment [3].

Preparation of environmental samples for alpha and beta radioisotope determination usually requires the application of multi-stage radiochemical separation procedures for isolation of radionuclides. This is also the case while using liquid scintillation spectrometry as a tool for radioactivity measurement. A final step of radiochemical procedure involves usually a solvent extraction of the radionuclide of interest. A sample obtained in this way is directly introduced into a scintillation cocktail. However, insufficient separation from contaminants, being matrix components, causes lowering of scintillation efficiency (so-called quenching). For this reason, the optimization of measurement conditions is an important factor in the determination of specific activity. Quenching is the main disadvantageous feature of liquid

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scintillation counting. A level of quenching is influenced by chemical composition of scintillation cocktail (whose precise composition is usually not known), chemical composition of the sample and a sample to cocktail volume ratio. There are many various scintillation cocktails available on the market which differ in their chemical composition and dedicated application to a given kind of samples [3]. The producers usually suggest to what kind of sample their cocktails are assigned. If one tries to utilize the cocktails in other conditions than suggested, then it is necessary to check what changes in measurement parameters can be introduced. These can cause various responses to quenching.

In our previous study a different susceptibility of commercial cocktails on quenching during tritium and ^{14}C measurements was proved [2].

Due to the necessity to reduce radioactive wastes, and taking into account high costs of liquid scintillation cocktails, the use of as small as possible cocktail volume is required. Therefore, the aim of our study was to investigate the influence of cocktail volume on measurement parameters of nine various commercial cocktails during counting of tritium and ^{14}C standard solutions in conditions of variable quench.

Such studies were not presented in the literature. There are very little comparative data concerning commercial cocktails. Only two papers refer to the influence of sample volume loading into a cocktail on results of measurement of tritium and ^{14}C [6, 7].

Pujol and Sanchez-Cabeza [6] have studied, among others, variations of background, counting efficiency and FOM during tritium measurement with seven different commercial cocktails. They observed the influence not only of the kind of a cocktail, but also of the type of vial on measurement parameters [6].

Verrezen *et al*. [7] have studied a quench resistance of nine various commercial cocktails and their long-term stability in PE vials. They found that some cocktails in PE vials were unstable. Efficiency lost during tritium and ^{14}C measurements was about 0.2% per day. Quenching equations (dependence of counting efficiency on CCl_4 volume addition) were also presented [7].

Experimental

The study was performed using two types of scintillation vials: high-performance, low-potassium glass vials (HP-G) and low-diffusion, teflon-coated polyethylene vials (LD-PE), both from PerkinElmer. Nine various scintillation cocktails were used: seven commercial cocktails and two prepared by dissolution of organic scintillators in a proper solvent (benzene or toluene). All known data about chemical composition of scintillating cocktails are presented in Table 1. As it is seen, five cocktails were based on simple organic solvent (benzene, toluene, xylene and pseudocumene) and four others contained *di*-isopropylnaphtalene isomers (DIN). The first group of cocktails is called the "fast cocktails" and the second the "slow cocktails" what relates to the time of pulse decay [4].

Radioactivity measurements were performed using an ultra-low level liquid scintillation spectrometer Quantulus 1220-002 (Wallac-PerkinElmer) with the EASY View and the WinQ software. Count rates of background and ^{14}C and ^{3}H standard solutions were measured in various quenching conditions (seven quench levels), made by the addition of CCl_4 ranging between 0–0.12 cm^3. The effect of various cocktail volumes between 2.5 and 15 cm^3 was also examined.

Sample preparation and measuring procedure were as follows: a set of two kinds of scintillation vials were prepared, vials were filled with a proper volume of scintillation cocktails and spiked in each vial optionally with 0.015 cm^3 (275 ± 1.4 Bq) of n-pentanol with ^{14}C standard solution or 0.02 cm^3 (293 ± 1.5 Bq) of tritiated toluene solution, both provided by Eurostandard (the Czech Republic).

Background measurements were performed during 150 min and those of the radioisotope spiked solutions during 15 min. A proper measurement option ("high energy" for ^{14}C and "low energy" for ^{3}H) was chosen in the Quantulus spectrometer and count rate was determined in the channel range 100–700 (^{14}C) and 5–400 (^{3}H). Before measurement, the samples were stored for 24 h inside the apparatus to minimize chemiluminescence. A quenching agent was added to each vial successively in 0.02 cm^3 portions. The SQP parameter was determined by the Quantulus software which utilized an external gamma source: ^{152}Eu [5]. In our study the quenching was realized by carbon tetrachloride addition. Quench level was followed by a SQP value. Its value is assumed to be 1000 for non-quenched sample and diminish with quench level increase. However, in measurement practice the SQP value equal to 1000 is not achievable.

Results of the activity measurement of ^{14}C and ^{3}H were background corrected. In the case of tritium random coincidence counts were subtracted (values in "MCA 12" minus "MCA 11").

Chemical compositions of the liquid scintillation cocktails used (as specified by the producers in the Material Safety Data Sheet enclosed to the product) are presented in Table 1. They were arranged in the following order: cocktails based on simple benzene--derived solvents (Insta Fluor, Permablend and butyl--PBD), pseudocumene-based cocktails (Insta Gel Plus and Hionic Fluor) and DIN-based (others). Nowadays, some of the scintillation cocktails, named as presented in Table 1, have different composition [5].

Results and discussion

Results of background measurements for two kinds of vials in two counting windows are presented in Tables 2 and 3 (for ^{14}C and tritium channel range, respectively). As it is seen, the background values increased with cocktail volume in every case. It is not incomprehensible because if cocktail volume is large, the cosmic ray interactions will increase. The highest increase is observed with the Hionic Fluor. This cocktail contains organophosphate compounds which can be contaminated with traces of uranium. This can explain such high background values.

One can see also that the LD-PE vials revealed almost the same background values in both counting windows. Background values of the glass vials (HP-G) were higher than those of LD-PE vials: in the ^{14}C window almost 2 times higher, but in the tritium channels

Table 1. Chemical composition of scintillation cocktails (manufacturer's Material Safety Data Sheet)

Cocktail	Producer	Solvent and additives	Scintillator
Insta Fluor	Packard	Ortho-xylene 97–99% n-Pentanol 1–2%	PPO ≤ 1% *bis*-MSB ≤ 1%
Permablend III* 7 g/dm^3	Packard	Toluene > 99%	PPO: *bis*-MSB = 10.1:1
Butyl-PBD* 15 g/dm^3	Fluka	Benzene > 98%	butyl-PBD
Insta Gel Plus	PerkinElmer	Pseudocumene 40–60% Ethoxylated alkylphenol 40–60%	PPO ≤ 2.5% *bis*-MSB ≤ 2.5%
Hionic Fluor	PerkinElmer	Pseudocumene 40–60% Diethanolamine-phosporic acid ester ammonium salt 10–20% Ethoxylated nonylphenol 10–20% Triethylphosphate 2.5–10% Sodium dioctyl sulfosuccinate 2.5–10%	PPO ≤ 2.5% *bis*-MSB ≤ 2.5%
Ultima Gold AB	PerkinElmer	DIN 60–80% Ethoxylated nonylphenol 20–40% 2-(2-butoxyethoxy)ethanol 10–20% Nonylphenyl polyoxyethylene ether phosphate < 2.5%	PPO ≤ 2.5% *bis*-MSB ≤ 2.5%
Ultima Gold LLT	PerkinElmer	DIN 40–60% Ethoxylated nonylphenol 20–40% 2-(2-butoxyethoxy)ethanol 2.5–10% Ethoxylated fatty alcohol ≤ 2.5% Nonylphenyl polyoxyethylene ether phosphate < 2.5% 3,6-dimethyl-4-octyne-3,6-diol ≤ 2.5%	PPO ≤ 2.5% *bis*-MSB ≤ 2.5%
OptiPhase HiSafe 2	PerkinElmer	DIN > 70% Sodium dioctyl-sulfosuccinate < 14% Poly(ethyleneglycol)mono(4-nonylphenyl)ether < 7% 2-(2-butoxyethoxy)ethanol < 5% N-lauroyl sarcosine < 5% Propylene glycol butyl ether < 3% Sodium borohydride < 1% Diethanolamine < 1%	PPO ≤ 2.5% *bis*-MSB ≤ 2.5%
OptiPhase HiSafe 3	PerkinElmer	DIN > 60% Poly(ethyleneglycol)mono(4-nonylphenyl)ether < 25–30% α-phenyl-ω-hydroxypoly(oxo-1,2-ethanediyl)phosphate < 10%	PPO ≤ 1% *bis*-MSB ≤ 0.1%

* Organic scintillating matter for preparation of scintillating cocktail.
PPO – 2,5-diphenyloxazole.
bis-MSB – 1,4-bis(2-methylstyryl)-benzene.
DIN – *di*-isopropylnaphtalene isomers.
Pseudocumene – 1,2,4-trimethylbenzene.

surprisingly about 5 times higher. It is clear that a glass of the HP-G vial surely contains some radioactivity. It is likely a result of the presence of natural ^{40}K which emits X-rays from ^{40}Ar, a potassium decay product [1, 8].

Table 2. Background values (cpm) in ^{14}C channel window for two kinds of vials: low-diffusion polyethylene (LD-PE) and high-performance glass (HP-G) vials without quenching at various cocktail volumes

Cocktail	LD-PE			HP-G		
	5 cm^3	10 cm^3	15 cm^3	5 cm^3	10 cm^3	15 cm^3
Insta Fluor	0.95 ± 0.06	1.70 ± 0.08	2.20 ± 0.09	2.13 ± 0.08	3.05 ± 0.10	3.75 ± 0.11
Permablend	0.85 ± 0.05	1.39 ± 0.07	1.96 ± 0.08	2.22 ± 0.09	2.90 ± 0.10	3.69 ± 0.11
Butyl-PBD	1.06 ± 0.06	1.66 ± 0.07	2.31 ± 0.09	2.19 ± 0.09	3.12 ± 0.10	3.98 ± 0.12
Insta Gel Plus	2.20 ± 0.09	3.54 ± 0.11	5.01 ± 0.13	3.44 ± 0.11	5.65 ± 0.14	6.63 ± 0.15
Hionic Fluor	3.02 ± 0.14	6.10 ± 0.20	8.97 ± 0.25	5.03 ± 0.18	7.92 ± 0.23	10.9 ± 0.27
Ultima Gold AB	1.39 ± 0.10	2.13 ± 0.12	3.16 ± 0.14	3.16 ± 0.14	3.89 ± 0.16	5.19 ± 0.18
Ultima Gold LLT	1.56 ± 0.10	2.30 ± 0.12	2.90 ± 0.14	2.94 ± 0.14	4.14 ± 0.16	5.15 ± 0.18
HiSafe 2	1.75 ± 0.11	2.90 ± 0.14	4.24 ± 0.17	3.22 ± 0.15	4.95 ± 0.18	6.15 ± 0.20
HiSafe 3	1.47 ± 0.10	1.93 ± 0.11	3.01 ± 0.14	2.82 ± 0.14	4.22 ± 0.17	5.09 ± 0.19
Mean	1.58 ± 0.30	2.63 ± 0.37	3.75 ± 0.46	3.02 ± 0.40	4.43 ± 0.49	5.62 ± 0.52

Table 3. Background values (cpm) in tritium channel window for two kinds of vials: low-diffusion polyethylene (LD-PE) and high-performance glass (HP-G) vials without quenching at various cocktail volumes

Cocktail	LD-PE			HP-G		
	5 cm^3	10 cm^3	15 cm^3	5 cm^3	10 cm^3	15 cm^3
Insta Fluor	2.03 ± 0.12	2.77 ± 0.14	3.61 ± 0.16	16.09 ± 0.33	19.11 ± 0.36	21.47 ± 0.38
Permablend	1.40 ± 0.10	1.86 ± 0.11	2.34 ± 0.13	12.60 ± 0.29	13.90 ± 0.31	13.26 ± 0.30
Butyl-PBD	1.44 ± 0.10	1.73 ± 0.11	2.26 ± 0.12	13.69 ± 0.30	13.17 ± 0.30	13.08 ± 0.30
Insta Gel Plus	4.03 ± 0.16	2.67 ± 0.13	2.94 ± 0.14	13.21 ± 0.30	14.54 ± 0.31	14.07 ± 0.31
Hionic Fluor	3.04 ± 0.14	5.21 ± 0.19	7.77 ± 0.23	14.67 ± 0.31	16.96 ± 0.34	18.53 ± 0.35
Ultima Gold AB	1.55 ± 0.10	1.88 ± 0.11	2.55 ± 0.13	13.42 ± 0.30	14.22 ± 0.31	14.26 ± 0.31
Ultima Gold LLT	1.63 ± 0.10	2.30 ± 0.12	2.30 ± 0.12	13.26 ± 0.30	13.07 ± 0.30	14.74 ± 0.32
HiSafe 2	2.30 ± 0.12	2.62 ± 0.13	3.56 ± 0.16	13.06 ± 0.30	14.35 ± 0.31	14.03 ± 0.31
HiSafe 3	1.79 ± 0.11	2.51 ± 0.13	2.69 ± 0.13	12.87 ± 0.29	12.47 ± 0.29	13.02 ± 0.30
Mean	2.13 ± 0.36	2.62 ± 0.40	3.34 ± 0.45	13.65 ± 0.91	14.64 ± 0.94	15.16 ± 0.96

Table 4. Counting efficiency (%) of ^{14}C measurement in two kinds of vials: low-diffusion polyethylene (LD-PE) and high-performance glass (HP-G) vials without quenching at various cocktail volumes

Cocktail	LD-PE			HP-G		
	5 cm^3	10 cm^3	15 cm^3	5 cm^3	10 cm^3	15 cm^3
Insta Fluor	81.4 ± 1.4	83.5 ± 1.4	90.4 ± 1.5	79.6 ± 1.4	87.6 ± 1.5	80.6 ± 1.4
Permablend	78.1 ± 1.4	85.4 ± 1.4	82.7 ± 1.4	85.0 ± 1.4	90.0 ± 1.5	83.3 ± 1.4
Butyl-PBD	78.0 ± 1.4	80.4 ± 1.4	76.1 ± 1.4	83.7 ± 1.4	87.5 ± 1.5	86.7 ± 1.5
Insta Gel Plus	81.3 ± 1.4	79.2 ± 1.4	80.5 ± 1.4	86.4 ± 1.5	82.2 ± 1.4	81.4 ± 1.4
Hionic Fluor	71.4 ± 1.7	72.9 ± 1.7	73.6 ± 1.7	72.9 ± 1.7	67.7 ± 1.7	80.2 ± 1.8
Ultima Gold AB	73.5 ± 1.3	74.9 ± 1.4	73.3 ± 1.3	79.3 ± 1.4	80.3 ± 1.4	80.2 ± 1.4
Ultima Gold LLT	72.8 ± 1.3	74.1 ± 1.3	76.6 ± 1.4	79.4 ± 1.4	77.7 ± 1.4	79.7 ± 1.4
HiSafe 2	72.7 ± 1.7	71.1 ± 1.7	73.6 ± 1.7	76.6 ± 1.8	73.6 ± 1.7	75.6 ± 1.8
HiSafe 3	68.9 ± 1.7	67.9 ± 1.7	71.9 ± 1.7	72.9 ± 1.7	68.8 ± 1.7	73.7 ± 1.7

Table 5. Counting efficiency (%) of ^{14}C measurement in two kinds of vials: low-diffusion polyethylene (LD-PE) and high-performance glass (HP-G) vials with maximal quenching (120 µl CCl_4 addition) at various cocktail volumes

Cocktail	LD-PE			HP-G		
	5 cm^3	10 cm^3	15 cm^3	5 cm^3	10 cm^3	15 cm^3
Insta Fluor	5.3 ± 0.4	37.5 ± 1.0	55.4 ± 1.2	6.9 ± 0.4	40.6 ± 1.0	56.0 ± 1.2
Permablend	2.7 ± 0.3	34.2 ± 0.9	49.4 ± 1.1	4.9 ± 0.4	41.6 ± 1.0	56.2 ± 1.2
Butyl-PBD	28.8 ± 0.8	58.3 ± 1.2	60.6 ± 1.2	43.7 ± 1.0	68.3 ± 1.3	74.7 ± 1.4
Insta Gel Plus	10.8 ± 0.7	42.2 ± 1.1	61.0 ± 1.3	11.0 ± 0.5	44.9 ± 1.0	60.9 ± 1.2
Hionic Fluor	1.2 ± 0.2	18.4 ± 0.9	37.7 ± 1.2	1.3 ± 0.2	21.5 ± 0.9	49.2 ± 1.4
Ultima Gold AB	12.5 ± 0.6	40.8 ± 1.0	53.2 ± 1.0	11.8 ± 0.5	48.4 ± 1.1	62.1 ± 1.2
Ultima Gold LLT	10.5 ± 0.5	39.5 ± 1.0	55.5 ± 1.2	13.3 ± 0.6	43.5 ± 1.0	60.1 ± 1.2
HiSafe 2	8.0 ± 0.6	36.2 ± 1.2	52.9 ± 1.5	13.4 ± 0.7	39.0 ± 1.3	54.5 ± 1.5
HiSafe 3	8.1 ± 0.6	30.0 ± 1.1	45.7 ± 1.4	10.8 ± 0.7	36.4 ± 1.2	51.9 ± 1.5

The influence of the cocktail volume on counting efficiency of ^{14}C and tritium (for two kinds of vials) are presented in Tables 4–7. As an example, only two quench conditions are presented. Table 4 shows the ^{14}C measurement results without quench, and Table 5 the same isotope measurements, but with a maximum quench

Table 6. Counting efficiency (%) of ^{3}H measurement in two kinds of vials: low-diffusion polyethylene (LD-PE) and high-performance glass (HP-G) vials without quenching at various cocktail volumes

Cocktail	LD-PE			HP-G		
	5 cm^3	10 cm^3	15 cm^3	5 cm^3	10 cm^3	15 cm^3
Insta Fluor	13.0 ± 0.7	54.9 ± 1.4	53.8 ± 1.4	57.2 ± 1.5	59.6 ± 1.5	59.0 ± 1.5
Permablend	46.9 ± 1.3	52.5 ± 1.4	53.9 ± 1.4	56.7 ± 1.5	57.7 ± 1.5	57.1 ± 1.5
Butyl-PBD	44.6 ± 1.3	50.2 ± 1.4	51.2 ± 1.4	52.3 ± 1.4	52.5 ± 1.4	55.0 ± 1.5
Insta Gel Plus	36.0 ± 1.2	38.5 ± 1.2	28.8 ± 1.0	45.1 ± 1.3	45.6 ± 1.3	47.2 ± 1.4
Hionic Fluor	29.9 ± 1.1	33.2 ± 1.1	35.3 ± 1.2	36.6 ± 1.2	39.0 ± 1.2	38.1 ± 1.2
Ultima Gold AB	41.0 ± 1.3	42.4 ± 1.3	44.5 ± 1.3	45.9 ± 1.3	48.1 ± 1.4	47.4 ± 1.3
Ultima Gold LLT	37.0 ± 1.2	43.2 ± 1.3	43.7 ± 1.3	43.8 ± 1.3	45.0 ± 1.3	45.4 ± 1.3
HiSafe 2	39.7 ± 1.2	44.0 ± 1.3	46.8 ± 1.3	46.7 ± 1.3	49.1 ± 1.4	47.9 ± 1.4
HiSafe 3	30.2 ± 1.1	36.2 ± 1.2	36.2 ± 1.2	37.9 ± 1.2	38.9 ± 1.2	38.3 ± 1.2

Table 7. Counting efficiency (%) of ^{3}H measurement in two kinds of vials: low-diffusion polyethylene (LD-PE) and high--performance glass (HP-G) vials with maximal quenching (120 µl CCl_4 addition) at various cocktail volumes

Cocktail	LD-PE			HP-G		
	5 cm^3	10 cm^3	15 cm^3	5 cm^3	10 cm^3	15 cm^3
Insta Fluor	0.18 ± 0.1	6.45 ± 0.5	12.20 ± 0.7	1.40 ± 0.2	8.67 ± 0.6	15.30 ± 0.8
Permablend	0.62 ± 0.2	5.29 ± 0.4	10.90 ± 0.6	1.17 ± 0.2	7.57 ± 0.5	15.10 ± 0.8
Butyl-PBD	6.18 ± 0.5	18.00 ± 0.8	26.30 ± 1.0	2.84 ± 0.3	21.90 ± 0.9	30.30 ± 1.1
Insta Gel Plus	1.53 ± 0.2	7.41 ± 0.5	10.90 ± 0.6	2.47 ± 0.3	10.50 ± 0.6	18.50 ± 0.8
Hionic Fluor	0.38 ± 0.1	3.58 ± 0.4	8.49 ± 0.6	0.55 ± 0.2	3.80 ± 0.4	9.88 ± 0.6
Ultima Gold AB	2.33 ± 0.3	13.20 ± 0.7	25.80 ± 0.6	2.62 ± 0.3	13.60 ± 0.7	26.90 ± 1.0
Ultima Gold LLT	1.91 ± 0.3	12.60 ± 0.7	26.20 ± 1.0	2.98 ± 0.3	14.00 ± 0.7	25.00 ± 1.0
HiSafe 2	1.77 ± 0.3	13.70 ± 0.7	26.70 ± 1.0	2.65 ± 0.3	12.30 ± 0.7	26.30 ± 1.0
HiSafe 3	1.30 ± 0.2	11.00 ± 0.6	21.50 ± 0.9	2.60 ± 0.3	11.00 ± 0.6	22.80 ± 0.9

(caused by 120 µl CCl_4 additions to a scintillation vial). Results for tritium are presented in the same arrangement in Tables 6 and 7 (unquenched and maximally quenched), respectively.

As can be seen from Tables 4–7, counting efficiency (without quench) are not strongly dependent on the scintillation cocktail volume. In general, with increasing volume a slight increase in counting efficiency is observed, both for tritium and ^{14}C measurements. Larger variations are only seen during tritium measurement in LD-PE vials (without quench).

Differences between various cocktails are observed clearly. In Table 4 one can see that the highest efficiency during measurement of ^{14}C without quench was obtained with cocktails based on benzene-derived solvents (Insta Fluor, Permablend, butyl-PBD and Insta Gel Plus). The smallest efficiency revealed HiSafe 3, what is likely caused by a low concentration of scintillators: PPO and *bis*-MSB (see Table 1). The same is in the case of tritium measurements without quench (Table 6). The best efficiency was obtained using cocktails with benzene--derived solvents (Insta Fluor, Permablend and butyl--PBD). The worst counting conditions were found using the Hionic Fluor and HiSafe 3 cocktails. The first one has a complicated chemical composition and was created especially for using with solubilizers [5], the second contains too small concentration of scintillators.

Increased quench dramatically changes the efficiency, especially in the case of a small cocktail volume. This is connected with a higher concentration of the quench agent introduced into the scintillation vial. Tables 5 and 7 present the results with a maximum quench condition, i.e. after introducing 120 µl of CCl_4 into vials. In both cases the highest efficiency was obtained with butyl-PBD dissolved in benzene, and the lowest with Hionic Fluor.

Concluding the results presented in Tables 4–7, one can state that, in general, the best counting efficiency is ensured by cocktails based on benzene-derived solvents, especially butyl-PBD dissolved in pure benzene. Unfortunately, this cocktail can be used only for non-aqueous samples.

Values of quench parameter (SQP) in all the studied samples increased with increasing volume of cocktail. Typical relationships are presented in Figs. 1 and 2 for two cocktails: butyl-PBD (the most stable in relation to quench) and Hionic Fluor (the most sensitive to quench). As is it seen, the ideal "non-quenched" condition was not attained – the highest SQP value reaches 850 which corresponds with about 90% efficiency.

An important parameter which describes a measurement quality of liquid scintillation method is a figure of merit. It combines the information about the efficiency and background and is described by equation below:

$$FOM = \frac{(\text{Efficiency } [\%])^2}{\text{Background } [\text{cpm}]}$$

Calculated values of FOM are presented in Figs. 3 and 4 (results of ^{14}C measurements in LD-PE and HP-G scintillation vials, respectively), and in Figs. 5 and 6 (for tritium measurements in LD-PE and HP-G vials). The figures present also the influence of cocktail volume on FOM value. For better visualization, a vertical scales of Figs. 4 and 6 (referred to HP-G vials) were extended twice in comparison with Figs. 3 and 5, respectively.

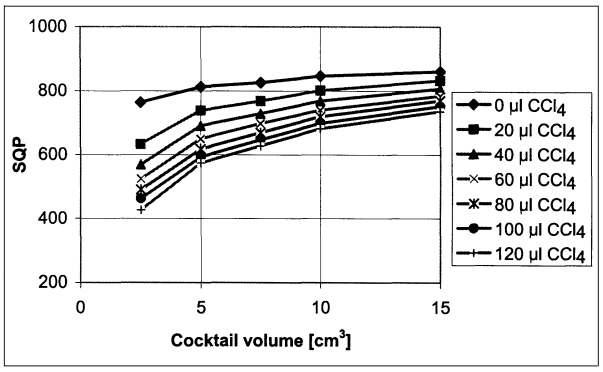

Fig. 1. The SQP vs. cocktail volume during tritium counting in the butyl-PBD cocktail (LD-PE vial) at various quench level made by CCl_4 addition.

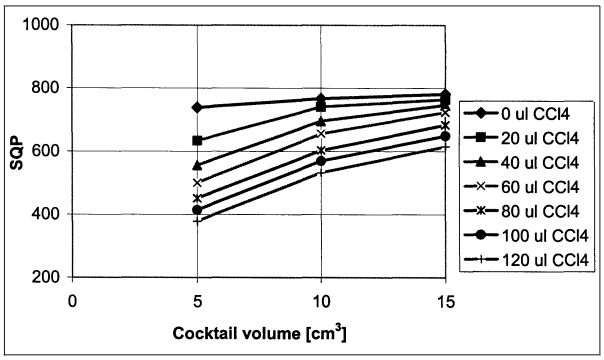

Fig. 2. The SQP vs. cocktail volume during tritium counting in the Hionic Fluor cocktail (LD-PE vial) at various quench level made by CCl_4 addition.

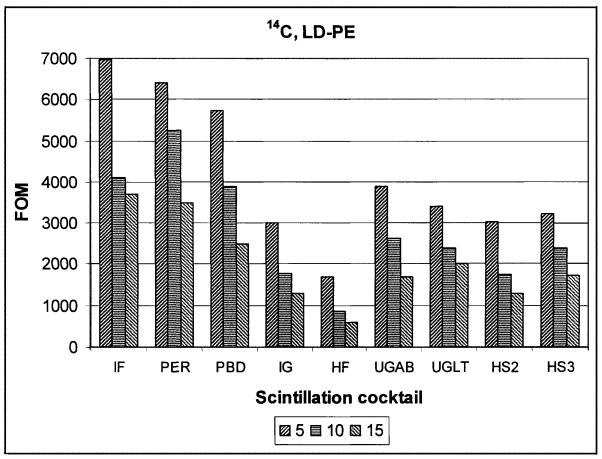

Fig. 3. The FOM values during ^{14}C measurements in LD-PE vials filled with 5, 10 and 15 cm^3 of cocktails: IF – Insta Fluor; PER – Permablend; PBD – butyl-PBD; IG – Insta Gel Plus; HF – Hionic Fluor; UGAB – Ultima Gold AB; UGLT – Ultima Gold LLT; HS2 – HiSafe 2; HS3 – HiSafe 3.

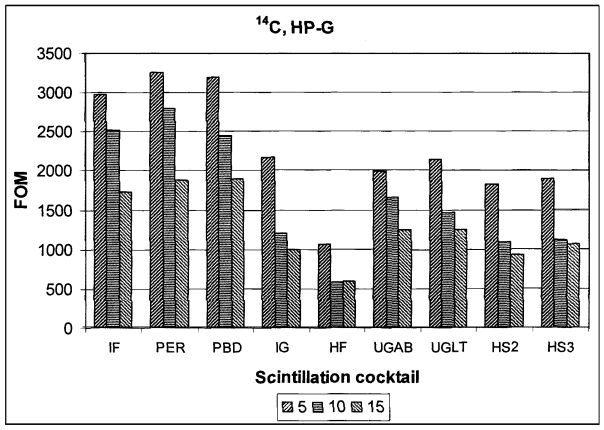

Fig. 4. The FOM values during ^{14}C measurements in HP-G vials filled with 5, 10 and 15 cm^3 of cocktails: IF – Insta Fluor; PER – Permablend; PBD – butyl-PBD; IG – Insta Gel Plus; HF – Hionic Fluor; UGAB – Ultima Gold AB; UGLT – Ultima Gold LLT; HS2 – HiSafe 2; HS3 –HiSafe 3.

It is interesting to notice that in each sample in the course of ^{14}C measurements (see Figs. 3 and 4) the FOM values diminish with increasing volume of cocktail. In this way, samples of 5 cm^3 volume reveal the highest FOM level. This is connected with a very low background value in this case. As it is seen from Table 2, increase in the cocktail volume from 5 to 15 cm^3 caused a 3 fold rise in background (in ^{14}C channel window). The values of FOM additionally confirmed that the best cocktails are those containing simple benzene-derived solvents as Permablend, Insta Fluor and butyl-PBD, which revealed the highest FOM value in both LD-PE and HP-G vials. The worst measurement conditions (the lowest FOM value) revealed Hionic Fluor (Figs. 3 and 4).

In the case of tritium, a volume dependence of FOM was not so distinctly visible (see Figs. 5 and 6). Only a half of the measured sample quantity demonstrated the highest FOM value. The smallest values of FOM were obtained in HP-G vials during tritium counting. This is a result of the very high background found in the tritium channel window using glass vials (see Table 3). Nevertheless, rather high FOM values found for tritium, measured in LD-PE vials, suggested that the best conditions can be obtained with Permablend and butyl-PBD cocktails. However, a very small FOM value observed in the case of Insta Fluor cocktail in LD-PE vial it is not understandable. This value correlates with a very small measurement efficiency found (see Table 6). A random error which resulted in an outlying value presence cannot be excluded.

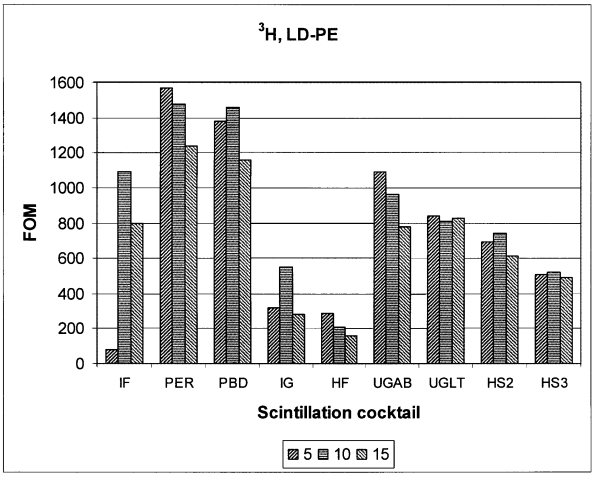

Fig. 5. The FOM values during ^{3}H measurements in LD-PE vials filled with 5, 10 and 15 cm^3 of cocktails: IF – Insta Fluor; PER – Permablend; PBD – butyl-PBD; IG – Insta Gel Plus; HF – Hionic Fluor; UGAB – Ultima Gold AB; UGLT – Ultima Gold LLT; HS2 – HiSafe 2; HS3 –HiSafe 3.

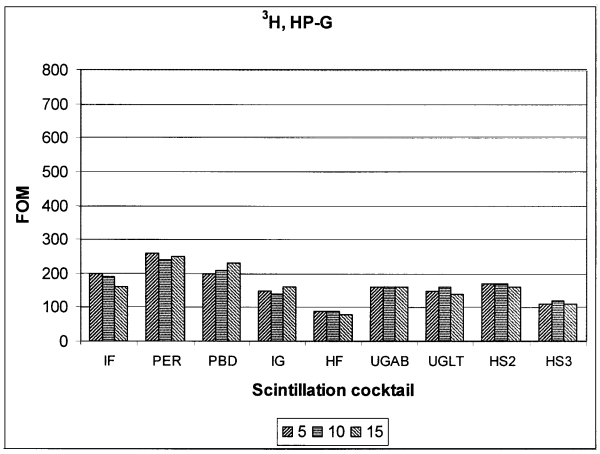

Fig. 6. The FOM values during ^{3}H measurements in HP-G vials filled with 5, 10 and 15 cm^3 of cocktails: IF – Insta Fluor; PER – Permablend; PBD – butyl-PBD; IG – Insta Gel Plus; HF – Hionic Fluor; UGAB – Ultima Gold AB; UGLT – Ultima Gold LLT; HS2 – HiSafe 2; HS3 – HiSafe 3.

Conclusions

It was found that the commercial scintillating cocktails reveal various quench sensitivity. The cocktail volume increase made increasing the counting efficiency and background as well. This causes diminishing the FOM values with increasing volume. The best cocktails for measuring ^{14}C and tritium are those based on benzene--derived solvent (especially butyl-PBD dissolved in pure benzene, Permablend dissolved in toluene and Insta Fluor). The worst cocktails are those which have complex chemical composition (as Hionic Fluor) or contain too small concentration of scintillators (as HiSafe 3).

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