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Reductions in Ichthyoplankton Entrainment with Fine-Mesh, Wedge-Wire Screens

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Abstract.—The exclusion efficiency of cylindrical wedge-wire screens was investigated at the Chalk Point Steam Electric Station in Aquasco, Maryland, by measuring entrainment of larval bay anchovies *Anchoa mitchilli* and naked gobies *Gobiosoma bosci* through screens with slot sizes of 1, 2, and 3 mm and through an unscreened intake. The degree of exclusion by the screens increased with fish size. Fish less than 5 mm long were not excluded by any of the screens. In contrast, more than 80% of larger ichthyoplankton were excluded by all screens. Virtually no ichthyoplankton larger than 10 mm were entrained through the 1-mm screen even when fish of this size were abundant and were entrained through the unscreened intake. The 2-mm and 3-mm-slot screens were not as effective at excluding ichthyoplankton as the 1-mm screen, but the effect of slot size on exclusion efficiency was small relative to the effect of fish size. These results suggest that entrainment through water intake structures can be successfully reduced by wedge-wire screens if the larval fish at risk exceed 5 mm in length.

Impingement and entrainment losses at water intake facilities potentially can distort aquatic communities. Considerable research has been devoted towards identifying ecologically sound and cost-effective intake structures to reduce these effects (Fletcher 1985). Wedge-wire screens (also referred to as profile wire screens or Johnson screens) are one such promising structure. These screens are constructed of V-shaped wire in a cylindrical configuration (Figure 1), typically designed with a through-slot velocity of less than 0.15 cm/s. In situ observations have shown that wedge-wire screens virtually eliminate impingement (Hanson et al. 1978; Lifton 1979; Browne et al. 1981; Great Lakes Research Division 1982). Laboratory (Heuer and Tomljanovich 1978; Hanson 1981) and field studies (Lifton 1979; Delmarva Ecological Laboratory 1980; Browne et al. 1981; Zeitoun et al. 1981) have shown that these screens can also substantially reduce ichthyoplankton entrainment.

Despite apparent success of these screens in reducing ichthyoplankton entrainment in a variety of environments, the degree to which they exclude organisms has been inconsistent among studies. For selected fish species, some studies have even found no significant difference in entrainment through wedge-wire screens and through an unscreened intake pipe (Browne et al. 1981; Zeitoun et al. 1981). The apparent inconsistency in effectiveness among studies may have resulted because of differences in screen mesh size among studies. Alternatively, it may have resulted because the relationship between entrainment and fish size has been considered in only a few tests of wedge-wire screens. No study has examined how fish size and screen slot size interact to determine exclusion efficiency.

Wedge-wire screens already have been installed at a number of intake facilities and are being considered for application at many others. A better understanding of factors that affect the screen's efficiency should result in more effective application of the technology. In this study, we measured entrainment rates through 1, 2, and 3-mm wedge-wire screens and through an unscreened intake to determine how exclusion efficiency was related to screen slot size and fish size.

Methods

Field testing.—Our study was conducted with a barge-mounted model intake test facility moored in the intake canal of the Chalk Point Steam Electric Station in Aquasco, Maryland. The test facility had twin intake ports, each equipped with an identical 18.6-kW turbine pump (Figure 2). Studies were conducted in the summers of 1982 and 1983. In 1982, each pump had a withdrawal rate of approximately 7.7 m^3/min. Refurbishment of the pumps prior to the 1983 studies increased the withdrawal rate to 12 m^3/min. The intake orifices, 35 cm in diameter, were located 2 m apart and 1 m below the water surface. Water exited each pump

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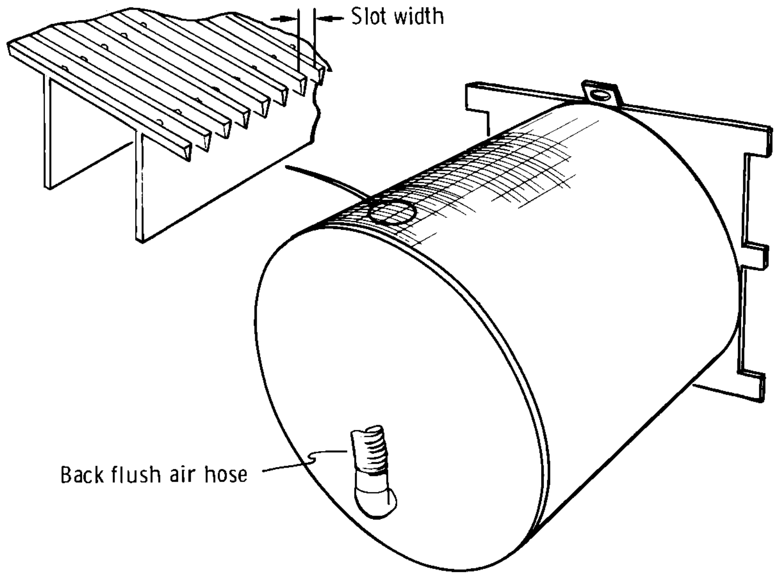

FIGURE 1.—Drawing of a bulkhead-mounted screen with cutaway of wedge-wire configuration.

through identical 25-cm-diameter pipes. The barge was situated in the canal so that one port was upstream of the other, and the axis of the screens was perpendicular to the current.

Screens of three slot sizes (1, 2, and 3 mm) were tested. All screen cylinders were 76 cm in diameter and had wire widths of 2 mm. Screens differed in length to compensate for the different percentages of open area. The average through-slot velocity for all screens was 13 cm/s in 1982 and 20 cm/s in 1983. Flow diffusers intended to equalize flow over the screen surface were built into all screens.

All testing was done at night to reduce fish avoidance of screens by visual cues. In 1982, six pairs of samples were taken on each of two nights. Entrainment through a 2-mm screen and entrainment through an open (unscreened) intake were measured on 19 August. Each condition was tested three times on each port in a random order. The same design was used on 22 August, except that a 1-mm screen was substituted for the 2-mm screen.

In 1983, four pairs of samples were collected on each of 11 nights from 12 July to 28 July. A stratified random sampling design was used in which four treatments (open intake, 1-mm screen, 2-mm screen, and 3-mm screen) were tested in random order on each intake each night.

In all tests, entrained ichthyoplankton were collected at the two discharges (Figure 2) in 1-m-diameter, 505-μm-mesh plankton nets. In 1982, 100 m^3 of water was pumped for each collection. The sample volume was increased to 360 m^3 in 1983.

For each set of samples in both years, an associated set of water quality and ambient ichthyoplankton density measurements also were made. Salinity, temperature, and dissolved oxygen measurements were made at the surface and bottom of the water column off the side of the test facility. Ambient ichthyoplankton density, immediately upstream of the test facility, was estimated by towing a bongo net (0.5-m diameter, 505-μm mesh) in a stepped oblique manner for 1 min each at the

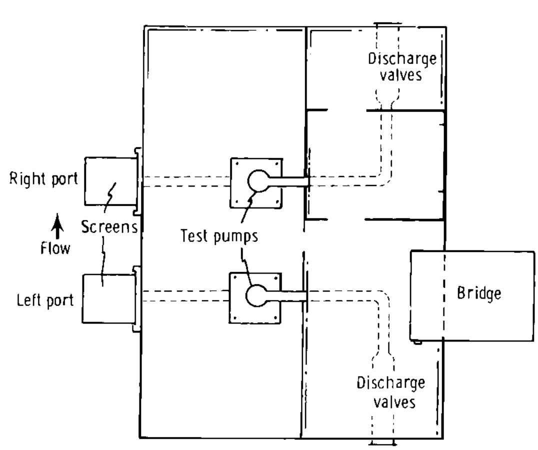

FIGURE 2.—Schematic diagram of the model intake test facility used in this study (top view).

surface and at depths of 1 and 2 m. Each tow filtered about 50 m^3 of water; the actual volume of water filtered was measured by a General Oceanics flowmeter installed inside the net.

All samples were preserved in the field with 5% formalin. In the laboratory, all fishes were sorted by species and standard lengths of each were recorded to the nearest millimeter. In some collections, fish eggs were too numerous to count. For these samples, fish larvae were removed, eggs were subsampled with a Folsom plankton splitter and counts were made of the subsamples.

Statistical methods.—For most analyses, variation in sample density was partitioned by either an analysis of variance (ANOVA) or an analysis of covariance (ANCOVA). A $\log_e(x + 1)$ transformation was used in all tests to meet the assumptions of these models.

Bay anchovy *Anchoa mitchilli* and naked goby *Gobiosoma bosci* were the only species collected in sufficiently large numbers to support data analysis. Data for these species were analyzed by size categories, which were selected by determining the smallest size increments that would not result in large numbers of empty cells. For bay anchovies, these size-classes were ≤4 mm, 5–7 mm, 8–10 mm, 11–14 mm, and ≥15 mm. For naked gobies, they were ≤4 mm, 5–6 mm, 7–8 mm, and ≥9 mm.

For data collected in 1982, the null hypothesis of no difference in the discharge densities of each size class between intake ports (upstream and downstream) or among screen conditions (open intake, 1-mm screen, 2-mm screen) was tested with a two-way ANCOVA, ambient density of fish in the canal being the covariant. In 1983, the null hypothesis of no difference in the densities of each size-class under varying conditions (open intake, 1-mm screen, 2-mm screen, and 3-mm screen) was tested with a blocked one-way ANCOVA; ambient ichthyoplankton density was the covariant and the 22 date–intake combinations were blocks. In both years, if the screen effect was significant, pairwise comparisons of the adjusted treatment means for the various screen conditions were conducted.

If the covariant was nonsignificant (i.e., the slope not significantly different from zero) or an interaction term involving the covariant was significant (i.e., slopes were unequal across treatment groups), ANOVA models were used. If the screen effect was significant in the ANOVA model, Duncan's new multiple-range test was used for comparisons among treatments.

When the assumption of homogeneity of variance could not be met by transformation of data, the Friedman rank-sum statistic was used. Observations were ranked within blocks and the ranks were then summed over treatments. Port (left, right) was used as the blocking factor for 1982 data; date–port combinations were used for 1983 data.

Results

Salinity during this study ranged from 7.3 to 11.3‰; mean values were 9.0 in 1982 and 7.2 in 1983. Water temperature ranged from 25.9 to 31.5°C, averaging 27.8°C in 1982 and 29.1°C in 1983. Dissolved oxygen concentrations were close to saturation on all sampling dates in both years.

Bay Anchovy

The size distribution of bay anchovy in ambient waters differed between years (Table 1). In August 1982, no eggs were found and larger larvae were most abundant; in July 1983, eggs and smaller larvae were prevalent.

Parametric statistics were used for most size-classes. However, it was necessary to use nonparametric methods for 5–7-mm fishes in 1982, 11–14-mm fishes in both years, and fishes 15 mm or larger in 1983. The use of ambient density as a covariant was found to be inappropriate for bay anchovies, with the exception of 8–10-mm fishes collected in 1983.

The screens did not have a significant effect on entrainment of bay anchovy eggs or larvae 4 mm or less in length in either year of the study (Table 2). Although there was almost an order of magnitude difference in the mean number of eggs entrained through the open intake and the 1- and 2-mm screens in 1983, this difference was small relative to the large variability among replicate samples and was not statistically significant.

Exclusion was apparent for 5–7-mm bay anchovies; approximately twice as many fish in this size category were entrained through the unscreened intake as through any of the screens in 1983 (Table 1). Although entrainment density in samples collected through the open intake was significantly higher than in samples collected through any of the screens, no difference in entrainment density through screens of different slot size could be detected (Table 2).

The degree of exclusion by screens increased with fish size (Table 1). Only one bay anchovy larger than 8 mm was collected through the 1-mm screen in either year of our study, even though these larger ichthyoplankton were abundant in the canal in 1982. For both the 11–14-mm and the larger size-classes, the number of ichthyoplankton collected through the unscreened intake was sig-

TABLE 1.—Mean densities (numbers/1,000 m^3 of water) of bay anchovies and naked gobies collected by the bongo net from the canal, through each wedge-wire exclusion screen, and through an open port in 1982 and 1983.

Fish size class	August 1982				July 1983				
	Bongo net	Open port	Screen 2 mm	Screen 1 mm	Bongo net	Open port	Screen 3 mm	Screen 2 mm	Screen 1 mm
Bay anchovy									
Eggs	0.0	0.0	0.0	0.0	19,610	2,341	1,707	18,435	10,966
≤4 mm	2.0	0.0	0.0	0.0	60	9.6	13.6	21.0	9.2
5–7 mm	4.5	4.1	0.0	0.0	37.6	20.1	11.3	9.2	10.8
8–10 mm	6.2	1.6	1.5	0.0	11.2	7.7	2.6	1.6	1.0
11–14 mm	152.9	31.1	10.5	0.0	3.5	1.3	0.3	0.0	0.0
≥15 mm	2,469.4	57.3	15.0	1.5	9.3	3.3	0.5	0.4	0.0
Naked goby									
≤4 mm	95.3	17.2	13.5	1.5	223.5	535.7	557.1	513.4	562.5
5–6 mm	117.6	22.9	19.5	6.0	514.8	148.7	87.6	81.6	66.5
7–8 mm	95.5	38.5	16.5	5.8	370.5	49.7	11.2	9.6	3.9
≥9 mm	342.3	201.5	64.6	35.8	243.7	49.1	7.8	4.4	1.9

nificantly greater than the number collected through any of the three screens. A greater number of ichthyoplankton were collected through the screens with the larger slot size but, with exception of the 11–14-mm size-class in 1982, these differences were not significant (Table 2).

Naked Goby

Parametric methods were appropriate for all naked goby analyses except for fishes in the largest size category in 1983. Ambient density was an appropriate covariant in both years for fishes 4 mm or smaller and for 5–6-mm fishes, but was inappropriate in both years for 7–8-mm or larger fishes.

In 1982, the mean density of naked gobies 4 mm or less was over 10 times greater in the discharge through the unscreened intake than in that through the 1-mm screen (Table 1). Despite this large difference, no significant screen effect was found for naked gobies of this size in either 1982 or 1983 (Table 2). Similarly, no significant reduction in entrainment of 5–6-mm naked gobies through the screens occurred in 1982 (Table 2). However, in 1983 the 1-mm slot-size screen entrained significantly fewer 5–6-mm fish than either the unscreened intake or the other two screens.

Significantly fewer 7–8-mm and larger naked gobies were entrained through the screens than through the unscreened intake in both years (Table

TABLE 2.—Statistical tests used to evaluate exclusions of bay anchovies and naked gobies by wedge-wire screens, *P*-values of those tests, and multiple comparison results for each size class of fish.

Fish size class	August 1982			July 1983		
	Statistical test[a]	*P*	Multiple comparison[b]	Statistical test[a]	*P*	Multiple comparison[b]
Bay anchovy						
Eggs	None			ANOVA	0.30	0 2 1 3
≤4 mm	None			ANOVA	0.26	2 3 0 1
5–7 mm	Friedman's	0.17	0 2 1	ANOVA	0.05	0 3 1 2
8–10 mm	ANOVA	0.69	0 2 1	ANCOVA	<0.01	0 3 2 1
11–14 mm	Friedman's	<0.01	0 2 1	Friedman's	<0.01	0 3 2 1
≥15 mm	ANOVA	<0.01	0 2 1	Friedman's	<0.01	0 3 2 1
Naked goby						
≤4 mm	ANCOVA	0.63	0 2 1	ANCOVA	0.38	3 1 0 2
5–6 mm	ANCOVA	0.75	0 2 1	ANCOVA	<0.01	0 3 2 1
7–8 mm	ANOVA	<0.01	0 2 1	ANCOVA	<0.01	0 3 2 1
≥9 mm	ANOVA	<0.01	0 2 1	Friedman's	<0.01	0 3 2 1

[a] ANOVA = analysis of variance; ANCOVA = analysis of covariance.

[b] 0 = unscreened intake; 1, 2, and 3 = screens with 1-mm, 2-mm, and 3-mm slot widths, respectively. Bars join screen conditions that did not differ significantly ($P > 0.05$) in the number of fish passed.

2). Differences in entrainment among screens of different slot size varied from year to year and between fish size classes, but the smallest screen mesh size consistently produced the lowest entrainment rate (Table 1).

Discussion

Wedge-wire screens are reputed to reduce entrainment by two mechanisms: (1) physical exclusion, which occurs when the slot size of the screen is smaller than the organism susceptible to entrainment; and (2) hydrodynamic exclusion, whereby the screen's cylindrical configuration quickly dissipates the flow field and allows ichthyoplankton with sufficient swimming ability to escape. The second mechanism is enhanced when ambient water velocity perpendicular to the screen surface exceeds the velocity through the screen (Hanson et al. 1978).

Our data provide evidence for both exclusion mechanisms. The hydrodynamic properties of the screen were apparent when 5-mm-long fish of both species were excluded by the 3-mm-mesh screen even though fish as long as 20 mm are narrow enough to fit through this screen. Physical exclusion was apparent from the greater exclusion offered by a 1-mm screen than by the 2- and 3-mm screens, even though the rate of water withdrawal was equal among screens. Because our measurements showed that head width of the fish species we studied exceeded 1 mm as the fish reach about 9 mm in length, physical exclusion is further suggested by the virtual absence of fish 10 mm or larger in samples collected through the 1-mm screen.

Regardless of their relative importance, both the physical and hydrodynamic exclusion mechanisms are related to fish size, which explains the importance of size in our study. Other studies examining how fish size affects entrainment through wedge-wire screens have found results similar to ours. In laboratory studies, Hanson (1981) found that yellow perch *Perca flavescens* less than 8 mm long (total length) were not excluded by a 1-mm screen, but exclusion reached 100% for yellow perch 13 mm long. Hanson found a similar pattern for striped bass *Morone saxatilis,* with total exclusion occurring for fish larger than 10 mm. Delmarva Ecological Laboratory (1980) conducted field tests of wedge-wire screens and found that a 1-mm screen was only marginally effective at excluding fish less than 10 mm long, but very effective at excluding larger individuals. Several other field studies, while not conducting data analysis by size category, also have noted that fish larger than 8–12 mm are generally not entrained through a 1-mm screen, even when fish of this size are abundant in ambient waters (Dames and Moore 1979; Browne et al. 1981; Otto et al. 1981).

Failure to consider fish size explains apparent inconsistencies in conclusions among some previous field studies of entrainment reduction by wedge-wire screens. Dames and Moore (1979) and Delmarva Ecological Laboratory (1980) both found close to 100% exclusion of bay anchovies, but Browne et al. (1981) found only 61% exclusion of this species. The mean size of bay anchovies caught by Delmarva Ecological Laboratory was about 13 mm, whereas the mean size of bay anchovies collected by Browne et al. was only about 4 mm. In the case of naked gobies, Dames and Moore (1979) found 56% exclusion by a 1-mm screen, whereas Browne et al. (1981) found no significant difference in collections made through a 1-mm screen and through an open intake. Again, the small mean size of naked gobies entrained through the unscreened intake in the latter study (4.8 mm) may account for the differing exclusion estimates.

Effect of Screen Slot Size

A significantly greater number of fish longer than 4 mm were consistently collected through the open intake than through screens, but we rarely found significant differences in entrainment among screens of different slot size. However, we consistently found a greater number of fish entrained through the larger-slot screens and suggest that a type-II error (failure to discern real differences in entrainment among screens) occurred because of the low numbers of fish captured. Low numbers of ichthyoplankton were collected because all screens reduce entrainment substantially. Low numbers cause variance to be large relative to the mean and make small differences in entrainment difficult to detect.

The inability to detect statistically significant differences in entrainment through screens of different slot sizes has been apparent in other studies. For example, Browne et al. (1981) found 80% greater entrainment of naked gobies and bay anchovies through a 2-mm screen than through a 1-mm screen. Dames and Moore (1979) found that 8% more fish were entrained through a 2-mm screen than through a 1-mm screen, and Zeitoun et al. (1981) reported that 40% more fish were entrained through a 9.5-mm screen than through a 2-mm screen. In all of these studies, however,

TABLE 3.—Exclusion efficiencies[a] of three wedge-wire screen sizes relative to an open port and to canal water for bay anchovies and naked gobies.

Fish size class	Relative to open port			Relative to canal water		
	1-mm screen	2-mm screen	3-mm screen	1-mm screen	2-mm screen	3-mm screen
			Bay anchovy			
Eggs	−368.4	−687.5	27.1	73.0	66.2	−10.4
≤4 mm	4.5	−118	−41.7	−100.0	−184.5	−78.9
5–7 mm	47.1	55.5	45.3	74.2	76.9	62.2
8–10 mm	87.2	77.8	66.2	89.6	77.6	74.5
11–14 mm	100.0	77.8	76.9	100.0	95.1	88.5
≥15 mm	98.7	80.0	84.8	99.9	99.5	99.4
			Naked goby			
≤4 mm	−4.7	4.2	−4.0	−153.0	−104.9	−174.6
5–6 mm	55.5	44.7	41.1	88.3	83.1	80.9
7–8 mm	97.3	79.3	77.5	98.8	96.0	96.6
≥9 mm	92.6	85.1	84.1	96.9	93.3	96.3

[a] Exclusion efficiencies are based on densities of fish in ambient canal water or in water after it had passed through the open port or screen. Efficiency = 100·[open port (canal) density − screen density]/open port (canal) density. Negative values indicate percentage increases in entrainment relative to the reference water.

the differences in entrainment among screens were not found statistically significant.

It is even less likely that previous studies could have detected a significant difference in entrainment among different sizes of screen because their analysis was not conducted by fish size category. Because very small fish are not excluded by even the smallest slot size, and very large ichthyoplankton possess sufficient swimming ability to avoid entrainment through any of the screens, pooling size groups of fish obscures differences in exclusion that may occur for fish in the intermediate size categories.

Management Implications

Section 316 of the U.S. Federal Water Pollution Control Act requires that the best technology available for minimizing adverse impacts be installed or retrofitted at cooling water intake structures. Many technologies are available for mitigating impingement, but fewer options are available when entrainment is the major concern. Inexpensive impingement mitigation strategies that rely on behavioral alteration of fish movement patterns (Edwards and Hutchison 1980; Stewart 1981; Hadderingh 1982; Patrick et al. 1982; Rodgers and Patrick 1985) are generally ineffective at reducing entrainment of larval fish.

Cooling towers are the most frequently used method for reducing entrainment. They do so by lessening water intake requirements—usually by 90% or more. However, this option is extremely expensive, particularly when retrofitted. Cooling towers also may be undesirable in some instances because they can produce unwanted side effects such as salt drift (Reynolds 1980).

Other mitigation options for reducing entrainment have been identified but may not be generally applicable. Fine-mesh panels placed on traveling screens have been used with some success (Murray and Jinette 1978; Taft et al. 1981b). However, this technology requires that larvae first be impinged and then returned to the water body by a fish return system. For many taxa, this process causes extensive mortality (Ecological Analysts 1979; Edwards et al. 1981), particularly if intake velocities exceed 15 cm/s or impingement duration exceeds 2 min (Taft et al. 1981a). Other technologies that work by reducing intake velocities, such as radial wells or sand filters, have not been applied at intakes requiring large water volumes.

Wedge-wire screens appear to offer a management alternative to cooling towers and fine-mesh travelling screens for mitigating entrainment. In most cases, their cost would be less than those for retrofitting cooling towers, and their effectiveness is likely to be higher than that for fine mesh screens. Our calculated exclusion efficiencies of wedge-wire screens for larger larvae regularly exceeded 80% relative to the unscreened intake, and 90% relative to ambient canal samples (Table 3). Zeitoun et al. (1981) suggested that an even greater degree of mitigation can be accomplished if the screens are located offshore or away from natural nursery areas of the fish to be protected.

Wedge-wire screens so far have generally been used to filter make-up water for closed-cycle cooling systems or for other low-volume water uses, and there remain two obstacles to their general application. First, the screens are deployed with a low screen-face velocity and thus a large number of screens are required for application at facilities with large water requirements. Second, the screens are deployed entirely underwater and thus may be subject to extensive biofouling. However, engineering solutions to both problems may exist. Wedge-wire screens arrayed in a manifold system have been successfully employed for several years in a relatively large-volume (21 m^3/s), once-through cooling system (Great Lakes Research Division 1982), and their application to larger systems appears to be viable. The fouling problem might be solved by toxic coatings or by back-flushing the screens with air (Weisberg et al. 1986). Our study indicated that wedge-wire screens significantly reduce entrainment. If the engineering problems discussed above can be overcome, wedge-wire screens represent a desirable alternative for mitigating entrainment losses, particularly at locations where cooling towers or fine-mesh travelling screens are not economically or ecologically applicable.

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