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The effects of power station entrainment passage on three species of marine planktonic crustacean, *Acartia tonsa* (Copepoda), *Crangon crangon* (Decapoda) and *Homarus gammarus* (Decapoda)

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Abstract

Experiments have been undertaken exposing larval common shrimp (*Crangon crangon*) and lobster (*Homarus gammarus*) and adult copepods (*Acartia tonsa*) to the key stresses of entrainment within power-station cooling-water systems. The apparatus has enabled the testing of mechanical, thermal, chlorine and realistic pressure effects both alone and in combination, the range of stressors spanning the standard conditions found within a temperate coastal direct-cooled power station. Mechanical stresses affected only lobster larvae, pressure changes affected only the *Acartia* adults. Residual chlorine caused significant mortality of *Acartia* and shrimp larvae, but had no effect on lobster larvae even at 1 ppm. The temperature increment significantly affected all three species, with a synergistic effect on chlorine sensitivity in the shrimp larvae, but only temperatures higher than would be experienced in a normally-operating power station affected the copepods. The majority of individuals of each species would survive passage through a power-station system under normal conditions. It is notable that, within the species tested, generalizations from the responses of one species to those of another are not valid.

Keywords: Chlorine; Crustacea; Entrainment; Plankton; Power-station; Temperature

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1. Introduction

Thermal power stations use large quantities of cooling water for condensing the boiler steam, the water being passed through a system of condenser tubes. Coastal direct-cooled (“once-through”) stations may use of the order of 60 m^3 s^{-1} of cooling water for a 1800–2000 MWe station. This water is initially screened through filters of approximately 1 cm mesh to remove material which may otherwise block the condenser tubes. Subsequently the water, together with any material remaining within it, passes through the system, where it is subjected to changes of temperature and pressure. In addition, many stations introduce biocidal chemicals (commonly hypochlorite) to control biofouling of the cooling-water system, for example by mussels or by bacteria.

The passage of material within the water body through the power station cooling-water system is known as entrainment. Entrained material includes holoplanktonic organisms (permanent members of the plankton, such as copepods, diatoms and bacteria) and meroplanktonic organisms (temporary members of the plankton, such as juvenile shrimps and the planktonic eggs and larvae of invertebrates and fish).

In the past, the effects on planktonic organisms of entrainment passage, with its extremes of pressure, temperature and biocide concentration, have been studied at power stations, looking at the survival of those organisms available or detectable (e.g. Dempsey, 1988; Lawler, Matusky, & Skelly Engineers, 2001). Of necessity, such studies were only able to test those organisms which were serendipitously available, and then only the effects of the totality of entrainment, although Coughlan and Davis (1981, chap. 73) were able to vary the biocidal chlorine dosing levels in their study of entrained whole plankton at Fawley Power Station, UK.

Specific studies on the differential effects of entrainment stresses are undertaken more ideally under controlled laboratory conditions, allowing the guarantee of the presence of test organisms in adequate numbers, and the control of entrainment characteristics in order to determine more precisely which (if any) of these may be responsible for any deleterious effects.

Bamber, Seaby, Fleming, and Taylor (1994) described an entrainment mimic unit (EMU) apparatus designed to mimic realistically the conditions of entrainment passage through the cooling-water system of a coastal power station, under laboratory conditions. The apparatus allows the assessment of the effects of the four key stressors of entrainment—temperature, pressure, biocide and mechanical effects—alone and in combination. Their original experiments on larvae of the Pacific Oyster *Crassostrea gigas* (Thunberg, 1793) gave a baseline comparison of the technique to a standard bioassay technique (the D-stage larval test) and demonstrated the suitability of the apparatus and experimental protocols to assessment of impacts of power-station entrainment.

The present paper describes a series of experiments using the EMU to test the responses of three species of crustacean, one holoplanktonic and two meroplanktonic, to entrainment stresses.

2. Methods

The EMU apparatus has been described by Bamber et al. (1994). Its core is a condenser tube of 22.5 mm internal diameter and 16.77 m length, surrounded by a water jacket through which hot water may be passed in a counter-current. All water passage is "once-through" only.

The connecting pipework into and out of the condenser tube incorporates a series of mechanical and solenoid valves which are controlled by a computer, as are those valves allowing the delivery of the hot water to the jacket. This system allows the replication of a complex pressure profile: the computerized timing and sequence of valve operation, allied to the main water pump, mimics the pressure profile known or predicted for an actual power station, in this case a coastal direct-cooled Pressurized Water Reactor (PWR), involving

(i) the vertical drop from the sea surface to the intake culvert;
(ii) entrance to the power station intake forebay;
(iii) passage through the filter screen;
(iv) passage through the pump;
(v) passage through and vertical drop from the condenser tube; and
(vi) release from the outfall culvert.

Fig. 1 shows the pressure profile generated for the present experiments, with the above pressure changes marked.

The effects of antifouling hypochlorite were tested by introducing sodium hypochlorite (GPR, with 14% w/v available chlorine) at a test dose level to the entire volume of water used during an experimental run: the hypochlorite was added, mixed and flushed through the system prior to the introduction of the test organisms. Test levels of "chlorine" (TRO, see below) in the water were varied by the volume of hypochlorite added, actual requisite dose levels being determined empirically before each day's run using 10 l of stock sea-water, to allow for the variation in chlorine demand of the sea-water. The standard dosing level at UK power stations is designed to achieve 0.2 ppm at the condenser.

The effects of temperature increase were tested by pumping hot water through the water jacket at such a rate and temperature so as to produce desired realistic temperature increments across the condenser tube. The normal operating temperature increment (ΔT) at a power station in temperate waters is of the order of 10 °C.

Pressure within the EMU was measured by "SE Laboratories" pressure transducers, temperature of the inflowing and discharge waters by mercury thermometer, and levels of "chlorine" (as total residual oxidant, TRO: the result of the chemical reactions between halides on introduction of hypochlorite to sea-water) were measured 7 min after inoculation (i.e. at the time of entry to the condenser tube) using the Palin FAS-DPD procedure with Lovibond colorimetric determination (Mattice & Zittel, 1976; Tintometer Co., 1972).

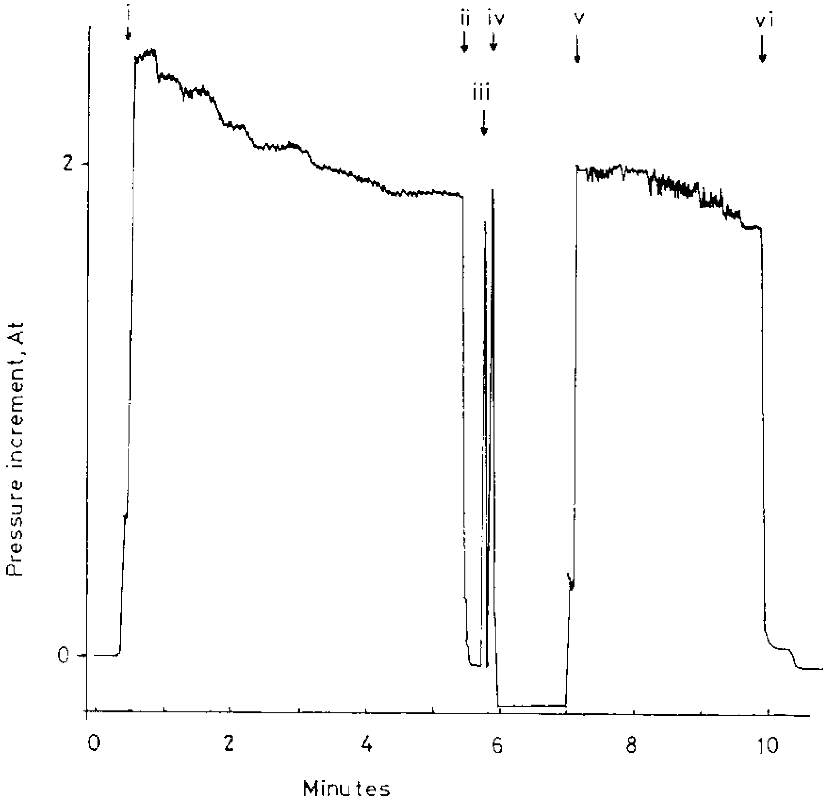

Fig. 1. Pressure profile mimicking conditions for a typical UK nuclear power station. Specific points in the cooling-water system are indicated by i–vi (see text).

All sea-water used for the experiments was pre-filtered through a gravel trap and a sand filter, and fully aerated. The salinity of the test water throughout was 34‰. Control water temperatures ranged from 15 to 18 °C. Control TRO levels were zero.

Test increments of temperature ranged from 0 to (exceptionally) 20 °C; normally actual water temperatures were constrained to 30 °C or below. Test increments of "chlorine" ranged from 0 to 1 ppm (although not for every species).

The mechanical effects of entrainment (physical abrasion, collisions, etc.) were an inherent feature of the apparatus and as such uncontrollable. Combinations of the other three stressors, either present or absent and, other than pressure, over a realistic range around the known standard operating levels for a temperate coastal power station, were available for testing.

The experimental protocol involved introduction of an aliquot of test organisms into a L-port valve before the apparatus had been pressurized. Here the organisms were subjected to the initial pressure changes and chlorine dose and decay (if used) until, at 7 min elapsed time, they were passed through the condenser and there subjected to the temperature increment (ΔT). The organisms were collected at the downstream end, exposed to the final phases of the pressure profile, and then removed with the test water. The entire volume of water used in each run was 60 l. The duration of a full passage run was 10 min, equivalent to the typical transit time at a UK coastal power station.

The test organisms were then held in the test water for a further 15 min to simulate downstream transport in an effluent plume, during which time the major reduction in temperature is caused by radiation to the air. They were then collected on a 95-μm mesh under water, and transferred to a 150 ml dish in fresh sea-water. They were counted under the microscope and examined for condition after 0, 6, 24 and 48 h (in ambient sea-water conditions of temperature, light, etc.) as appropriate to the results.

Two types of control experiment were run. Apparatus controls involved passing the test animals through the EMU without the pressure cycle, chlorine addition or temperature enhancement; these runs allowed the assessment of the potential mechanical stress of entrainment alone. Handling controls involved the dispersion of an aliquot of test animals in 60 l of sea-water, then retrieving them by the standard sieving procedure; these were used as the ultimate control animals.

The experiments were undertaken at Fawley Aquatic Research Laboratories, Hampshire, UK.

The planktonic stages of three species of crustacean were tested. The neritic copepod *Acartia tonsa* Dana, 1849 is an estuarine/marine species used as a standard test organism in ecotoxicological studies. Copepods not only represent the major crustacean group of the permanent plankton, they are also a significant component of the diet of planktivorous species, for example the commercially important clupeid fish. Adult *Acartia tonsa* were obtained from laboratory culture at Guernsey Sea Farms. The animals were 25–27 days old, having been cultured at 20 °C in water of 35‰ and fed on a diet of the algae *Skeletonema/Monochrysis*. The test stock was acclimatized to Fawley sea-water for 24 h, and fed ad libidum with *Monochrysis* throughout the experiments and the recovery periods. The copepods were introduced in batches of 20–30 at a time. They were counted and examined for condition, damage and mortality after 16 and 24 h; some batches examined after 48 h showed no change in mortality. A total of 36 experiments was run to cover replicates and ranges of stressor combinations.

The common shrimp, *Crangon crangon* (L., 1758), is a commercially important species in northwest Europe, predominantly within artisanal fisheries, and is the principal prey species for a number of fish, including the commercially important gadoids. Berried females were obtained from Sizewell Power Station, Suffolk, and maintained individually in tanks in sand-filtered sea-water (34‰ salinity); 60% of the water was exchanged daily. The adults were fed pelletized food every 4 days; there were no mortalities. Newly hatched larvae were removed by wide-mouthed pipette to a nursery tank, mixing the offspring of at least three females for each experimental series. Tests were undertaken on actively swimming larvae of 24–36 h old. Larvae were introduced into the apparatus in aliquots of approximately 20 per run. Damage and torpidity were observed immediately following a test run, and numbers of larvae either dead or alive were recorded after 24 and 48 h. A total of 32 experiments was undertaken.

The lobster, *Homarus gammarus* (L., 1758), is the prized subject of significant commercial fisheries in the UK and elsewhere in Europe. Larvae hatch in early spring/summer and spend 15–35 days in the plankton depending on the water temperature (e.g. Aiken, 1980, chap. 2). Berried female lobsters were obtained from off Plymouth under agreement with the then MAFF, and held at the Plymouth Marine Laboratory. Larvae were collected as they hatched and were transported under controlled ambient temperature to Fawley. The larvae were acclimatized to local sea-water for 24 h, and tested at 2–4 days old (including pre-rostrate and first-moult larvae, Stage 1 of Beard & McGregor, 1991). The larvae were introduced into the apparatus in aliquots of 12–15 at a time, and were subsequently examined for condition, damage and mortality after 15–24 h; some batches examined after 48 h showed no change in mortality. A total of 33 experiments was undertaken.

All test results were compared to control data by *t*-tests on arcsin-transformed data to test for significant deviation (percentage mortality); synergistic or antagonistic effects within combinations of stressors were elucidated by partial correlation analysis; generalization across combinations of stressors were enabled by bivariate spline interpolation of the data from all experiments (e.g. Meinguet, 1979).

3. Results

3.1. *Acartia tonsa*

The results of the tests on *Acartia tonsa* are shown in Table 1. There was a mean of 4.75% mortality in the handling control replicates. Other protocols were compared with these data, *t*-tests being applied to arcsin-transformed mortality data to determine significance. The apparatus controls exhibited fewer, but not

Table 1
Mean 24 h mortalities (±S.D.) of *Acartia tonsa* for exposures to pressure cycle, temperature (ΔT) and hypochlorite (TRO)

Pressure	ΔT (°C)	TRO (ppm)	Mortality
	Controls		4.75±3.02
Off	0	0	1.03±1.46
On	0	0	11.03±3.23*
Off	8.3–10	0	8.27±2.11
On	7.6–11.5	0	12.1±3.08*
Off	0	0.14–0.56	22.57±2.04*
On	0	0.13–0.70	31.22±28.13*
On	0	0.13–0.24	13.47±3.69*
Off	6.8–19.6	0.09–0.25	28.10±7.14*
Off	6.8–9.0	0.09–0.25	24.75±6.55*
On	10.7–11.8	0.16–0.24	23.87*±9.97*

[a] Mortalities significantly greater than controls (*t*-test, $P < 0.05$).

significantly different, mortalities than the handling controls, indicating no deleterious effect of the mechanical stresses of entrainment.

The pressure cycle alone caused a significantly greater mortality of the copepod, of the order of 11%.

Application of a ΔT of between 8.3 and 10 °C had no significant effects on the test animals. However, a ΔT of between 7.6 and 11.5 °C in combination with the pressure cycle resulted in significant mortalities which bore no relation to the ΔT level, of the order of 12%: these mortalities were attributed to the effects of the pressure stress alone.

All tests involving the application of hypochlorite, over a TRO range of 0.14–0.7 ppm, caused significant mortalities. The test at 0.7 ppm retrieved only seven animals, statistically an insufficient number; results in Table 1 are presented with and without this result, and subsequent analyses exclude it. Tests with hypochlorite and pressure or temperature showed no significantly different mortalities from those with hypochlorite lone.

All the above tests were run at actual exposure water temperatures of <28 °C. One test undertaken with an unrealistic ΔT of 19.6 °C (at 0.25 ppm TRO; actual exposure water temperature 34.6 °C) showed an increase in mortality of 13.5% over tests at the same TRO level with a ΔT of 9 °C, but was hardly greater than mortalities at 0.37 ppm TRO and a ΔT of 0 °C (35% versus 31%). This excessive ΔT was also excluded from the subsequent multivariate analyses.

Multiple correlation analyses apportioned 78.1% of the variance in mortalities to the TRO level and 4.5% to the pressure cycle, both being shown to be significant by partial correlation ($P<0.001$ and 0.025 respectively). Temperature enhancement showed no significant relationship to mortality even when the other stressors were partialled out. The far greater effect of TRO in comparison with the pressure cycle precluded any demonstration of synergistic effects; however, at TRO levels between 0.1 and 0.24 ppm, mean mortality was of the order of 13.5% without pressure stress; thus the combined mortality of the two, with no synergism or antagonism, would be of the order of 23%.

Fig. 2 plots predicted mortality contours in excess of controls against ΔT and TRO, generated by bivariate spline interpolation; the lowest contour is set at 10% mortality, approximating the mean mortality from tests with the pressure cycle alone. The effect of TRO in increasing mortality is evident. The plot predicts effectively 20% mortality under standard power station operating conditions, comparable with the combined TRO-pressure figure calculated above.

3.2. Crangon crangon

Results from the test on the common shrimp are shown in Table 2. Although all tests involving either TRO or ΔT showed increased mortality after 24 h when compared with the controls, none of the 24 h results was significant. The 48 h results only are discussed here.

There was no difference in mortality between apparatus control and handling control tests. Of 570 larvae tested, only two showed any damage which may be

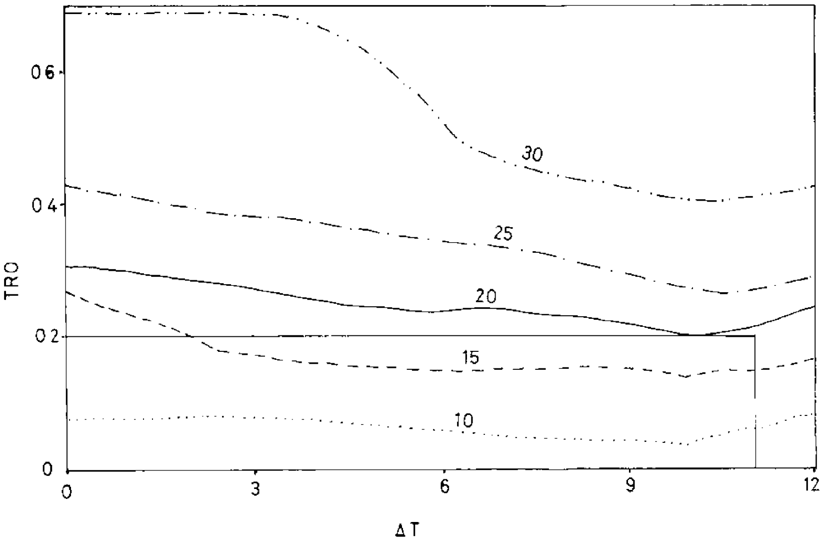

Fig. 2. Contour plot of percentage mortality of entrained *Acartia tonsa* in relation to ΔT (°C) and TRO (ppm), generated by bivariate spline interpolation. The bounds of conditions during typical power station operation are indicated.

Table 2
Mean 48 h mortalities (±S.D.) of larval *Crangon crangon* for exposures to pressure cycle, temperature (ΔT) and hypochlorite (TRO)

Pressure	ΔT (°C)	TRO (ppm)	Mortality
Off	0	0	1.35±1.34
On	0	0	3.39±3.09
Off	0	0.13–0.3	0
Off	0	0.53	38.44±9.88*
On	0	0.45–0.53	30.08±1.69*
Off	11.2	0	27.62±12.17
On	7.0–13.5	0	5.59±8.36
Off	10.6	0.5	34.03±6.89*
On	10.5	0.2–0.3	24.48±2.03
On	10.5	0.4–0.5	33.43±7.76*

* Mortalities significantly greater than controls (*t*-test, $P < 0.05$).

attributable to mechanical effects of passage through the apparatus. Neither ΔT nor the pressure cycle showed significantly greater mortalities than the controls either alone or in combination with each other. All the tests were run at actual exposure water temperatures of $\leqslant 29$ °C.

Of the experiments involving hypochlorite dosing alone, the only mortalities occurred at TRO levels of 0.4 ppm or above, and these mortalities were significantly greater than controls. All experiments involving combinations of other stressors and hypochlorite at levels at or above 0.4 ppm lead to significantly higher mortalities after 48 h.

As neither temperature nor pressure had shown direct effects on survival, their results were compared between all tests with TRO $\geqslant 0.4$ ppm and all tests with TRO $\leqslant 0.3$ ppm (there having been no intermediate levels); mortalities in the former series were significantly greater ($31.33 \pm 12.72\%$) than those in the latter series ($11.98 \pm 13.19\%$) ($t = 3.58$ for 21 df.; $P < 0.01$).

However, as it may be the case that the TRO effect is masking effects of the other stressors which might otherwise be indicated by the larger (total) data set, partial and multiple correlation analyses were conducted on the full data set. No effects of the pressure cycle were indicated. When effects of TRO were partialled out, a significant increase in mortality was demonstrated in relation to increasing ΔT ($F_{\mathrm{TRO}} = 17.32$, $P < 0.001$; $F_{\Delta T} = 8.58$, $P < 0.01$).

Fig. 3 shows a 3-dimensional surface plot of the predicted mortality values over the range of ΔT and TRO tested, generated by bivariate spline interpolation of the full experimental data set. The plot confirms the effect of increasing ΔT, with significant mortalities of shrimp larvae at any temperature increment with a TRO value > 0.3 ppm, this critical level falling to 0.1 ppm at ΔT values $\geqslant 8$ °C. The implication is that the higher ΔT levels increase the sensitivity of shrimp larvae to chlorine, resulting in their being adversely affected at lower TRO levels.

Fig. 4 plots contours of predicted mortality in excess of controls against ΔT and TRO concentration, derived from Fig. 3. While confirming the synergistic effects of

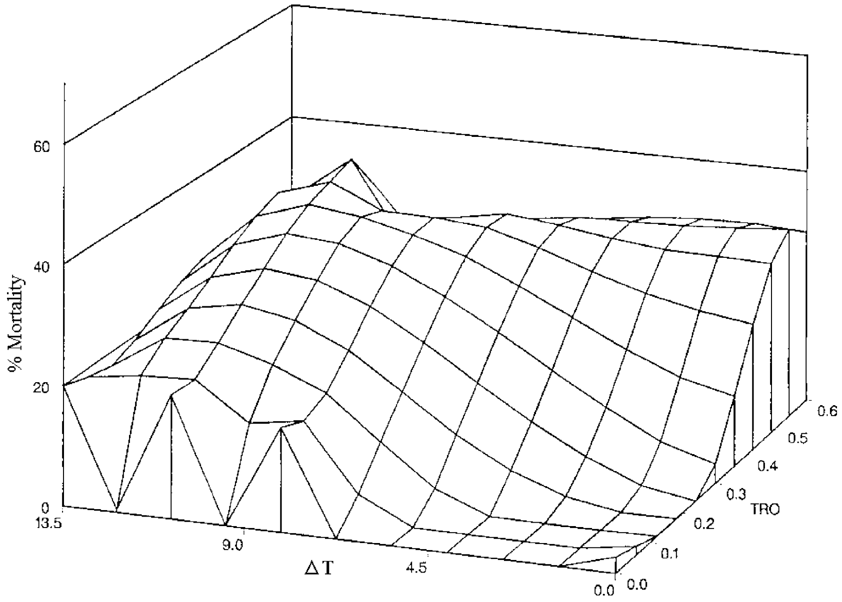

Fig. 3. Three-dimensional surface plot of mean 48 h mortality of *Crangon crangon* larvae in relation to ΔT (°C) and TRO (ppm), generated by bivariate spline interpolation.

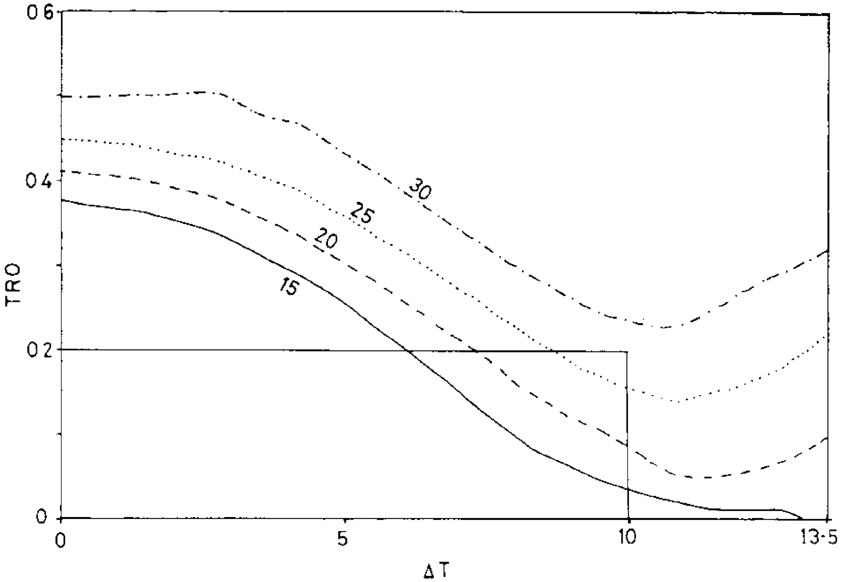

Fig. 4. Contour plot of percentage mortality of entrained *Crangon crangon* larvae in relation to ΔT (°C) and TRO (ppm), generated by bivariate spline interpolation. The bounds of conditions during typical power station operation are indicated.

temperature and TRO, the plot predicts an entrainment mortality of approximately 25% under standard power station operating conditions.

3.3. Homarus gammarus

The results from the experiments on lobster larvae are summarized in Table 3. No differences were demonstrated between survivals of pre-rostrate and of first-moult larvae, and they are hereafter considered together.

There was no mortality in the handling control replicates.

The apparatus controls exhibited a mean of 17.18% mortality, indicating a deleterious effect of the mechanical stresses of entrainment on the larvae. The most evident expression of this effect was the loss of all or part of the abdomen, observed in some 3% of tested larvae. Other experimental protocols were compared with these data, *t*-tests being applied to arcsin-transformed mortality data.

The pressure cycle alone caused no significantly different mortality of the larvae. Application of a ΔT of between 4.0 and 12.0 °C (actual exposure water temperatures of $\leqslant$30 °C) had no significant deleterious effects on the larvae, some of these tests resulting in 100% survival. Tests undertaken at more extreme temperature levels (ΔT 12.5–20 °C) resulted in significant mortality levels, of 25% at 12.5 °C up to 100% at $\geqslant$19.5 °C (actual exposure water temperature 37 °C). Gruffydd, Rieser, and Machin (1975) found the instantaneous median lethal temperature for *Homarus gammarus* to be 34 °C.

Table 3
Mean 24 h mortalities (±S.D.) of larval *Homarus gammarus* for exposures to pressure cycle, temperature (ΔT) and hypochlorite (TRO)

Pressure	ΔT (°C)	TRO (ppm)	Mortality
	Controls		0
Off	0	0	17.18±6.84
On	0	0	11.47±4.83
Off	4.0–12.0	0	5.82±5.38
Off	20.0	0	100*
On	8.0–11.0	0	13.4±9.69
Off	0	0.24–1.0	2.70±3.86
On	0	0.48–0.53	0
Off	4.5–9.3	0.11–0.53	5.8±4.11
Off	12.5–19.5	0.27–0.64	46.5±34.9*
On	9.7–10.0	0.24	13.25±2.15
Off or On[a]	0–12.0	0–0.63	7.69±7.26

[a] All experiments with $\Delta T < 12.5$ °C.

* Mortalities significantly greater than apparatus controls (*t*-test, $P < 0.05$).

All tests involving applications of hypochlorite over a TRO range of 0.11–1.0 ppm (five times normal operating level) caused no significant mortalities.

Partial multivariate analyses over the data set for stressor levels at or below normal power station operation conditions showed no significant effects other than mechanical. The mean effect of this parameter alone, taken from 28 tests undertaken with $\Delta T \leqslant 12$ °C, was a mortality of 7.69% (Table 3).

4. Discussion

All three species tested suffered some significant mortalities from the totality of entrainment passage, of the order of 10–20%, and thus in all three most individuals survived for at least 48 h. While there is much to be said for assessing survival over as long a period as possible, longer monitoring was considered impractical owing to the confounding factors of other stresses involved in maintaining numerous batches of planktonic organisms in artificial laboratory conditions.

The mechanical stresses of entrainment were only deleterious to lobster larvae, which suffered low but consistent mortalities owing to this factor alone. The sporadic incidence of abdominal damage was consistent with these comparatively large animals (ca. 9 mm total length) being susceptible to a small but real incidental risk resulting in “major” damage, while lesser stresses such as transient impacts during passage did not impair survival. While unquantifiable, it may be reasonably assumed that the mechanical/physical stresses present within the EMU apparatus will be less than in a power-station cooling-water system, although the latter may present larger volumes where no mechanical stresses occur. On the other hand, since 10 of the 28 tests run with ΔT levels below 12 °C resulted in 100% survival, a mean level of 8% mortality may be a reasonable approximation.

The pressure cycle, involving changes of up to 2 At (ca. 2×10^6 Pa), had no effect on lobster or shrimp larvae, but caused a significant mortality of copepod adults of the order of 11%. Coughlan and Davis (1981, chap. 73), working at various power station sites, found a calanoid 48 h mortality of 8.7% with no chlorination, which compares favourably with the present findings for the pressure cycle (*A. tonsa* showing no significant mortality in response to ΔT in the present studies, see below).

Levels of residual chlorine (TRO) caused a significant mortality of *Acartia tonsa*, with a mean of 13.5% mortality between 0.14 and 0.24 ppm, i.e. within the range of normal biocide-dosing at a coastal power station. *Homarus gammarus* larvae showed no adverse response to TRO even up to 1.0 ppm. In experiments involving no temperature enhancement, *Crangon crangon* larvae only suffered significant mortalities in response to TRO at unrealistically high levels of 0.4 ppm or above. However, as ΔT increased, so did the sensitivity to TRO, such that at a $\Delta T \geqslant 8$ °C significant mortalities occurred at 0.1 ppm TRO.

Other than this apparent synergism, no significant effect of ΔT on shrimp larvae was found. Temperature enhancement also had no significant adverse effects on *Acartia tonsa*, nor on lobster larvae at normal power-station operational levels, significant mortalities occurring in this species at ΔTs of $\geqslant 12.5$ °C (water temperatures > 30 °C).

Thus, in combination, the stresses of entrainment under standard power-station operating levels would result in approximately 20% mortality of *Acartia tonsa* (from pressure and TRO) and *Crangon crangon* larvae (from the combination of TRO and ΔT), and approximately 10% mortality of *Homarus gammarus* larvae from physical damage (Table 4).

Previous laboratory studies elsewhere on entrainment effects on crustacean plankton were insufficiently precise for valuable comparison. Poje, Riordan, and O'Connor (1981) undertook experiments on estuarine fish and arthropods using a condenser tube simulator. Their apparatus was unable to generate the complex pressure profiles characteristic of power-station cooling-water systems, as it relied on the water pump rates and the fixed head of water in the system as configured for each experiment. The only vaguely comparable crustaceans which they tested were oligohaline mysids (*Neomysis americana*) and amphipods (*Gammarus* spp.). These species showed median lethal temperatures within the range 33–38 °C. These species also showed high survival at TRO concentrations below 1.0 ppm.

Plankton studies at actual power stations have been undertaken in North America, where interpretation of the results was inhibited by the non-random dispersal of

Table 4
Summary of significant mortalities (%) in response to the stresses of entrainment

Species	Mechanical	Pressure	ΔT	TRO, ppm	net
Acartia tonsa	No	10%	No	0.14–0.25 14%	Pr + TRO = 20%
Homarus gammarus	8%	No	> 12.5 °C	No	~10%
Crangon crangon	No	No	No	only > 0.4 ppm	
Crangon crangon			> 8 °C enhances:	0.1 ppm	~20%

copepods in the water column. Carpenter, Peck, and Anderson (1974) looked at numbers of copepods (apparently including *Acartia tonsa*) at the intake and the discharge of the Millstone Nuclear Power Plant (Long Island Sound). From the lower numbers collected at the discharge they concluded that "about 70%" of copepods died as a result of mechanical or hydraulic stresses of entrainment. No difference in losses could be associated with levels of chlorine (up to 0.23 ppm at the intake), nor with ΔT (0–15.8 °C) nor discharge temperatures (4.9–32.8 °C). To what extent the "disappearance" of copepods between the sampling points is a measure of entrainment mortality is clearly debatable.

Similarly, Heinle (1976), sampling copepods (including *A. tonsa*) from three North American power plants, concluded that neither the mechanical effects of passage nor elevated temperatures (not clearly specified, but of the order of 5 °C ΔT leading to up to 33 °C at the discharge) caused significant mortalities of entrained copepods. However, "the use of chlorine … caused extensive mortalities"; chlorine levels ("continuous low-level") were apparently not measured. The author does highlight inconsistencies in the results, and that the difficulty in achieving even modest statistical confidence (of ±30% of the mean), poor replication and thus high variances resulting from attempts at field sampling at power stations mean that only "poor estimates with very wide confidence limits" can be achieved.

Coughlan and Davis (1981, chap. 73), in their in situ studies, found no effects of ΔT or mechanical stresses on calanoid copepods. They did record mortalities of between 4 and 10% after 1 hour with chlorination (later mortalities not being measured). Studies at Fawley Power Station, UK (Davis & Coughlan, 1978, chap. 28) found mortalities of 22% of adult copepods 48 h after entrainment at TRO levels up to 0.25 ppm; their samples included calanoids and harpacticoids, and the potential different sensitivity of these two taxa is unknown. However, these data, together with their finding of 8.7% mortality attributable to pressure mentioned earlier, are consistent with the results found here for *Acartia tonsa*, which may be considered representative of calanoid copepod responses to entrainment stress.

Generally, however, the field studies tend rather to highlight the necessity for undertaking controlled laboratory experiments in order to gain a valid insight into the effects of entrainment passage on planktonic organisms.

Unfortunately, the results of the present series of experiments on crustaceans demonstrate their different responses to the different stressors, thus inhibiting generalizations on the effects of entrainment on plankton other than the opening sentence of this discussion.

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