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LEAKAGE FLUX, LIFE-TIME AND SPECTRA OF COLD NEUTRONS FROM H_2-MODERATORS WITH VARIOUS REFLECTORS

G. Bauer[1], H. Conrad[2], W. Fischer[3], K. Grünhagen[1] and H. Spitzer[2]

1) Projekt Spallationsneutronenquelle, KFA Jülich GmbH, D-5170 Jülich, FRG
2) Institut für Festkörperforschung, KFA Jülich GmbH, D-5170 Jülich, FRG
3) Schweizerisches Institut für Nuklearforschung, Villigen, Switzerland

Abstract

Results are presented of leakage flux, neutron life-time and spectra measurements of nine different cold hydrogen moderators (grooved and flat vessels of varying size) embedded in heavy water, graphite and lead reflectors respectively. Nearly no shape and size dependence of the leakage fluxes from the different vessels in a D_2O reflector was observed. Both graphite and lead reflectors yielded lower average fluxes than heavy water, but lead gave the highest peak flux value due to the shortest neutron life-time of that moderator-reflector combination. The neutron temperature was found to be about 80 K in almost all cases, therefore being much higher than the thermodynamic value. Correspondingly, lower gain factors than for deuterium cold sources will be expected.

1. Introduction

The measurements and results presented here are part of an experimental programme for optimizing the cold moderator of the German spallation source SNQ. Although according to the feasibility study (Bauer, 1981) and the project proposal (SNQ project staff, 1985) a liquid deuterium source is the design choice for one of the two moderators placed on both sides of the target wheel, we started our experiments with a comprehensive study of light hydrogen sources. Admittedly, on the one hand, hydrogen is known to give lower gain factors than deuterium sources. This is because of the higher neutron temperatures only obtainable due to strong cold neutron absorption. On the other hand, however, hydrogen sources are much smaller than deuterium sources. Therefore, higher peak flux values are expected as compared to large deuterium sources. This is due to the shorter neutron life-time in a small volume of high slowing-down density medium like liquid hydrogen. Furthermore, the technical problems (related to the large nuclear heat deposition in a 30ℓ deuterium containing vessel) are much less severe with a 0.5-ℓ-vessel for hydrogen.

As besides a high peak flux value the SNQ concept also requires the biggest possible time average flux, a high performance reflector tightly coupled to the cold moderator is inevitably necessary. Both large average flux and large peak flux may be contradictory demands, the reconciliation of which may finally be a matter of compromise. With respect to this problem we investigated three different reflector materials: D_2O, graphite and lead. The two moderating reflectors are expected to contribute essentially to the effective neutron life-time, consequently resulting in low peak flux values. Accordingly, the non-moderating lead reflector should yield a higher peak flux and presumably a lower time average flux.

The ultimate goal of this study, the first part of which is presented here, is the optimization of the cold source with respect to at least three parameters: gain factors for cold neutrons, time average flux and peak flux. Therefore the conclusions drawn in this paper from the hydrogen data may have to be revised on the basis of the results from the forthcoming deuterium experiments.

2. Experimental

The measurements have been performed with the 600 MeV protons at SIN (Swiss Institute for Nuclear Research), where since a couple of years an SNQ target-moderator-reflector mock-up has been utilized for basic neutronics experiments. The arrangement is depicted in Fig. 1. It mainly consists of a large rectangular tank (1.7 x 1.7 x 2.5 m^3) into which targets, moderators and reflectors are installed. The targets (Pb or ^{238}U) are placed on a table, which also serves as a support for the solid reflectors piled around the cold moderator chamber above the target. In the case of a D_2O-reflector the whole tank is flooded up to a level of 85 cm above the target midplane. For technical reasons the space below the target could not, according to the SNQ design, filled with lead and iron, representing the reflector of the ambient temperature moderator and part of the shielding. The neutron reflecting action of both these non-moderating materials was simulated in the present experiments by filling the tank with D_2O up to the lower target surface and decoupling the D_2O by a 0.1 cm Cd layer just below the target.

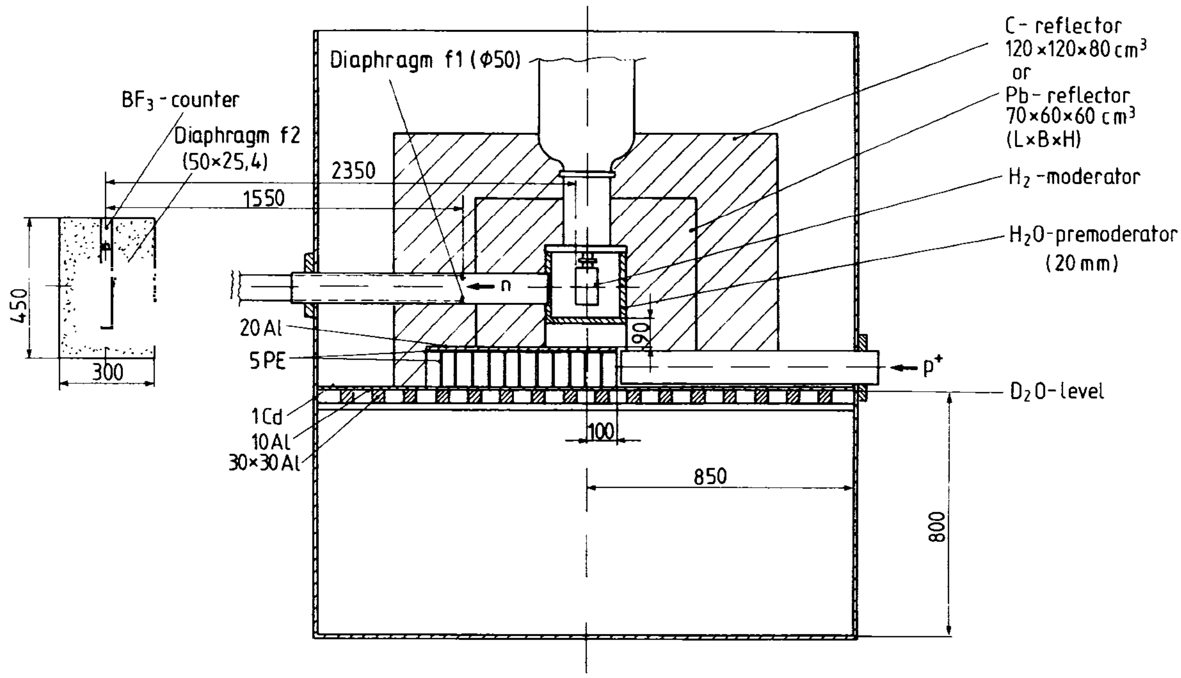

Fig. 1 Schematic representation of the experimental set-up
(For the sake of simplicity both carhon and lead reflectors are shown together. They were not used together in one measurement.)

The hydrogen has been liquified in situ employing the evaporation of liquid helium within a heat exchanger plate, which served as the common support onto which the different moderator chambers have been tightly attached. Each vessel was permanently connected to a surge tank ($V \approx 1\ m^3$) filled with gaseous hydrogen up to 2 bars. The pressure decrease during condensation has been used as a measure of the filling level of the cold chambers. Altogether four pairs of moderator vessels have been investigated. Each pair consisted of a flat and grooved vessel, both having the same volume and the same dimensions perpendicular to the neutron beam hole. Thus, the four pairs differed only in the "effective" thickness along the neutron beam direction, being equal to 2.5, 3.6, 5.6 and 7.8 cm respectively. In all but one case both the normal and the para-modification have been measured. The para-modification has been generated by submerging a Fe_2O_3 catalyst into the liquid hydrogen. The completed conversion has been determined by the vapour pressure increase in the isochorous system.

The neutron life-time in the cold moderators has been measured with a small boron-10-depleted BF_3 counter mounted on the vacuum container wall. This counter has been shielded against thermal neutrons from the reflector by a cadmium cover. The neutron counts have been stored time-dependently, the time-zero signal being generated by a pick-up unit on the proton chopper. The proton pulses had nearly triangular shape of about 250 µs FWHM. The cold neutron spectra have been recorded simultaneously with the life-time data, the latter being the "resolution" function for the former ones. The flight path used was the 235 cm long beam channel shown in Fig. 1. The leakage fluxes have been measured in the same configuration but with a continuous proton beam on target.

3. Data Evaluation and Results

3.1 Leakage Fluxes

The absolute values of the time average cold neutron fluxes have been deduced from measurements of the neutron current at the end of a beam hole of

Target	Moderator thickness [mm] f = flat g = grooved		time average cold neutron fluxes $\overline{\phi}_{sth}$ $[10^{14} cm^{-2} s^{-1}]$				
			Reflector				
			D_2O		C + premoderator		Pb + premod.
			hydrogen modification				
			n	p	n	p	n
Pb	25	f	3.2 ± 0.2	3.3	-	-	-
		g	3.3	-	-	-	-
Pb	36	f	3.1	3.0 ± 0.2	2.9 1.9(no premod.)	2.8	2.3
		g	3.4	3.4	3.0 2.8(refl.cooled)	-	2.2
Pb	56	f	2.9	3.0	-	-	-
		g	3.1	2.9	-	-	-
Pb	78	f	2.7	2.8	-	-	-
		g	3.1	2.9	-	-	-
Pb	96	f	3.0	-	2.5	2.5	2.2
^{238}U	36	f	-	5.8 ± 0.4	-	-	-

Table 1 Time average fluxes for various cold H_2-moderators in different reflector environments

known geometry. The neutron counting rates have been corrected for epithermal background (cadmium difference data), energy dependent detector efficiency and geometrical factors. By simultaneously counting the protons via a scintillator telescope viewing a scatterer in the proton beam, the absolute fluxes given in the Tab. 1 have been obtained by scaling the proton current to 10 mA. This corresponds to the SNQ design values of 5 mA at 1100 MeV.

The results from Table 1 obtained with the complete set of moderator vessels, filled with both normal and para hydrogen, and measured with the D_2O reflector are shown in Figure 2.

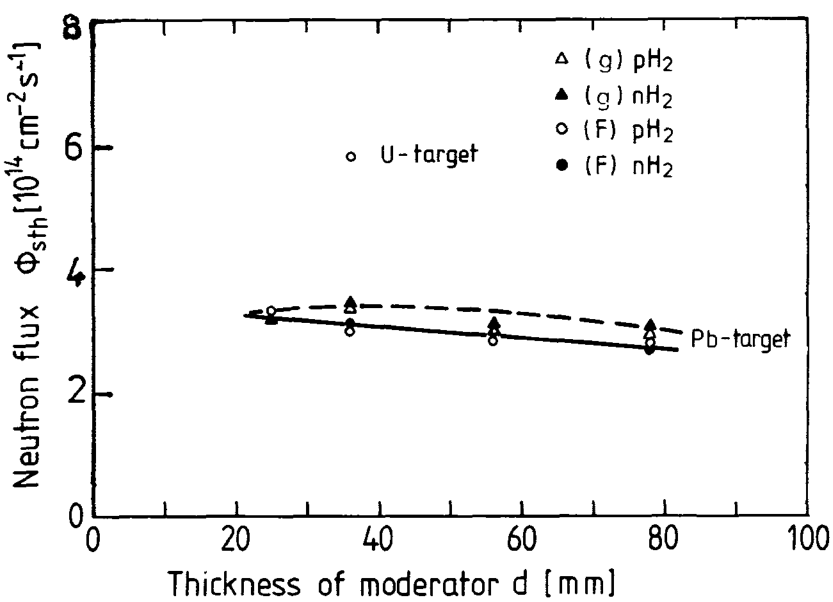

Fig. 2 Time average cold neutron fluxes (D_2O reflector) as a function of moderator thickness d. Full symbols denote normal hydrogen, open symbols the para modification. Circles stand for flat vessels, triangles for grooved ones. Data connected by guide lines for the eye have been obtained with a Pb target, the single data on top is for a ^{238}U target.

3.2 Life-times of cold neutrons in H_2 moderators in different reflector environments

The build-up and decay of the neutron field in the moderator has been measured with a small counter attached to the vacuum container as mentioned above. Although the time dependence of the overall neutron signal is determined both by the proton pulse shape and the decay constants of the moderator, the latter ones solely describe the signal shape for times greater than the proton pulse duration. From a semilogarithmic plot of the time signal the decay constants can be obtained without any deconvolution of the data. Figure 3 shows such plots for the "optimum" moderator in D_2O, graphite and lead reflectors respectively.

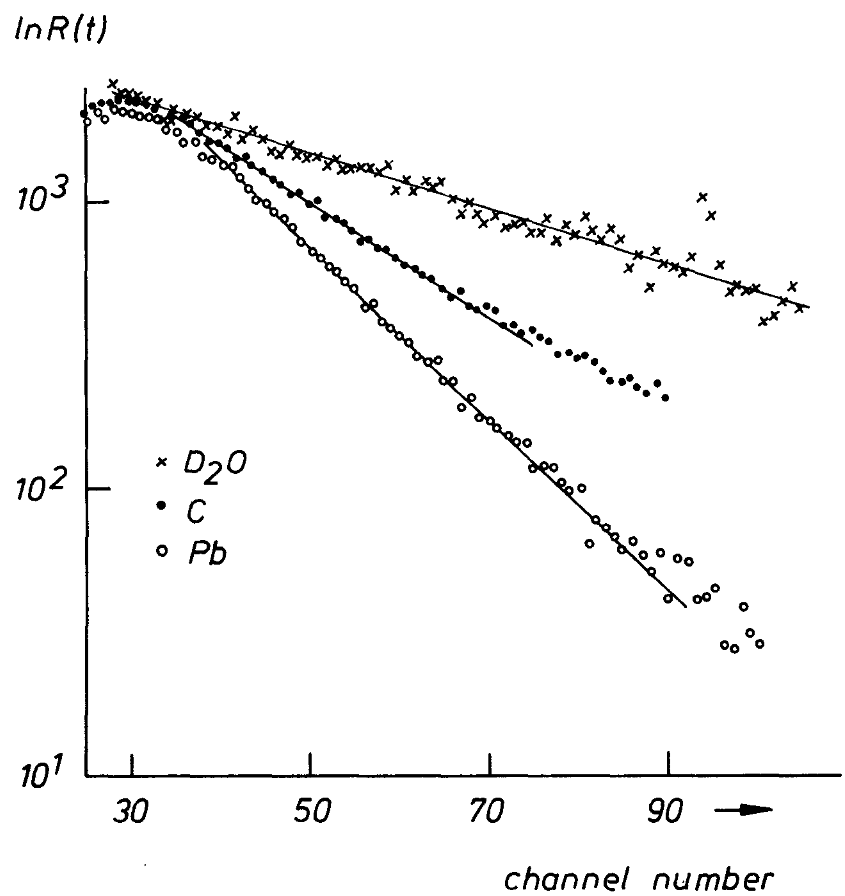

Fig. 3 Semilogarithmic plots of the time signal obtained for the optimum moderator in various reflector environments. (The channel width is 16 µs.)

The decay constants determined from the slopes of the semilogarithmic plots are (in units of microseconds):

710	for	D_2O
350	for	graphite
230	for	lead.

The consequences of these figures will be discussed in section 4.

3.3 Spectra and Neutron Temperatures

In order to deduce the neutron temperature from our measured time-of-flight spectra we proceeded in the following way. Firstly, we assumed that a Maxwellian velocity distribution is the proper description of the equilibrium part of the spectra and that the slowing-down process may be described by a simple $1/E^{1-\alpha}$ law. Secondly, we had to compute convolution-like integrals containing both the above expressions and the time signal from section 3.2 as the resolution finction for the Maxwellian as well as the proton pulse shape as the generating function of the slowing-down peak. In this step we also took into account both the unavoidable overlap contribution of the low velocity tail of the Maxwellian and a correction for detector efficiency. Thirdly, we fitted by a numerical procedure the resulting expression (eq. 1) to the experimental data.

$$I(t) = \int_{t_o}^{t} P(t')E(t-t')\varepsilon(t-t')dt' + \int_{o}^{t} R(t')M(t-t')\varepsilon(t-t')dt' + \int_{o}^{t_c} R(t')M(t + t_c - t')\varepsilon(t + t_c - t')dt' + B \qquad (1)$$

The notations are: proton signal P(t) with t_o as its starting time, the slowing-down spectrum E(t)

$$E(t)dt = E_o \cdot t^{-(1+2\alpha)} \, dt/(1 + 5^7(t/t_T)^{14})$$

where the denominator acts as a joining function to the Maxwellian. R(t) is the experimental resolution function for the Maxwellian, i.e. the time behaviour of the moderator neutron field measured during one chopper period t_c. The energy-dependent detector efficiency is denoted by $\varepsilon(t)$, a time-independent background by B. The third term of equation (1) describes the frame overlap from one previous chopper cycle. The Maxwellian assumes the form

$$M(t)dt = M_o \cdot t^{-5} \cdot \exp(- t_T^2/t^2) \cdot dt.$$

The fit parameters have been E_o, α, M_o, t_T and B. The neutron temperature T is given by the expression

$$T = 3.35 \cdot 10^{-4}(Ks^2) \cdot t_T^{-2}$$

In Table 2 is presented a compilation of selected neutron temperature data from various cold moderators in different reflecting environments.

Target	Moderator thickness [mm] and shape F = flat G = grooved		Effective neutron temperature T_N[K]							
			Reflector							
			D_2O				C + premoder.		Pb + premoder.	
			normal-H_2	para-H_2	moderator decoupled n-H_2	moderator decoupled p-H_2	n-H_2	p-H_2	n-H_2	p-H_2
Pb	25	F	94 ± 7	82 ± 5	-	-	-	-	67±18	68±24
		G	88 ± 6	-	-	-	-	-	-	-
Pb	36	F	82 ± 5	78 ± 5	-	-	76±5	-	72±7	-
		G	84 ± 6	-	54±9	53±11	81±6	-	81±8	-
Pb	56	F	76 ± 5	82 ± 4	58±7	-	-	-	-	-
		G	83 ± 6	87 ± 6	-	-	-	-	-	-
Pb	78	F	83 ± 5	81 ± 4	-	-	-	-	-	-
		G	79 ± 5	78 ± 5	57±7	53±7	-	-	-	-
Pb	96	F	-	-	-	-	73±4	72±4	-	-
^{238}U	36	F	-	-	-	-	-	-	-	79±5

Table 2 Selected results from the numerical determination of the neutron temperature

A typical set of experimental data, i.e. the proton signal, the time behaviour of the neutron field and a time-of-flight spectrum, the latter together with the fitted curve, is shown in Figure 4.

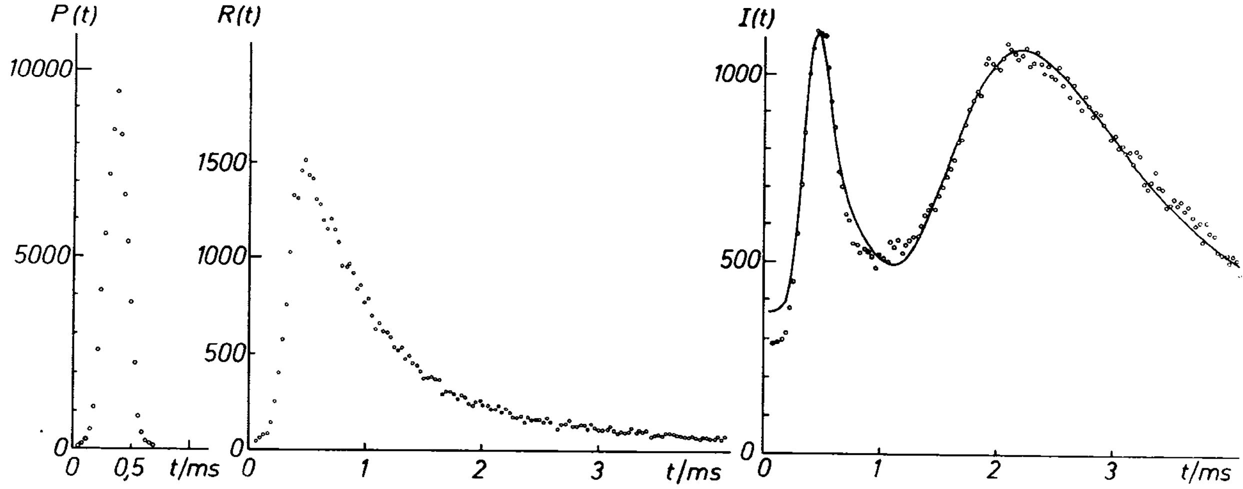

Fig. 4 Example of experimental proton signal, neutron time signal and time-of-flight spectrum with fitted theoretical curve. The corresponding neutron temperature is T = 78 ± 5 K. (para-H_2, vessel F36, D_2O reflector)

4. Discussion and conclusions

Surprisingly, the leakage flux values do neither depend significantly on hydrogen modification nor on moderator "thickness" (i.e. vessel dimension perpendicular to neutron beam) and shape. Apparently, gain factors of 2, as obtained with ambient temperature moderators with grooved survaces (Bauer et al. 1981) are missing with cryogenic moderators. A possible explanation might be the fin width of 1.3 cm, which was the same for all vessels and adapted to the about 60% longer scattering mean free path of slow neutrons in liquid hydrogen as compared to H_2O, but which nevertheless might be too large because of stronger absorption of cold neutrons. Absorption may also be the reason for the missing flux dependence upon vessel thickness. Obviously, the "radiating" depth of the H_2 moderator is only about 2.5 cm, the thickness of our smallest vessel, therefore the trivial vanishing of the flux with vanishing moderator volume could not be observed. With increasing vessel thickness no decrease is observed as the increased number of primary fast neutrons from the target intercepted by the moderator may be just cancelled by absorption of the slow neutrons. Only a weak, if any dependence at all on moderator thickness is expected for the para modification as observed. In this case absorption plays only a minor role as the "escape path" is much shorter due to the large scattering mean free path of about 8 cm.

An essential feature in optimizing both time average flux and peak flux is the action of a premoderator between cold moderator and reflector. For solid state reflectors, which potentially yield higher peak fluxes than D_2O, only the use of a premoderator (in our case a 2 cm layer of H_2O all around the cold vessel) gave comparable time average fluxes like D_2O. With graphite, for example, the gain in time average flux using a premoderator amounted to more than 50% (compare Table 1). Including the unavoidable losses due to the reflector coolant, the time average flux with graphite reflector plus premoderator is more than 80% of the D_2O value (compare Table 3 below). The highest peak flux has been obtained with the lead reflector, the time average flux in this case being about 65% of the D_2O-value. The summary Table 3 gives a concise compilation of the most essential results of the fluxes and neutron life-times and the deduced neutron pulse widths.

reflector material, dimensions [cm^3]	average cold flux $\overline{\phi}_{sth}$ [10^{14} $cm^{-2}s^{-1}$]	neutron life-time [$10^{-6}s$]	$\hat{\phi}/\overline{\phi}$	neutron pulse width [$10^{-6}s$] (for proton pulse duration of 250 μs)	peak flux $\hat{\phi}$ [$10^{14}cm^{-2}s^{-1}$]
D_2O 170x170x85	6.6 ± 0.4	710	12	620	79.
C (cooled) 120x120x80	5.4 ± 0.4	350	20	390	108.
Pb 60x60x60	4.3 ± 0.3	230	27	320	116.

Table 3 Results for a liquid H_2-source (11x11x3.5 cm^3) grooved, ^{238}U-target

Inspection of Table 3 shows that a gain in peak flux is paid for by a loss in time average flux and vice versa. It seems that the graphite reflector is a good compromise.

Let us finally discuss the results of the spectra measurements. The high neutron temperatures deduced from the time-of-flight data are at least qualitatively consistent with experimental results of wavelength-dependent gain factors of hydrogen sources (P. Ageron et al. 1969). A quantitative agreement can hardly be expected because the experiments are never performed in the sense of the definition of the gain factors, i.e. replacement of the cold moderator by an ambient temperature one. In an experiment the gain factors are determined by comparing the intensities of the filled, cold vessel with those of the empty one. Nevertheless, assuming a neutron temperature of 70 K (compare our results!) the experimental gain factors for a hydrogen source can be verified.

Whether this surprisingly high temperature is due to a spectral hardening because of absorption, or due to insufficient moderation or a combination of both, can only be clarified in a high resolution time-of-flight experiment. In such an experiment possible deviations from the Maxwellian could be observed. In the experiments planned for the study of deuterium sources, such high resolution measurements will be performed by chopping the neutron beam adequately. (In the present experiment we chopped the proton beam.) A very interesting phenomenon was observed by completely decoupling the cold moderator from the D_2O reflector: the neutron temperatures fell significantly below the values obtained in the undecoupled cases (compare Table 2). As the fluxes also decreased drastically (about an order of magnitude), thereby impressively demonstrating the importance of the reflector, this decoupling makes no sense as a means in lowering the effective neutron temperature.

References

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