Response to the comments of D. R. Blackman and Y. Peleg (*JRA* 14, 411-14)

Paul Kessener

The comments on my article (*JRA* 13, 104-32) by Blackman and Peleg, which are much appreciated, reflect prevailing discussions on Roman hydraulic engineering practices as well as on the relevant paragraphs of Vitruvius (8.6). Blackman focuses mainly on technical aspects, while Peleg aims at archaeological arguments.

Blackman starts with a discussion of the term 'siphon', which he regrets being used as it could lead to misunderstanding: 'siphon' would represent a "real" siphon, not an "inverted" siphon, suggesting that I must have meant that there was a real siphon at Aspendos. However, in archaeology 'siphon' is generally accepted to represent an inverted siphon.[1] There is no misunderstanding: at Aspendos we have an inverted siphon, and since real siphons are not known in classical aqueduct systems,[2] there is no objection to using 'siphon' and 'inverted siphon' for one and the same notion. Subsequently he states: "The presence of air pockets and so on is almost irrelevant to operations [of siphons] if no point in the system lies above the Hydraulic Gradient Line; were it not so, no garden hose would work reliably" This is a misconception. It is only due to the fact that our garden hoses are connected to supplies with elevated pressures that we get water from them. If we would connect the hose to a low-pressure source (e.g., to a rainwater container standing at ground level), we have to straighten out the coils before water will emerge. If the hose is coiled up, for example, on a wall support but positioned below the free water surface in the container to which it is connected, while we are holding the free end somewhere near the ground, we have nothing but an inverted siphon with high points. If air pockets are irrelevant, water should come out, but it does not if air is in the hose. For problems associated with air pockets in gravity-driven closed conduit systems (which classical siphons must be considered to be), see G. Corcos, *Air in water pipes* (1989) and H. T. Falvey, *Air-water flow in hydraulic structures* (1980).

Blackman adds to confusion by introducing a discussion on sub-atmospheric pressure conditions in pipe systems (para 2), which do not apply for classical conduits. Subsequently he argues that, for inverted siphons, air trapped at high points (which is the cause of a loss of pressure head driving the siphon, and which he implicitly acknowledges to occur) "will tend to be taken into solution", while "the confused internal flow at such point will be very efficient at entraining and so removing air". Indeed, some air may be dissolved into the water due to increased static pressure. But the absorption into water of, for instance, nitrogen gas (air is 80% nitrogen gas) is just 15.5 ml per liter of water of 20°C for each bar of pressure increase (C. H. Best and N. B. Tailor, *The physiological basis of medical practice* [1966] 967), and the gas will be released again as soon as the pressure diminishes, for example at a high point. Furthermore, an air pocket may be reduced in size due to entrainment of air by the flow away from the air pocket, but it may increase in size too because of air entrained at the header tank and transported to the high point. Both processes must be taken into account in order to see whether the air at high points will be purged out or not. Entrainment of air is a complicated process in which pipe slope, bubble size, conduit diameter, roughness of pipe interior, flow velocity, and viscosity of water are critical factors.[3] It may be shown that for the Madradag siphon at Pergamon the air pockets at the high points were purged out by the flow so that the siphon evolved to maximum capacity on its own; in contrast, the Yzeron siphon at Lyon would have come to a halt had the Craponne tower not been built to release the air (my article 125-26).

Further on (para 3) Blackman refers to internal roughness and to water hammer, which, as he says, are indeed separate subjects. His statements that significant roughness increases hydraulic loss and that cavita-

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1 A. T. Hodge, *Roman aqueducts and water supply* (London 1992) 147, and n.38: "By 'siphon' a classical archaeologist traditionally refers to what an engineer more strictly calls an 'inverted siphon' ... "

2 Only in one case has a real siphon from Roman times been claimed, the Barratina siphon at Termini Imerese (O. Belvedere, *L'acquedotto Cornelio di Termini Imerese* [Rome 1986] 115-27). This siphon presumably carried water to the city by means of a 1300-m lead piping passing over the top of an intermediate tower at the far side of a valley. The top of this tower rose more than 6 m above the Hydraulic Gradient Line. One wonders why the Roman engineers at Termini Imerese would have wanted to include a *constructed* intermediate high point, rising over 6 m above ground level, when they would have had no problems leaving it out. It seems more likely that the construction is related to the Figurella/ Favara aqueduct which ran nearby.

3 In a conduit sloping down, an air bubble will move with the flow if the velocity exceeds a specific critical value which is related to bubble size etc. The steeper the slope and the larger the bubble size, the less readily will the bubbles move with the flow. In certain conditions large air bubbles ('slugs') may move against the flow while small bubbles move with the flow (H. P. M. Kessener, "Vitruvius and the conveyance of water," *BABesch* 76 [2001] n.42).