Hart, J. L. and MacKernan, D. L. (1969). International Passamaquoddy Fisheries Board Fisheries Investigations 1956–59: Introductory account. *J. Fish. Res. Bd Can.*, 17, 127–131.

1931/33; (2), 1–40.

Trites, R. W. (1961). Probable effects of proposed Passamaquoddy power project on oceanographic conditions. *J. Fish. Res. Bd Can.*, 18, 163–201.

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REPORTS

The Effect of Temperature on the Toxicity of Chlorinated Cooling Waters to Marine Animals—A Preliminary Review

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The effect of temperature on the toxicity of free chlorine and chloramine to several species of marine animals is reviewed. For all species tested, except the copepod *Acartia tonsa*, temperature has a synergistic effect on the toxicity of both halogen forms. It is suggested that the effect of temperature in enhancing the toxic effects of chlorinated cooling waters to marine animals is due to an interaction of uptake rates and regulation of physiological rates and the greatest enhancement in sensitivity could be expected at the upper limit of a species' thermal tolerance.

Temperature is an important factor in the control of both physiological rates and ecological distribution of marine poikilothermic animals (Wieser, 1973). With the increasing number of power generating stations in coastal environments and the discharge of thermal effluents into receiving waters, temperature may become a stress factor and may act synergistically with other environmental stresses in limiting the tolerance zone of marine animals. Cairns *et al.* (1975) reviewed the literature concerning the effects of temperature on the toxicity of several chemicals to aquatic organisms. They suggested that if a chemical toxicant affected cellular enzymes involved in energy metabolism or caused a change in respiratory activity, then toxicant exposure combined with an increase in temperature may result in increased uptake and enhanced toxic effects in aquatic organisms.

The use of chlorine for fouling control at coastal power stations necessitates concern for the combined effects of temperature and chlorine to marine animals. Organisms small enough to become entrained in cooling waters or those residing in receiving waters may be exposed to simultaneous thermal and chemical shocks. The problem is further complicated by the reactivity of chlorine with several constituents of seawater, resulting in the production of halogen toxicants in addition to free chlorine ($HOCl$, OCl^-) including free bromine ($HOBr$, OBr^-; Wong & Davidson, 1977), monochloramine ($ClNH_2$; Johannesson, 1958) and organohalogen compounds (Jolley, 1975). The toxicants produced are dependent on the nature of the receiving waters; in seawater with low ammonia and organic concentrations, free bromine would be the dominant toxicant; whereas, in receiving waters with high ammonia and organic concentrations, there would be a significant production of chloramine and organohalogen compounds.

Many authors have shown chlorinated cooling waters to be toxic to many species of marine animals (see reviews by Brungs, 1976; Davis & Middaugh, 1976; Whitehouse, 1975); however, the effect of temperature on toxicity has not been clearly defined. This report is a preliminary review of the problem of temperature-chlorine toxicity based on data obtained in this study and from other published reports.

Methods

All bioassays conducted in this laboratory were carried out in a continuous flow assay system, where simultaneous toxicant and temperature shocks could be delivered for a designated exposure period. The toxicant, added as free chlorine ($NaOCl$) or chloramine ($ClNH_2$), and seawater were added separately to each assay unit by peristaltic pumping. After a 30 or 60 min exposure period, the toxicant was removed from solution by the addition of sodium thiosulfate and the temperature was reduced to the acclimation temperature for each organism. The exposure time to chlorinated cooling waters experienced by an organism in field conditions is dependent on the time of passage through the condensers, the chlorination schedule of the power plant in question and the time of discharge to receiving waters. Exposure times may vary from several minutes to several hours and the 30–60 min exposure period used in this study is a conservative estimate of field conditions.

Residual toxicant levels were measured by amperometric titration prior to the addition of test organisms to the assay units. A linear relationship of applied and residual levels of both toxicants was established:

$$Y\,(\text{residual}) = 0.18\,X\,(\text{applied}) - 0.04;\ r = 0.88.$$

Mortality was assessed 48 h after exposure and LC_{50} values were estimated by log-probit analysis according to the methods described by Finney (1971). All species tested were acclimated to laboratory conditions at the designated acclimation temperature before use in the assays. Although not fed during the exposure period, all animals were fed daily during the remainder of the experimental period. A more detailed account of the bioassay procedure is reported elsewhere (Capuzzo *et al.*, 1976).

Results and Discussion

A summary of the LC_{50} and LC_{100} values for each species tested at the various toxicant-temperature conditions is presented in Table 1; included are values fro other published studies. Because of the differences in toxicant sensitivity, the invertebrate species (*Acartia*, *Brachionus*, *Crassostrea* and *Homarus*) will be discussed separately from the fish species (*Fundulus* and the two species of *Oncorhynchus*). The four invertebrate species were more sensitive to chloramine than the free halogen form; a gradual increase in mortality was observed over a wide range of applied halogen levels as indicated by the differences in LC_{50} and LC_{100} values. Larvae of the American oyster *Crassostrea virginica* were the most sensitive of the species tested, followed by the rotifer *Brachionus plicatilis*, the copepod *Acartia tonsa*, and larvae of the American lobster *Homarus americanus*. For all species tested, except *A. tonsa*, temperature had a synergistic effect on the toxicity of both halogen forms. Control mortality for all species at the various exposure temperatures was <10%, except

TABLE 1

Summary of LC_{50} and LC_{100} values at various temperature-toxicant stresses.

Species	T – °C* A	E	Exposure time min	Toxicant	LC_{50} †	LC_{100} †
Acartia tonsa	10.0	10.0	30	free chlorine	0.82 ± 0.02	3.56 ± 0.10
(this study)		15.0	30	free chlorine	0.82 ± 0.02	3.56 ± 0.10
		20.0	30	free chlorine	0.82 ± 0.02	3.56 ± 0.10
	20.0	20.0	30	free chlorine	0.82 ± 0.02	3.50 ± 0.10
		25.0	30	free chlorine	0.86 ± 0.02	3.60 ± 0.10
		28.0	30	free chlorine	0.82 ± 0.02	3.50 ± 0.10
	10.0	10.0	30	chloramine	0.34 ± 0.02	1.22 ± 0.05
		15.0	30	chloramine	0.23 ± 0.02	1.05 ± 0.05
		20.0	30	chloramine	0.23 ± 0.02	1.05 ± 0.05
	20.0	20.0	30	chloramine	0.32 ± 0.02	1.15 ± 0.05
		25.0	30	chloramine	0.32 ± 0.02	1.15 ± 0.05
		28.0	30	chloramine	0.32 ± 0.02	1.15 ± 0.05
Brachionus plicatilis	20.0	20.0	30	free chlorine	0.18 ± 0.02	1.76 ± 0.02
(this study)		25.0	30	free chlorine	0.09 ± 0.01	0.52 ± 0.02
		27.5	30	free chlorine	0.01 ± –	0.46 ± 0.01
	20.0	20.0	30	chloramine	0.02 ± –	0.82 ± 0.02
		25.0	30	chloramine	<0.01	0.50 ± 0.02
		27.5	30	chloramine	–	0.19 ± 0.02
Crassostrea virginica	20.0	20.0	30	free chlorine	0.12 ± –	1.40 ± 0.05
7 day larvae (this study)		25.0	30	free chlorine	0.08 ± –	0.86 ± 0.02
	20.0	20.0	30	chloramine	0.01 ± –	0.48 ± 0.02
		25.0	30	chloramine	<0.01	0.16 ± 0.01
Fundulus heteroclitus juveniles	25.0	25.0	30	free chlorine	–	0.65 ± 0.02
(Capuzzo *et al.*, 1977)		30.0	30	free chlorine	–	0.25 ± 0.02
	25.0	25.0	30	chloramine	–	1.20 ± 0.05
		30.0	30	chloramine	–	0.85 ± 0.02
Homarus americanus Stage I larvae	20.0	20.0	60	free chlorine	–	–
(Capuzzo *et al.*, 1976)		25.0	60	free chlorine	2.90 ± 0.10	9.00 ± 0.20
		30.0	60	free chlorine	0.41 ± 0.02	1.60 ± 0.05
	20.0	20.0	60	chloramine	0.69 ± 0.05	1.40 ± 0.05
		25.0	60	chloramine	0.32 ± 0.05	0.90 ± 0.05
		30.0	60	chloramine	0.06 ± 0.01	0.65 ± 0.05
Oncorhynchus gorbuscha	13.6	13.6	30	free chlorine	0.25 ± –	–
(Stober & Hanson, 1974)	12.4	17.4	30	free chlorine	0.10 ± –	–
	12.4	22.3	30	free chlorine	0.10 ± –	–
Oncorhynchus tshawytscha	11.7	11.7	30	free chlorine	0.25 ± –	–
(Stober & Hanson, 1974)	11.7	16.6	30	free chlorine	0.10 ± –	–
	11.6	21.6	30	free chlorine	0.05 ± –	–

* A = acclimation temperature; E = exposure temperature.
† mg/l total residual chlorine.

mortality equalled 30% and 40%, respectively.

Fundulus heteroclitus was more susceptible to the free halogen form than chloramine at both 25° and 30°C and responded to both toxicants in a step or threshold fashion, i.e., mortality was observed over a narrow range of concentrations and therefore only LC_{100} values are reported. In the study of Stober & Hanson (1974), pink salmon (*Oncorhynchus gorbuscha*) and chinook salmon (*O. tshawytscha*) were only exposed to free chlorine and only LC_{50} values were reported. In both studies the synergistic effect of temperature was again noted. No mortality of control animals was detected.

The exceptional response of *A. tonsa* may be explained by its unique response to temperature. Gonzalez (1974) suggested that its eurythermal adaptation (−1° to +32°C) was manifested in the shifting of lethal limits, reproduction and metabolic activities, allowing this species to tolerate a wide range of thermal stresses. The regulation of physiological rates in response to the exposure temperature may be a factor in preventing increased susceptibility of *A. tonsa* to chlorinated cooling waters at higher exposure temperatures.

The specific mechanisms of toxic action of chlorine and chloramine to marine animals has not been identified. Exposure to chlorinated cooling waters results in reduced oxygen consumption and growth of larval lobsters (Capuzzo *et al.*, 1976; Capuzzo, 1977), reduced feeding and egg production in rotifers and copepods (unpublished results), and reduced oxygen consumption and gill damage in marine fish (Capuzzo *et al.*, 1977; Davis & Middaugh, 1976). It is apparent that both toxicants interfere with energy metabolism in all invertebrate species tested as indicated by the reductions in reproduction and growth following exposure; however, the reduced respiration rates of fish following exposure to the toxicants may be due to either a reduction in energy metabolism or gill damage or a combination of both. The effect of temperature in enhancing these toxic effects is possibly due to an interaction of uptake rates and regulation of physiological rates and the greatest enhancement in sensitivity could be expected at the of physiological changes associated with the various temperature-toxicant stresses should lead to a greater understanding of the toxic action of chlorinated cooling waters to marine animals.

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Brungs, W. A. (1976). Effects of wastewater and cooling water chlorination on aquatic life. U.S. Environmental Protection Agency, Ecological Research Series. EPA 600/3-76-098.

Cairns, J., Heath, A. G. & Parker, B. D. (1975). The effects of temperature upon the toxicity of chemicals to aquatic organisms. *Hydrobiologia*, 47, 135–171.

Capuzzo, J. M., Lawrence, S. A. & Davidson, J. A. (1976). Combined toxicity of free chlorine, chloramine and temperature to stage I larvae of the American lobster *Homarus americanus*. *Water Res.*, **10**, 1093–1099.

Capuzzo, J. M. (1977). The effects of free chlorine and chloramine on growth and respiration rates of larval lobsters (*Homarus americanus*). *Water Res.*, **11**, 1021–1024.

Capuzzo, J. M., Davidson, J. A., Lawrence, S. A. & Libni, M. (1977). The differential effects of free and combined chlorine on juvenile marine fish. *Estuar. Coast. Mar. Sci.*, **5**, 733–741.

Davis, W. P. & Middaugh, D. P. (1976). A review of the impact of chlorination processes upon marine ecosystems. In *The Environmental Impact of Water Chlorination, Proceedings*, R.L. Jolley (ed.). Oak Ridge National Laboratory, Oak Ridge, Tennessee. pp. 299–325.

Finney, D. J. (1971). *Probit Analysis*, 3rd edition. Cambridge University Press, Cambridge.

Gonzalez, J. G. (1974). Critical thermal maxima and upper lethal temperatures for the calanoid copepods *Acartia tonsa* and *A. clausi*. *Mar. Biol.*, **27**, 219–223.

Johannesson, J. K. (1958). The determination of monobromamine and monochloramine in water. *The Analyst*, **83**, 155–159.

Jolley, R. L. (1975). Chlorine containing organic constituents in chlorinated effluents. *J. Wat. Pollut. Control Fed.*, **47**, 601–618.

Stober, Q. J. & Hanson, C. H. (1974). Toxocity of chlorine and heat to pink (*Oncorhynchus gorbuscha*) and chinook salmon (*O. tshwaytscha*). *Trans. Am. Fish. Soc.*, **103**, 569–576.

Whitehouse, J. W. (1975). Chlorination of cooling water: A review of literature on the effects of chlorine on aquatic organisms. Central Electricty Research Laboratories, Laboratory Memorandum No. RD/L/M 496, Leatherhead, England.

Wieser, W. (1973). Temperature relations of ectotherms: A speculative view. In *Effects of Temperature on Ectothermic Organisms*, W. Wieser, (ed.). Springer-Verlag, Berlin. pp. 1–23.

Wong, G. T. F. & Davidson, J. A. (1977). The fate of chlorine in seawater. *Water Res.*, **11**, 971–978.