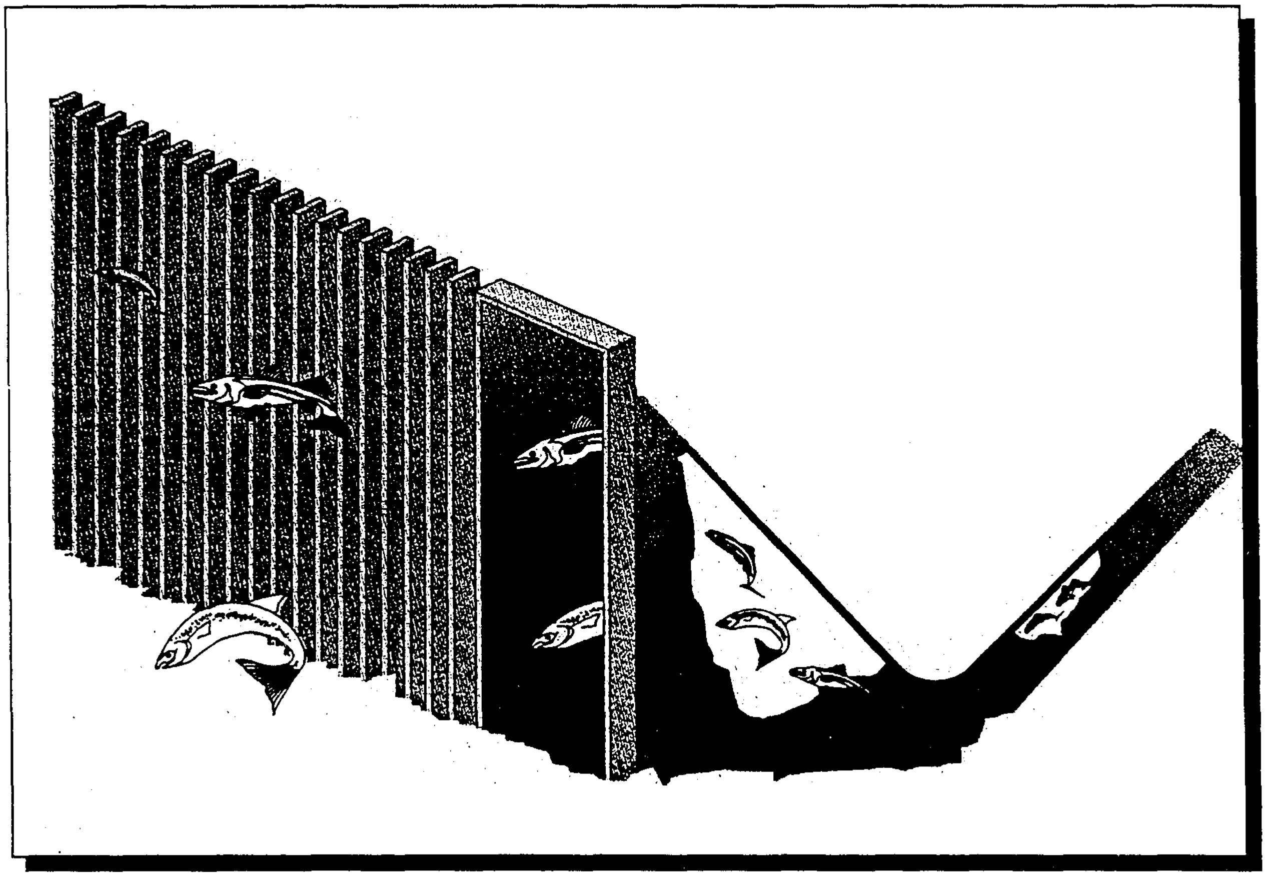

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Reducing Predation Mortality at the Tracy Fish Test Facility: Review and Analysis of Potential Solutions

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Reducing Predation Mortality at the Tracy Fish Test Facility:

Review and Analysis of Potential Solutions

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Introduction

The Tracy Fish Collection Facility (TFCF) is a U.S. Bureau of Reclamation facility constructed in the 1950s to salvage fish drawn into the Tracy Pumping Plant in the Sacramento-San Joaquin Delta, which provides water to southern California as part of the Central Valley Project (Liston et al. 1994). The TFCF is an older louver-type fish screening and collection facility, originally designed to focus on diversion and salvage of small striped bass (*Morone saxatilis*) and chinook salmon (*Oncorhynchus tshawytscha*) smolts from intake flows (Liston et al. 1998). Flow through the collection facility can reach 5000 cubic feet per second, depending on number of pumps operating to deliver water to the Delta-Mendota Canal, tidal influences, and operations at the nearby State pumping facility. Although water was originally pumped through the TFCF only during the summer irrigation season, year-round pumping began in 1968 when the San Luis Reservoir was completed to store water during winter.

In the current Tracy Fish Collection Facility, fish are separated from the main flow and diverted into bypasses using a large, long primary louver system, and further concentrated using a set of two secondary louvers located in a smaller flume (see Liston et al. 1998 for complete description and diagrams). It was originally believed that most fish either were deflected by both sets of louvers into a series of holding tanks, later to be transported and released back into the Bay-Delta system, or slipped through the primary louvers into the intake channel leading to the pumps. However, recent research indicates that larger juvenile and adult striped bass and white catfish (*Ictalurus catus*) are able to maintain position upstream from the secondary louvers in the flume (Liston et al. 1994), despite high velocities there (L. Hess, personal communication). An initial removal of these predators during 3-4 day periods in four separate months in 1991 resulted in collecting 1,866 striped bass ranging 1.5-28.4 inches total length, and 514 white catfish ranging 1.3-26.0 inches (Liston et al. 1994). Similarly, 4,683 striped bass and 4,286 white catfish of similar size ranges were removed during eight periods throughout 1992.

These predatory fishes that collect within the secondary channel of the current Tracy Fish Collection Facility may eat large numbers of the fishes that are swept by. Striped bass are known to be highly predaceous (e.g., Morris and Follis 1978), and indeed 36% of the 187 striped bass stomachs sampled during the Tracy predator removal efforts in 1991-1992 contained fish (Liston et al. 1994). Highest predation was in May (78% of striped bass stomachs sampled contained fish) when up to 51 fish were found per stomach (small postlarvae were present). These predaceous bass ranged 4.3 to 15.1 inches. In contrast, only 1 of 33 catfish stomachs (26 white catfish, 7 channel catfish, *I. punctatus*) examined had fish remains.

These data indicate that there is potential for these predatory fish in the secondary forebay to remove a substantial number of native fishes drawn into the TFCF to be salvaged. These include outmigrating smolts of the federally endangered winter run chinook salmon and the federally threatened steelhead trout (*O. mykiss*), delta smelt (*Hypomesus transpacificus*), and splittail (*Pogonichthys macrolepidotus*). Moreover, the predatory striped bass and catfish that are mixed with these species in the holding tanks and transport trucks may also eat large numbers of these native species.

During 1998 and 1999, planning efforts have been underway to design a new Tracy Fish Test Facility (TFTF) near the site of the older TFCF, in order to develop and test a variety of state-of-the-art technologies in fish protection. Among the many improved features proposed are the use of fish crowders to usher predators into the facility and through various screens and bypasses, and fish size sorting via a 'leaky louver' system and fish separators in above ground fish holding chambers (Liston et al. 1998). The purpose of these measures is to separate predators from sensitive prey as soon as possible after entering the facility to reduce mortality, especially of the listed species.

The purposes of this report are three-fold. First, I review available published literature on means of crowding potential predators to usher them into the facilities, and for sorting predators and prey into various size classes. Second, I combine mathematical relationships from the literature on fish predation and commercial grading of fish with an analysis of available data on the sizes of fish collected at the TFCF to evaluate proposed and alternative sorting criteria for TFTF facilities to minimize predation. Third, I make a few brief recommendations about further research of these technologies to be conducted at the Bureau's Denver Technical Services Center and TFTF. Research on these facilities will likely be broadly applicable to other large fish screening facilities called for in future CALFED operations.

Potential Solutions to Reduce Predation Mortality via Crowding and Grading Fish

The range of potential solutions for moving predators into the new Tracy Fish Test Facility, and also retrofitting the older existing TFCF, all involve some kind of crowding of fish toward and through louvers or screens, or into the bypass channels. Crowding might be accomplished using behavioral repellants like light or sound, high water velocity, or mechanical means such as automatic crowders. I review the literature on each of these options below.

Once predators are moved into holding tanks (Liston et al. 1998), reducing predation might be accomplished by sorting fish into several size fractions so that large predator fish are excluded from smaller fish that they might eat. This could be accomplished by crowding fish through one or more fish graders (usually floor graders made from horizontal bars at given spacing, oriented with the long axis of the fish), as is standard practice in many aquaculture operations (Brown and Gratzek 1980). A final option is the one that has been pursued at the current TFCF, physical drawdown of the secondary channel followed by manual removal of predators (Liston et al. 1994). The literature on each of these options is also reviewed below.

Literature Search

Seven major databases were searched for this literature review, including five within the Aquatic Sciences and Fisheries Abstracts (ASFA) of Cambridge Science Abstracts, and Fish and Fisheries Worldwide (which includes >210,000 citations, 1971 to present). The five databases in ASFA, and the periods they cover, are listed below.

1. Aquaculture Abstracts	1984-present
2. Biological Sciences and Living Resources Abstracts	1978-present
3. Ocean Technology, Policy, and Non-living Resources Abstracts	1978-present
4. Aquatic Pollution and Environmental Quality	1990-present
5. Marine Biotechnology Abstracts	1989-present

Keywords searched included a wide variety of combinations of fish, attractants, deterrents, repellants, crowding, grading, sorting, screens, striped bass, catfish, predation, gape size, and variants of these terms.

Behavioral Repellants

Behavioral repellents have often been used in attempts to deter fish from entering hydropower facilities (see reviews in EPRI 1994; Popper and Carlson 1998). Stimuli that have been tried include light, sound, electricity, chains, bubble curtains, and various visual cues, as well as combinations of these stimuli. Electric fields are potentially dangerous to humans and other terrestrial and aquatic organisms, and may have limited usefulness because they can occur only between fixed electrodes (Popper and Carlson 1998), so they are not considered further here. Neither bubble curtains, chains, or other visual cues have been studied enough to draw conclusions about their effectiveness (Popper and Carlson 1998). For example, some authors suspected that bubbles deterred fish more due to the sound they produced than visual effects. Therefore, I focus here on light and sound as two stimuli that have been sufficiently studied to draw some conclusions about their effectiveness, and might be used to move predator fish into and through the new Tracy Fish Test Facility.

Sound

Sound has advantages for controlling fish behavior because it is rapidly transmitted (sound travels much faster in water than air), is unaffected by light or turbidity, and attenuates slowly (Popper and Carlson 1998). Fish sense sound via their lateral line system, which detects mainly low frequency vibrations within one or two body lengths of the fish, and through their inner ear, which detects higher frequency vibrations that travel longer distances. Some fish, like American shad (*Alosa sapidissima*) and other alosids, have connections between their gas bladder, which acts as a resonating organ, and the inner ear and are called 'hearing specialists.' In contrast, others like salmonids (salmon and trout) lack these and are termed 'hearing generalists' (Popper and Carlson 1998). As a result, these different groups of fishes differ widely in the range, amplitude, and frequencies of sounds that they can detect. Most fish can detect sounds within the range of 50-2,000 Hz (1 Hz = 1 cycle per second). However, many hearing specialists tested can hear frequencies outside this range, which Popper and Carlson (1998) divide into ultrasound (>20,000 Hz, very high frequency), low-frequency sound (35-300 Hz), and infrasound (<35 Hz). Unfortunately, low-frequency sounds propagate poorly in shallow water such as fish collection flumes, because the wavelength is greater than the water depth. For example, at 1 m deep the lowest frequency that can propagate for any distance is 300 Hz. Thus, low-frequency sounds are likely to be transmitted only to fish that are within a few meters of the sound source.

Attempts to use sound to control fish behavior have ranged from failure to limited success under specific conditions (see Knudsen et al. 1992; reviews in EPRI 1994; Popper and Carlson 1998). For example, pneumatic "poppers" or "hammers" are reported to not be very effective, or results were inconclusive, and at high intensity such sounds may damage sensory systems of other fishes in their vicinity. However, several studies have reported some success in repelling schools of alosids (e.g., American shad, alewife, *Alosa pseudoharengus*) from entering hydroelectric turbine intakes using ultrasounds at frequencies above those detectable by humans (120,000-130,000 Hz), but these effects differed with light, temperature, and species. Investigators have speculated that these herring species may be adapted to detect such high frequencies to avoid echolocating predators, much as some insects detect echolocating bats. In contrast, salmonids have relatively poor hearing, and respond mainly to low frequency sounds <300 Hz. For example, Knudsen et al. (1992) reported that wild Atlantic salmon (*Salmo salar*) smolts responded most to very low frequency sounds of 5-10 Hz, but only within 2 m of the sound source, so using such infrasound likely has limited application for fish collection facilities.

Overall, because only low frequency sounds (<200 Hz) would likely be detected by a wide range of fish species, and these are difficult to propagate for any distance in shallow water, sound alone is unlikely to be useful as a repellant for crowding fish at collection facilities like Tracy. It may, however, be useful in combination with other repellants, or in a secondary louver system with small spatial extent.

Light

Mercury lamps and strobe lights have most often been used for controlling fish behavior, but like sound they vary widely in success (Popper and Carlson 1998). A wide range of fish species can be repelled by strobe lights, especially at night in clear water, but their effectiveness varies among species and life stage. Unfortunately, as with sound, many other factors may influence the response of fish to lights, and these were often not measured or controlled, so results were often equivocal. However, strobe lights have been successfully used to repel juvenile American shad from intakes at the York Haven Hydroelectric Project on the Susquehanna River at night, thereby directing them to a sluiceway around the dam (EPRI 1994).

Mercury lamps also have been used successfully to attract salmonids and herring to bypass routes, but other species like channel catfish and walleye (*Stizostedion vitreum*) are reported to be repelled in laboratory tests (EPRI 1994). Moreover, too much light, or abrupt changes in light levels, have been reported to deter passage of fish species the lights were designed to attract. Although the damaging effects of high light levels on fishes are relatively unknown, Popper and Carlson (1998) suggest that there is also the potential for unnatural light regimes (e.g., strobes or mercury lights at night) to alter the feeding and reproductive cycles either of target species or non-target species that reside near facilities, with unknown consequences.

Conclusions on Behavioral Repellants

In their extensive and comprehensive review of use of sound and other stimuli to control fish behavior, Popper and Carlson (1998) conclude that, with a few interesting exceptions like use of ultrasound to repel clupeids, "...no behavioral methods for fish guidance work consistently or have currently operational success." Thus, the ultimate goal of using behavioral stimuli over long distances, large areas, and long periods to direct fish from regions of high risk to low risk has not been realized. There is hope of 'designing' sounds to repel certain species over others for specific applications. However, combinations of light and sound with mechanical means, such as screens and louvers, hold the most promise because they provide multiple stimuli capable of repelling different species and life stages under different temperature, flow, and light conditions when their responses may differ (Popper and Carlson 1998). Questions remain, however, about the effects of such intense stimuli on producing damage or stress in fish.

Flow

Popper and Carlson (1998) report that fish response to flow fields often overrides or supersedes responses to other stimuli like light and sound. High water velocities might be useful for crowding by discouraging predators from holding positions upstream from louvers or other screens where they can intercept potential prey. However, striped bass are reported to hold positions in velocities of 3 ft/s (ca. 1 m/s) upstream from the secondary louver array now used at the TFCF (L. Hess, personal communication). Velocities faster than this would likely cause smaller fish to be damaged by screens or bypass systems.

Flow may hold some promise to facilitate sorting of fish through grading panels after they move through bypass channels and enter the collection tanks of the new test facility (Liston et al. 1998). For example, McComas et al. (1998) report on using high velocity flow to move steelhead and salmon smolts over inclined grading panels that separated the larger steelhead from the smaller salmon smolts. The two size groups are separated to decrease mortality during holding and barging downstream from Columbia River dams to the ocean. Broadhurst and Kennelly (1996) describe using grading panels inside of Australian shrimp trawls that allow the shrimp to pass into the cod end but exclude bycatch of larger fish and crabs, which are ejected through a chute in the side of the trawl (see also Tokai et al. 1996 for similar work on Japanese shrimp trawls). This is another system where high flows coupled with mechanical devices are effective at facilitating sorting fish and other aquatic animals into size groups.

Drawdown and Physical Removal of Predators

Liston et al. (1994) describe initial efforts to dewater the secondary channel of the current Tracy Fish Collection Facility and physically remove the predators residing there. This required installing a hinged screen to prevent predators from escaping upstream through bypass channels, screening the secondary louver bypass channels, and manually seining and dipnetting predators from the secondary channel. A total of 60 such drawdowns during 12 periods throughout 1991 and 1992 resulted in removal of about 18,800 fish totaling about 2,600 pounds. A large percentage of this biomass was striped bass and white catfish.

Liston et al. (1994) recommended that drawdown of the secondary forebay and predator removal be continued at least monthly, or when large fish were observed, as part of regular maintenance of the TFCF. However, this alternative is undoubtedly costly, and seems a poor option for minimizing predation in the new test facility. The relatively large number of moderate-sized striped bass (e.g., 6-8-inch fish) that may reside in the facility between removal periods likely consume a large number of small fish, especially during early summer when juveniles of many species are abundant.

Mechanical Crowding

Given the uncertain effectiveness of light, sound, or flow to usher predatory fish into and through a collection facility, and the labor required to drawdown such a facility and manually remove predators, periodic mechanical crowding appears the best option at present. In standard aquaculture facilities, manually operated crowder screens are used in raceway channels to confine fish to ends where they are more easily netted, or to force the smaller ones to swim through grading panels that consist of vertically oriented bars. A few of the larger aquaculture operations and fish handling facilities at dams (e.g., McNary, Little Goose, and Lower Monumental Dams on the Columbia River) have mechanical crowders that run the lengths of 8 X 100 foot raceways (Brian Miller and Brad Eby, U.S. Corps of Engineers, personal communication), but only one published report describing such an automated system was found (Theis 1976). Crowders at McNary Dam have side seals of nap brush, rubber seals on the bottom, and ride on rollers. All reports indicate that these automated crowders tend to sweep relatively slowly (100 ft in 5 min), partly to reduce the head differential fore and aft (especially if debris is present) and partly to avoid applying undue stress to fish being crowded or graded. However, a crowder could be moved downstream at flow velocity, thereby avoiding head differential, and cleaned of debris frequently using an automated device.

Grading

Mechanical crowding along and through primary louvers, and through grading panels of appropriate spacing in holding tanks, would be a feasible option for separating potential predators from susceptible prey in the Tracy Fish Test Facility. Separating fish by size class is standard operating procedure in aquaculture facilities to reduce predation and competition and thereby increase survival and growth (e.g., Ludwig and Tackett 1991). With respect to performance of grading panels, many studies have been conducted to empirically determine the lengths of fish retained by graders of different spacings, primarily for commercially important food and bait fishes like channel catfish (e.g., Greenland and Gill 1972, 1974; Greenland et al. 1972; Dorman 1991; Lovshin and Phelps 1993), striped bass (Ludwig and Tackett 1991; Easter and Libey 1992), golden shiners (*Notemigonus crysoleucas*; Ludwig and Stone 1997), and eels (Anguillidae; Gallagher 1984; Wickens and Jones 1985). The best of these publications present data that can be used to calculate relationships between grader spacing and the lengths of fish retained in front of the grading panel (Figure 1).

Grading panels are oriented either as a vertical wall, in which case the bars are oriented vertically, or as a floor panel, in which case the bars are oriented horizontally with the long axis of the fish. Although fish culturists are most interested in developing relationships between the length of fish retained and grader spacing, the critical measure is clearly body width (for laterally compressed fish like striped bass) or depth (for dorsoventrally flattened fish like sculpins). For example, Tokai et al. (1996) demonstrated that selectivity of grading panels for shrimp in Japanese shrimp trawls depended almost entirely on the ratio of carapace width or depth to grader spacing. However, in addition to body width or depth, fish behavior when encountering grading panels may also cause differences in grader efficiency for different fish species.

The effectiveness of reducing predation by separating predators and prey into different holding tanks using grading panels can be assessed in a preliminary way by combining predictions of predator sizes retained by graders of given spacing with relationships of maximum prey sizes eaten by predators of a given size, both of which are available in the literature. In the next section, I present such an analysis to show how predation risk can be calculated for different alternatives of grader spacing proposed for TFTF.

Analysis of Predation

Potential Predators and Important Prey

Of the species most commonly entrained in the current facility (TFCF), striped bass, white catfish, channel catfish, and yellowfin goby (*Acanthogobius flavimanus*) are the potential predatory species that are either common or abundant (Liston et al. 1998). Large individuals of striped bass and white catfish enter the facility throughout the year (Figures 2 and 3; channel catfish are less abundant), so that 4-16-inch bass and catfish (100-400 mm total length [TL]), the sizes likely to prey on smaller fish, are always present. Moreover, medium-sized individuals of both groups (e.g., 4-8-inches, 100-200 mm) are the most abundant size class within this group, and represent a large supply of predators that may eat large numbers of potential prey. The potential for yellowfin goby and other gobies to be significant predators is completely unknown.

Striped bass are known to be voracious predators (e.g., Morris and Follis 1978), whereas white and channel catfish (and other bullhead species; *Ameiurus* spp.) of all but the largest sizes are not (Moore 1972; Starostka and Nelson 1974; Marsh 1981; Tyus and Nykirk 1990; Marsh and Douglas 1997; H. R. Robinette, Colorado State Univ., pers. comm.). Overall, catfish are reported to be opportunistic omnivores (Marsh and Douglas 1997), and tend not to become piscivorous until they reach ca. >300 mm TL. Thus, I focus here on analysis of predation by striped bass, although I also present grader selectivity curves for catfish.

The potential prey of most concern to State and Federal regulatory agencies charged with their management are those species listed as threatened or endangered under the Endangered

Species Act. These include the endangered winter run chinook salmon, and the threatened delta smelt, steelhead, and splittail. I analyzed the lengths of potential predators and prey entrained into the TFCF using data on the periodic 10-minute fish collections made at the TFCF, which are available on the World Wide Web (*www.iep.water.ca.gov/dfishfa/*). I chose three different years that spanned the range of flow regimes from wet (1995) to above normal (1993) to critically dry (1994).

Among the potential prey, delta smelt live only one year and spawn during winter through early summer (Liston et al. 1998). Both spawning adults (55-70 mm TL) and migrating larvae (20-30 mm TL) are highly susceptible to predation due to their small size (Table 1; Figure 4). Outmigrating chinook salmon juveniles, also small enough to be susceptible to predation (ca. 75-150 mm TL; Fig. 5), are most numerous during January through June (Liston et al. 1998), and juveniles of winter run chinook are entrained during February through April. Because steelhead smolts outmigrate at older ages they are larger than chinook (175-300 mm TL; Fig. 6) and therefore less susceptible to predation by all but the largest predators. Splittail grow to large size (to 375 mm TL; Fig. 7) and so adults are less susceptible to predation. However, their young are smaller (25-100 mm TL, depending on season) and are likely to be susceptible to predation when they first appear in the facility in May and June (e.g., Figs. 8-9). They likely outgrow the mouth size of all but the largest predators by fall. Overall, based on size alone, juveniles of chinook salmon and splittail, and juvenile and adult delta smelt, are most likely to be susceptible prey when they appear in winter through early summer.

Table 1. Ranges in total lengths (mm) of four potential prey and two potential predators entrained into the Tracy Fish Collection Facility in three years of different flow regime. Flows were above normal in 1993, critically dry in 1994, and wet in 1995. Data are from regular 10-minute fish samples collected year round at the TFCF.

Year	Delta smelt	Splittail	Chinook salmon	Steelhead	Striped bass	White catfish
1993 (above normal)	20-70	25-375	150-225	125-325	25-325	25-325
1994 (critically dry)	15-75	25-375	75-225	175-425	15-175	25-300
1995 (wet)	55-75	50-150	50-250	175-375	25-300	20-325
Overall	15-75	25-375	50-250	125-425	15-325	20-325

Grader Selectivity

Using grading panels to separate predators from prey that are susceptible to them requires knowing what sizes of predators can be removed with given grader spacing. Commercial aquaculturists have developed tables of grader selectivity for both channel catfish (Dorman 1991), and striped bass (Ludwig and Tackett 1991). For striped bass I fit a curve to predict total lengths of fish retained as a function of spacing between the grader bars (Figure 10). Total lengths of striped bass and catfish retained are similar for grader bar spacings ranging about 12-22 mm and fish lengths about 50-160 mm TL, but may diverge at greater spacing widths (Figure 1). At widths greater than about 1 inch (25 mm) graders may retain longer catfish than striped bass, which seems likely because catfish are more dorsoventrally compressed than striped bass and therefore wider for a given length. Unfortunately, no data are available for striped bass for these greater grader widths to allow such a comparison. However, because striped bass are much more predaceous at smaller sizes than catfish, grading to remove the smaller striped bass of concern would also certainly remove the larger catfish likely to be strong predators.

Example of use of curves (see Figure 10): Grader spacings of ½" (13 mm), 3/4" (19 mm), and 1" (25 mm) would retain striped bass of 102 mm (4"), 145 mm (6"), and about 165 mm total length (6.5"; requires extrapolating beyond the data slightly). Total length is defined as length from the tip of the snout to the tip of the longest lobe when the tail fin is squeezed together.

Prey Selectivity by Predators

Relationships are also available in the literature that describe the maximum prey size that striped bass can ingest (Chervinski et al. 1989). Fish are among the most important foods of striped bass longer than 100 mm (Humphries and Cumming 1973), but spiny-rayed fish like tilapia (*Tilapia* spp.), sunfish (*Lepomis* spp.), and bass (*Micropterus* spp.) are less susceptible to predation than soft-rayed fish like carp (*Cyprinus carpio*). Chervinski et al. (1989) determined the maximum size of redbelly tilapia (*Tilapia zilli*) and carp eaten by striped bass by introducing successively larger prey into tanks with striped bass predators. The curves they present (Figure 11) show that, for example, 200 mm TL striped bass can ingest carp as large as 73 mm TL, but tilapia only as large as 60 mm TL, probably due to their spines.

Because maximum prey size depends mostly on predator gape size (the size of the mouth opening) relative to prey body depth, knowing these two measures for fish of different sizes would allow better estimates of predation risk. Chervinski et al. (1989) present gape width (maximum vertical opening of the mouth) for striped bass (Figure 12), and body depths could be measured for important prey of different lengths captured at the Tracy facilities. Chervinski et al. (1989) present relationships for body depth vs. total length only for carp and redbelly tilapia.

Risk of Predation for Alternative TFTF Designs

Combining information on grader selectivity with maximum prey size for striped bass allows preliminary analyses of alternative designs for louvers and grading panels in the new Tracy Fish Test Facility. Here I compare two alternatives, one based on preliminary criteria for louver and grader spacing presented in Liston et al. (1998), which I call the 'Proposed Design', and another alternative based on modified criteria, the 'Alternative Design.' For both designs I assume that mechanical crowders would be used to usher fish in and through the facility to prevent large predators from holding positions in front of louvers and screens. In addition, automated debris cleaning devices would be needed on louvers and screens to maintain sorting efficiency. *Also, I emphasize that these analyses are intended only to be guides, because the prey selectivity curves used are based only on carp, and fish behavior may play a strong role in the success of leaky louvers and grading panels in fish holding tanks. Further tests will be required to refine these criteria and the resulting designs.*

In the proposed design of the Tracy Fish Test Facility (Liston et al. 1998), fish first pass through a trashrack, given that they are small enough to fit through the bars. They then encounter the primary louver array, at which some fraction of the fish, including those too large to pass through the primary louver slats, are shunted through a bypass to a holding tank. Those that pass through the leaky louver encounter a positive barrier screen and are shunted into another bypass to another holding tank. Once in the two holding tanks, fish are graded into two size groups through a grading panel. Thus, the question to be addressed is what sizes of fish end up in each of the four holding areas, and how susceptible are the potential prey to the predators housed with them?

Proposed Design

For this alternative, I set the following criteria:

Trashrack spacing -	3 inch free opening
Primary louver -	1 inch free opening
Grader spacing in holding tanks -	3/4 inch free opening

Trashrack spacing was not specified in Liston et al. (1998), primary louver spacing was proposed at 1-4" (I used the minimum here, see their p. 53), and grader spacing in holding tanks was set at 3/4" (19 mm, p. 65).

I estimate that 3" trashrack spacing will allow striped bass and other fish up to 400 mm TL (16") to enter the facility and encounter the primary louvers. Although not all fish have the same cross sectional body shape, most species are shaped more like striped bass (i.e., laterally compressed) than channel catfish, so here I estimate the selectivity of graders for all fish based on the curve for striped bass (Figure 10). Of the large number of fish that pass through the trashracks, those larger than about 165 mm that cannot fit through the 1" primary louvers, and many smaller fish that are guided along the louvers, will be shunted into the first bypass and holding tank 1 (Figure 14). Small and medium-sized fish <165 mm TL may pass through the louvers and encounter the positive barrier screen, thereby entering the second bypass and holding tank 2.

Fish entering holding tanks will be graded through 3/4" graders, which retain fish of about 145 mm TL and larger (Figure 10), so the largest striped bass entering holding tank 1 (up to 400 mm) will be housed with potential prey as small as 145 mm (holding tank 1A, see Figure

14). I estimate that striped bass this large may eat prey up to 150 mm, but this requires extrapolating beyond the data because Chervinski et al. (1989) fed carp only of 120 mm TL and less to striped bass (Figures 11 and 13). However, it appears plausible that the smallest fish in holding tank 1A, such as 145-mm splittail and juvenile chinook salmon, may be susceptible to predation by the largest striped bass.

In holding tank 2, fish retained by the 3/4" graders (i.e., in holding tank 2A) will range about 145-165 mm TL (Figure 10). The largest striped bass (165 mm) are capable of eating soft-rayed prey up to about 65 mm (Figure 13), so the medium-sized fish in this tank are at no risk of predation. However, in holding tanks 1B and 2B, the largest striped bass capable of passing through the 3/4" graders (145 mm TL) are predicted to eat prey as large as 61 mm (Figure 13), so many small delta smelt and splittail, among other species, are likely at high risk of predation.

Alternative Design

The relationships presented, if strengthened with additional site specific data on grader selectivity and body depths for Delta species of interest, could be used to design alternative spacings to reduce predation risk in the holding tanks. *I emphasize again that these would require extensive lab and field testing to account for differences among species in fish behavior.*

For this alternative, I set the following criteria:

Trashrack spacing -	3 inch free opening
Primary louver -	1.5 inch free opening
Grader spacing in holding tanks -	Holding tank 1: 20 mm, Holding tank 2: 10 mm

As before, fish smaller than about 400 mm TL can penetrate the trashrack, based on the 3" spacing. Those larger than about 300 mm that encounter the 1.5"-spaced primary louvers are shunted into holding tank 1 (assuming that the louvers act partly as a grading panel, see Figures 1, 10, and 15), along with many smaller fish that avoid the louvers (Figure 16). Those that pass through the primary louvers will be shunted by the positive barrier screen to holding tank 2, as before. Although these fish will all be <300 mm TL, the majority will be <200 mm because larger fish are less abundant for most species (e.g., see the lengths of striped bass in Figure 2).

In holding tank 1, striped bass and other species larger than about 150 mm TL will be retained by the 20 mm grader (tank 1A in Figure 16), and should generally be safe from predation from even the largest striped bass (i.e., 150 mm carp is maximum prey size for 400 mm striped bass). Striped bass that pass through the bars may eat prey up to 62 mm, but most fish this small will likely pass through the leaky louvers and end up in holding tank 2.

In holding tank 2, the 10-mm grader will retain fish of about 75 mm and larger (Figure 10), so the majority of the striped bass retained in tank 2A should be 75-200 mm. Based on Figure 15, the maximum prey size of 200 mm striped bass is about 73 mm, so there should be little predation in this tank.

In holding tank 2B, only striped bass less than about 75 mm would have passed through the 10 mm grader, and their maximum prey size would be about 50 mm. Clearly, the smallest delta smelt and striped bass, among other species, would be susceptible to these predators (see Table 1).

Initial Recommendations

This analysis is intended to provide a starting point for designs of louvers and graders to reduce predation in the new Tracy Fish Test Facility. The analysis shows that with effective application of mechanical crowding through a leaky louver and grader system that predation may be substantially reduced. I recommend that further refinements of the analysis be pursued by:

1. Measuring body depths and lengths of potential prey fishes encountered at Tracy, to refine the sizes of each that would pass through graders of given spacing (Figure 10), and could be eaten by striped bass with given gape width (see Figure 12).

2. Once appropriate designs are developed, testing these with several target fish species in the Denver Laboratory facility.

3. Field tests of the resulting technology at the Tracy Fish Test Facility.

Acknowledgments

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Figure Captions

Figure 1. Predicted total lengths of striped bass and channel catfish retained by graders of different spacing. Data for channel catfish lengths retained are from tables in Brown and Gratzek (1980) and Dorman (1991). Curve for striped bass was fit to predicted lengths and grader bar spacings in Table 2 of Ludwig and Tackett (1991), because their published curves are apparently incorrect. The quadratic equation fit is:

Total length retained (mm) = - 61.1745 + 16.8842 * Bar spacing (mm) - 0.3162 * $(\text{Bar spacing})^2$ $R^2=0.999$

Range of data: grader spacing 10.7-24.6 mm, striped bass total length 83-163 mm

Figure 2. Lengths of striped bass reported from all 1993 10-minute fish collections at the Tracy Fish Collection Facility.

Figure 3. Lengths of white catfish reported from all 1993 10-minute fish collections at the Tracy Fish Collection Facility.

Figure 4. Lengths of delta smelt reported from all 1993 10-minute fish collections at the Tracy Fish Collection Facility.

Figure 5. Lengths of chinook salmon reported from all 1995 10-minute fish collections at the Tracy Fish Collection Facility.

Figure 6. Lengths of steelhead trout reported from all 1993 10-minute fish collections at the Tracy Fish Collection Facility.

Figure 7. Lengths of splittail reported from all 1993 10-minute fish collections at the Tracy Fish Collection Facility.

Figure 8. Lengths of splittail reported from 1995 10-minute fish collections during January through March at the Tracy Fish Collection Facility.

Figure 9. Lengths of splittail reported from 1995 10-minute fish collections during April through June at the Tracy Fish Collection Facility.

Figure 10. Predicted total lengths of striped bass retained as a function of grader bar spacing (see equation in Figure 1 caption), showing examples of three common bar spacings in inches.

Figure 11. Predicted maximum total lengths (TL) of two species eaten by striped bass. Curves were refit from those in Chervinski et al. (1989), because theirs had striped bass total length as the dependent (Y) variable. Equation for carp as prey is:

Maximum carp prey TL (mm) = 46.2554 + 0.006304 * Striped bass TL (mm) + 0.0006458 * (Striped bass TL)^2 R^2=0.997
Range of data used: carp TL 50-120 mm, striped bass TL 37-450 mm

Equation for redbelly tilapia as prey is:

Maximum tilapia prey TL (mm) = 1.9171 + 0.2915 * Striped bass TL (mm) R^2=0.999
Range of data used: tilapia TL 22-135 mm, striped bass TL 37-450 mm

Figure 12. Predicted vertical gape size of striped bass for a given total length. Equation for curve, from Chervinski et al. (1989; Figure 3) is:

Vertical gape (mm) = -1.503 + 0.125 * Total length (mm) - 0.00005 * (Total length)^2 R^2=0.92

Figure 13. Example of using the grader selectivity curve (Figure 10) combined with the maximum prey length curve (Figure 11) to estimate predation risk to prey housed with predators in holding tanks. Graders of 1-inch spacing would pass striped bass smaller than about 165 mm TL, which in turn could eat carp (or other soft-rayed) prey smaller than 65 mm TL. Similarly, 3/4-inch graders would pass striped bass smaller than 145 mm TL, which could eat carp smaller than 61 mm TL.

Figure 14. Tracy Fish Test Facility 'Proposed Design' based on 1" spacing of primary louvers and 3/4" spacing of graders in holding tanks (see Liston et al. 1998). Arrows at right show routes of fish diverted from primary louvers into holding tank 1, and then through the graders into tanks 1A (larger fish) and 1B (smaller fish). Arrows down and to left show routes for fish passing through the leaky louver into the holding tanks, and then through the graders into tanks 2A (medium sized fish) and 2B (small fish). See text for details.

Figure 15. Maximum prey lengths for striped bass that pass through graders of 1.5-inch spacing (about 300 mm TL), 20-mm spacing (150 mm TL), and 10-mm spacing (75 mm TL), and for 200 mm TL striped bass. These maximum prey lengths are used in analysis of the 'Alternative Design' for TFTF. See text and Figure 16 for details.

Figure 16. Tracy Fish Test Facility 'Alternative Design' based on 1.5" spacing of primary louvers and 20 mm and 10 mm spacing of graders in holding tanks. Arrows at right show routes of fish diverted from primary louvers into holding tank 1, and then through the 20-mm grader into tanks 1A (larger fish) and 1B (medium-sized fish). Arrows down and to left show routes for fish passing through the leaky louver into the holding tanks, and then through the 10-mm grader into tanks 2A

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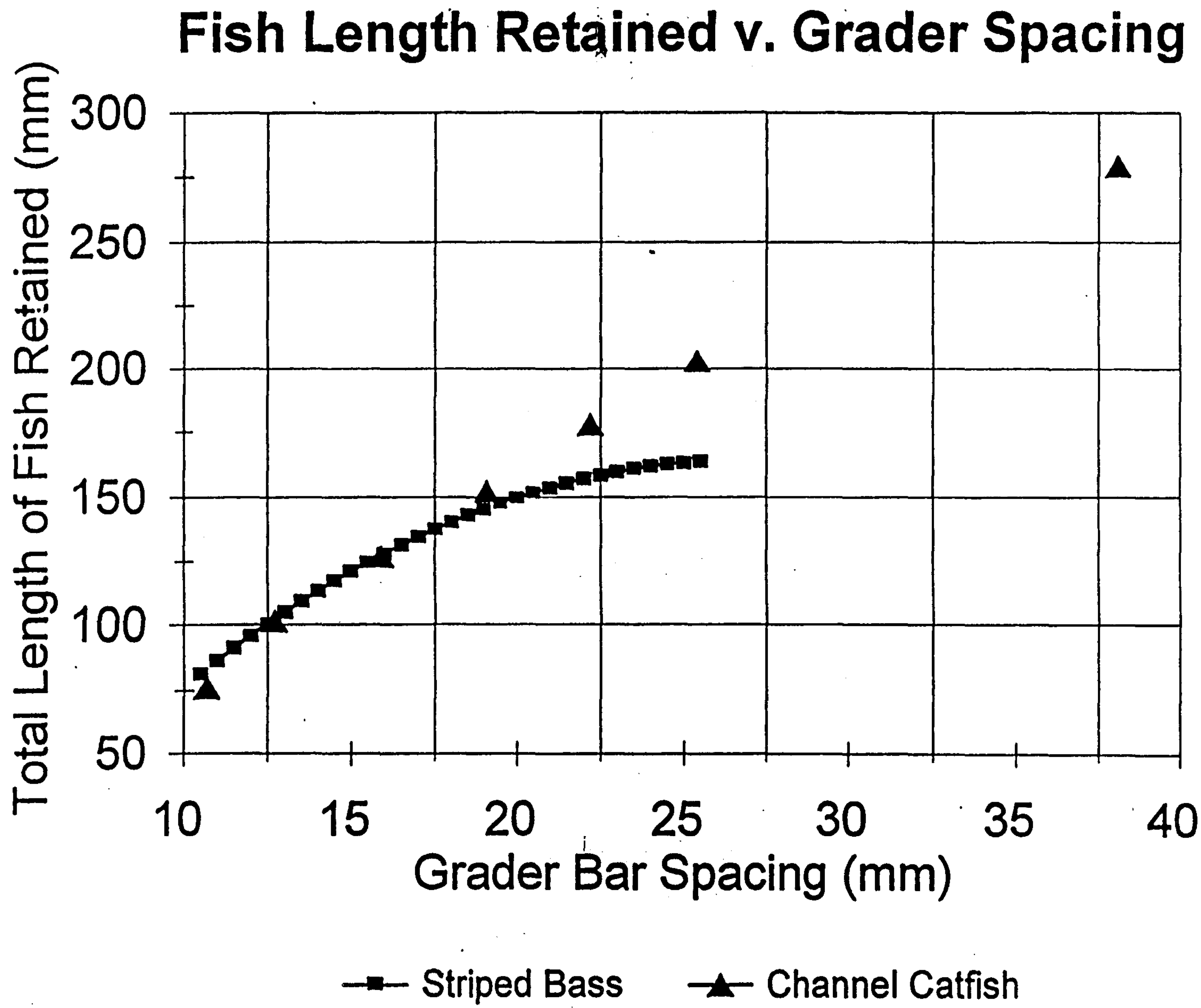

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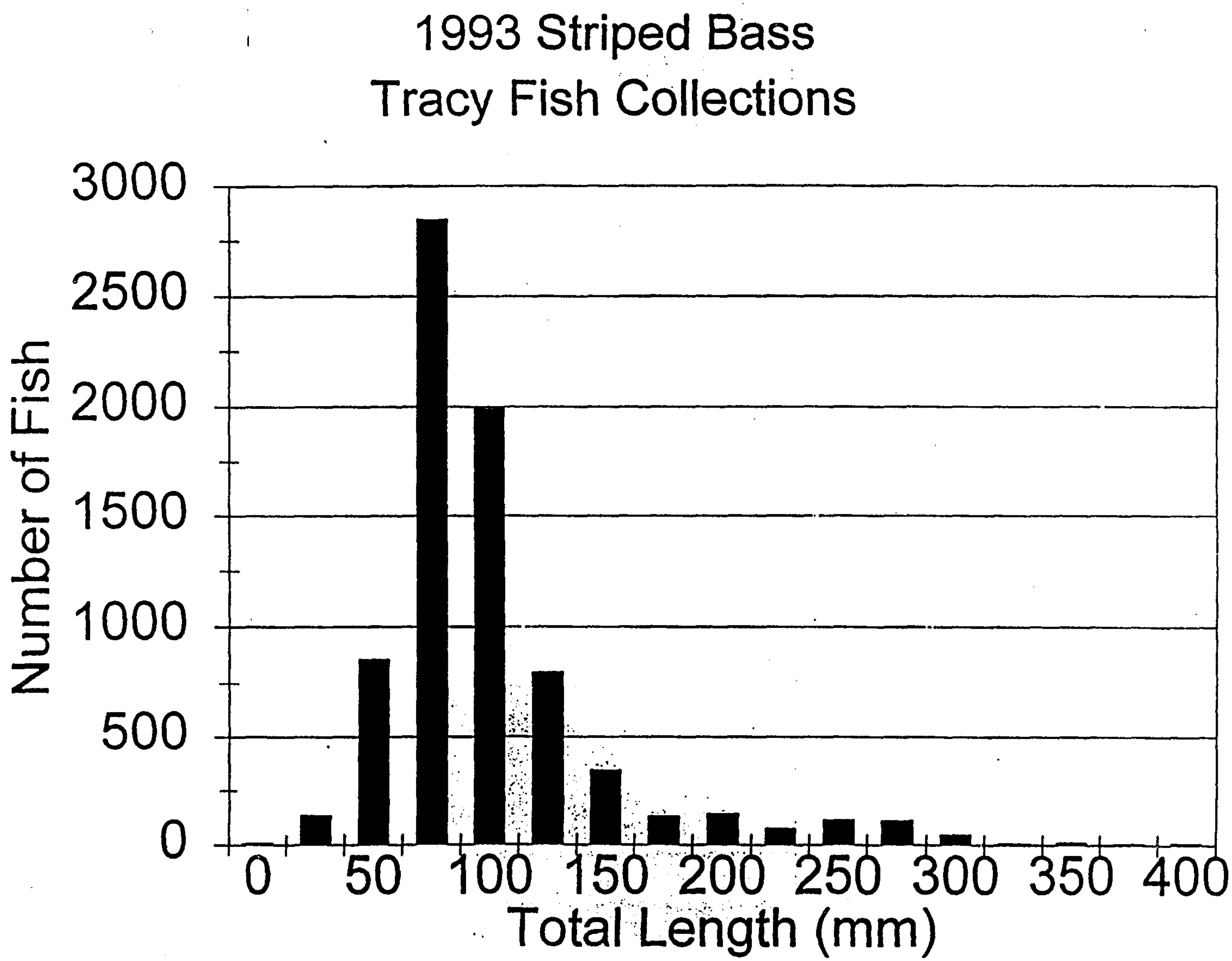


Figure 2. Lengths of striped bass reported from all 1993 10-minute fish collections as the Tracy Fish Collection Facility.

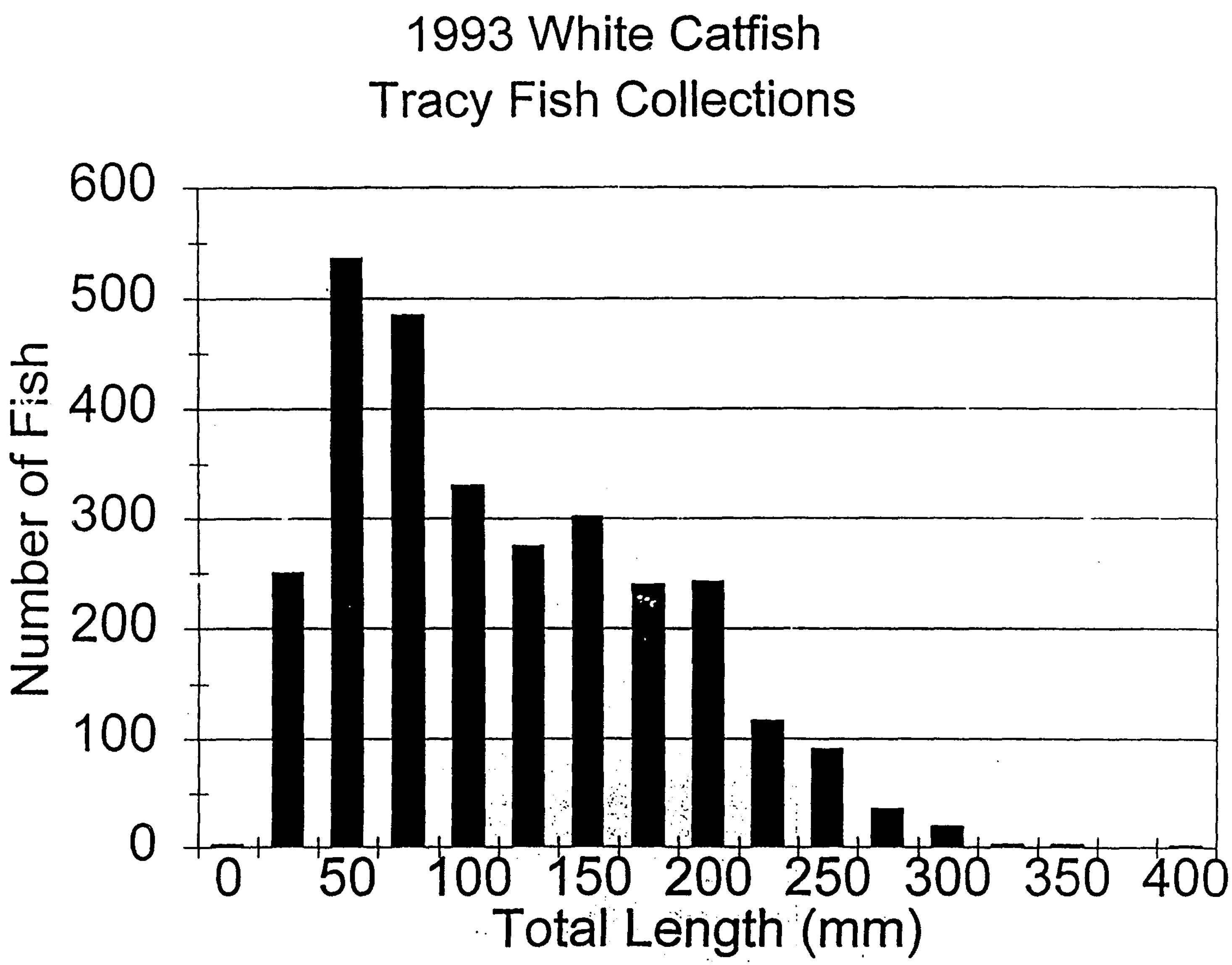


Figure 3. Lengths of white catfish reported from all 1993 10-minute fish collections at the Tracy Fish Collection Facility.

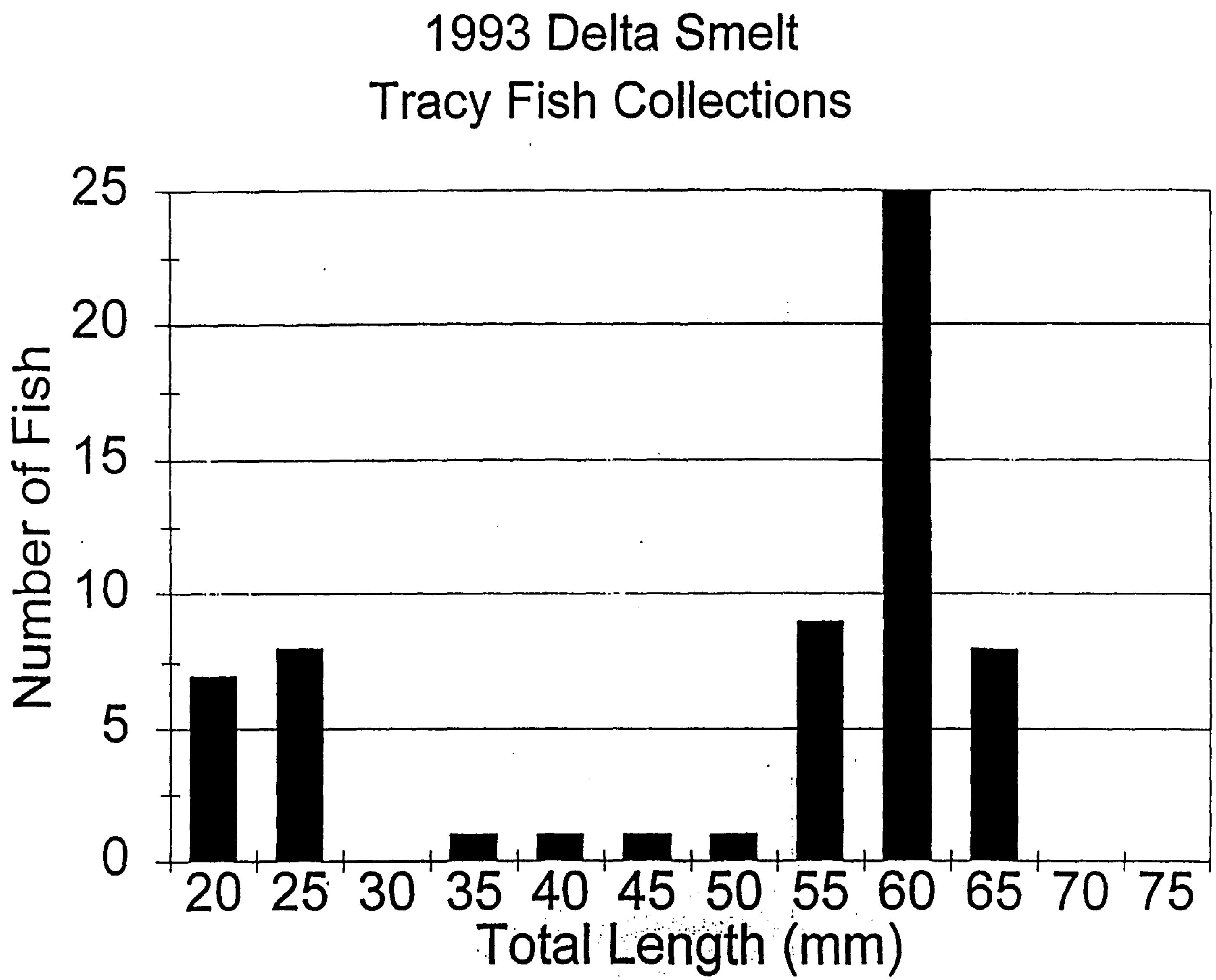


Figure 4. Lengths of delta smelt reported from all 1993 10-minute fish collections at the Tracy Fish Collection Facility.

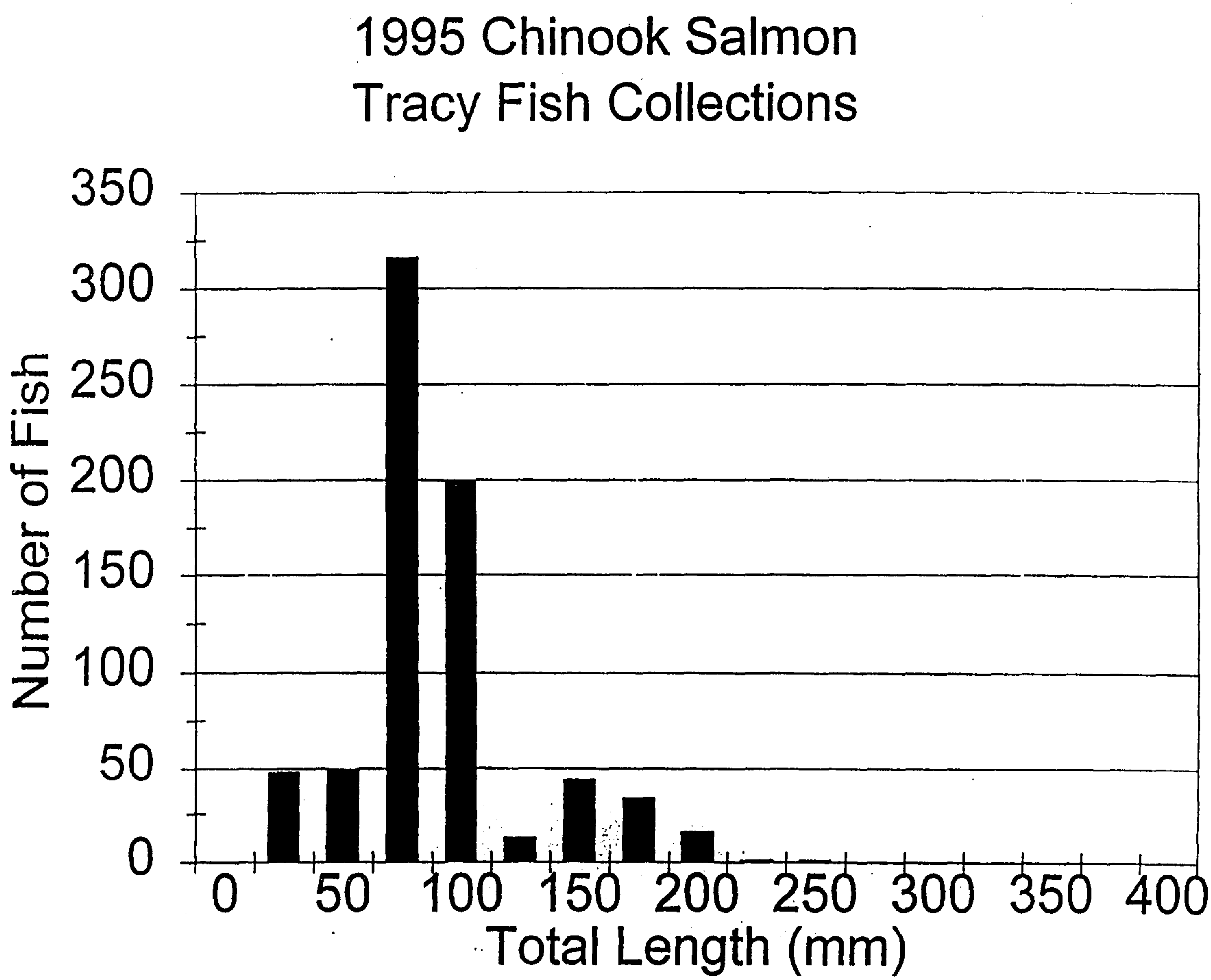


Figure 5. Lengths of chinook salmon reported from all 1995 10-minute fish collections at the Tracy Fish Collection Facility.

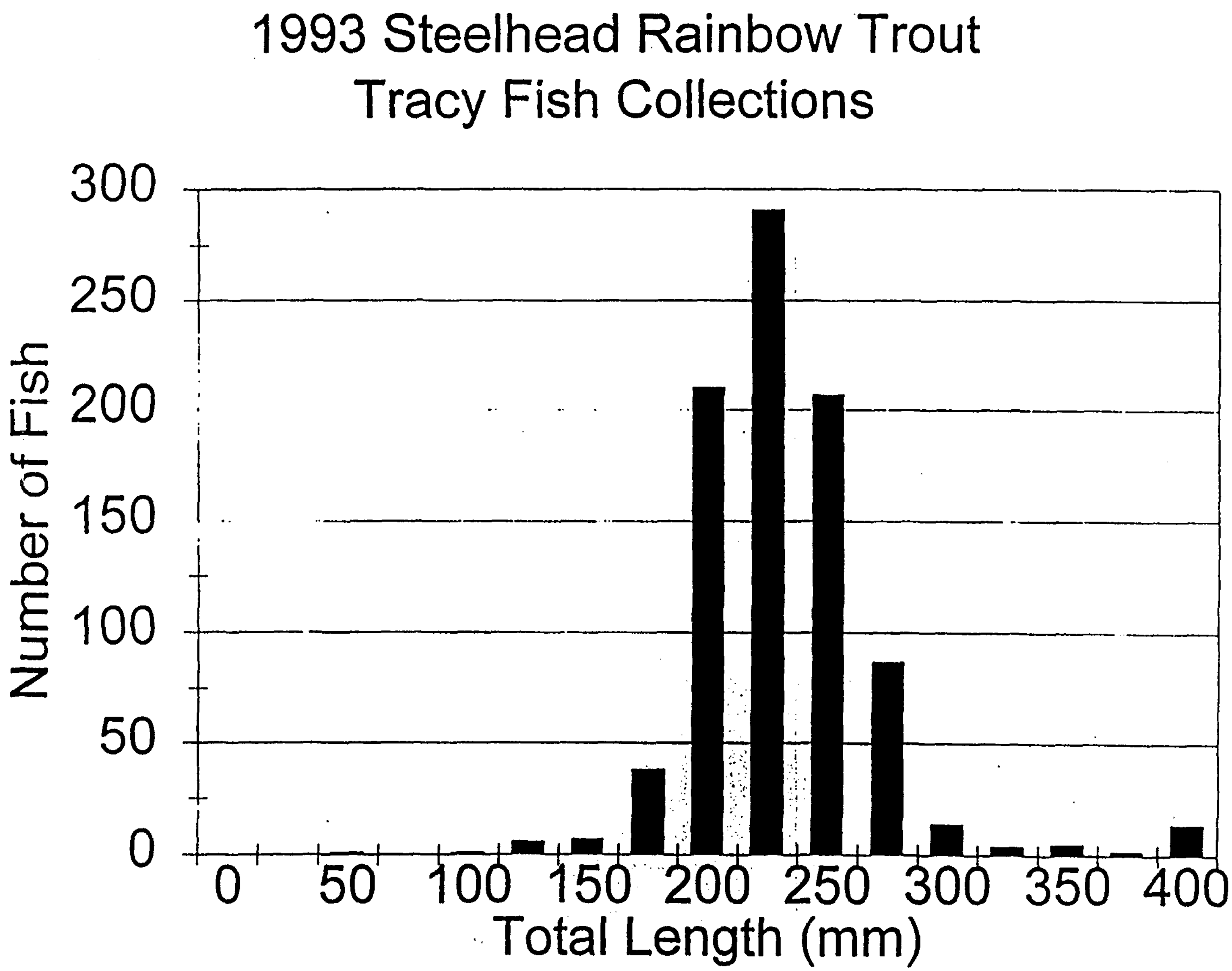


Figure 6. Lengths of steelhead trout reported from all 1993 10-minute fish collections at the Tracy Fish Collection Facility.

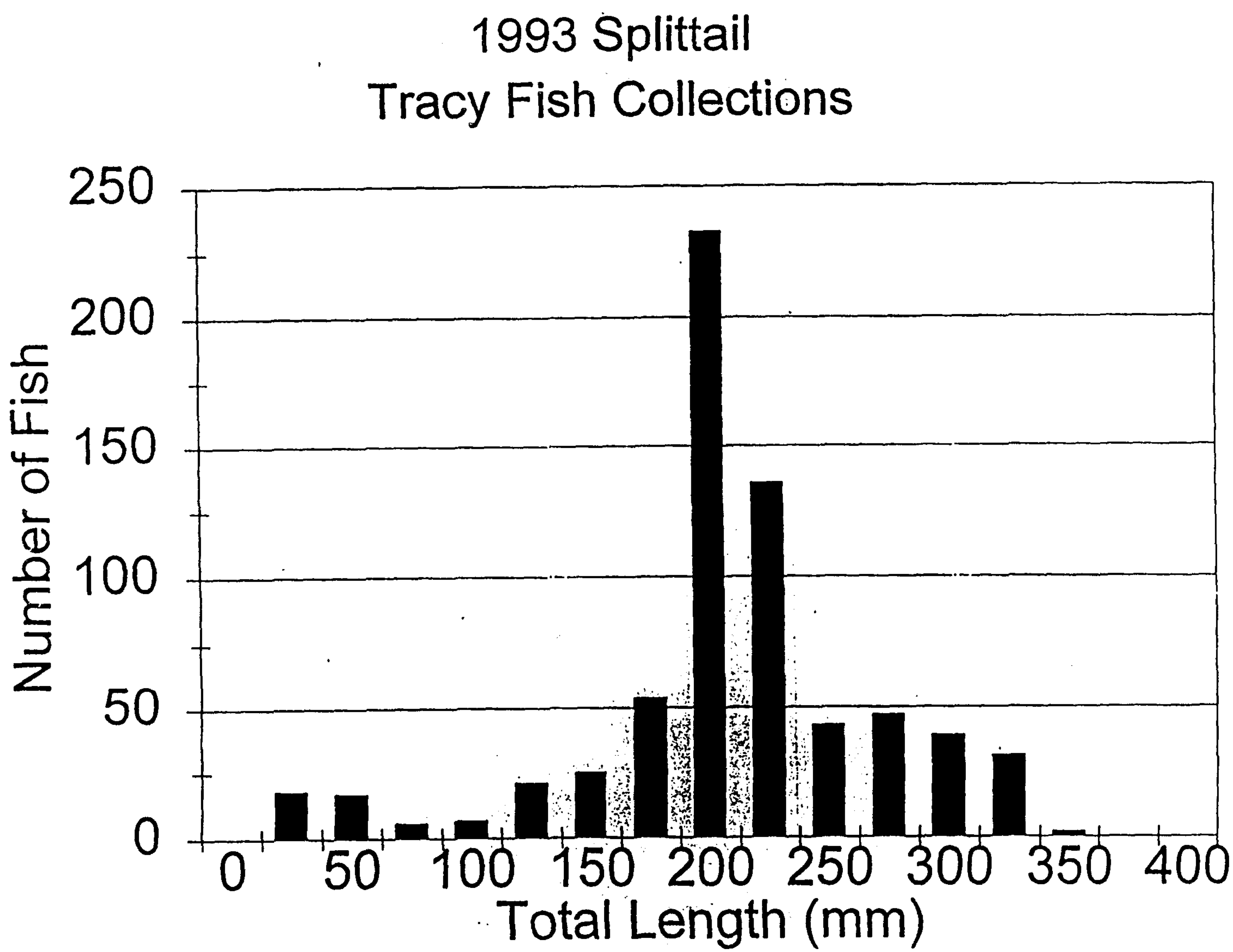


Figure 7. Lengths of splittail reported from all 1993 10-minute fish collections at the Tracy Fish Collection Facility.

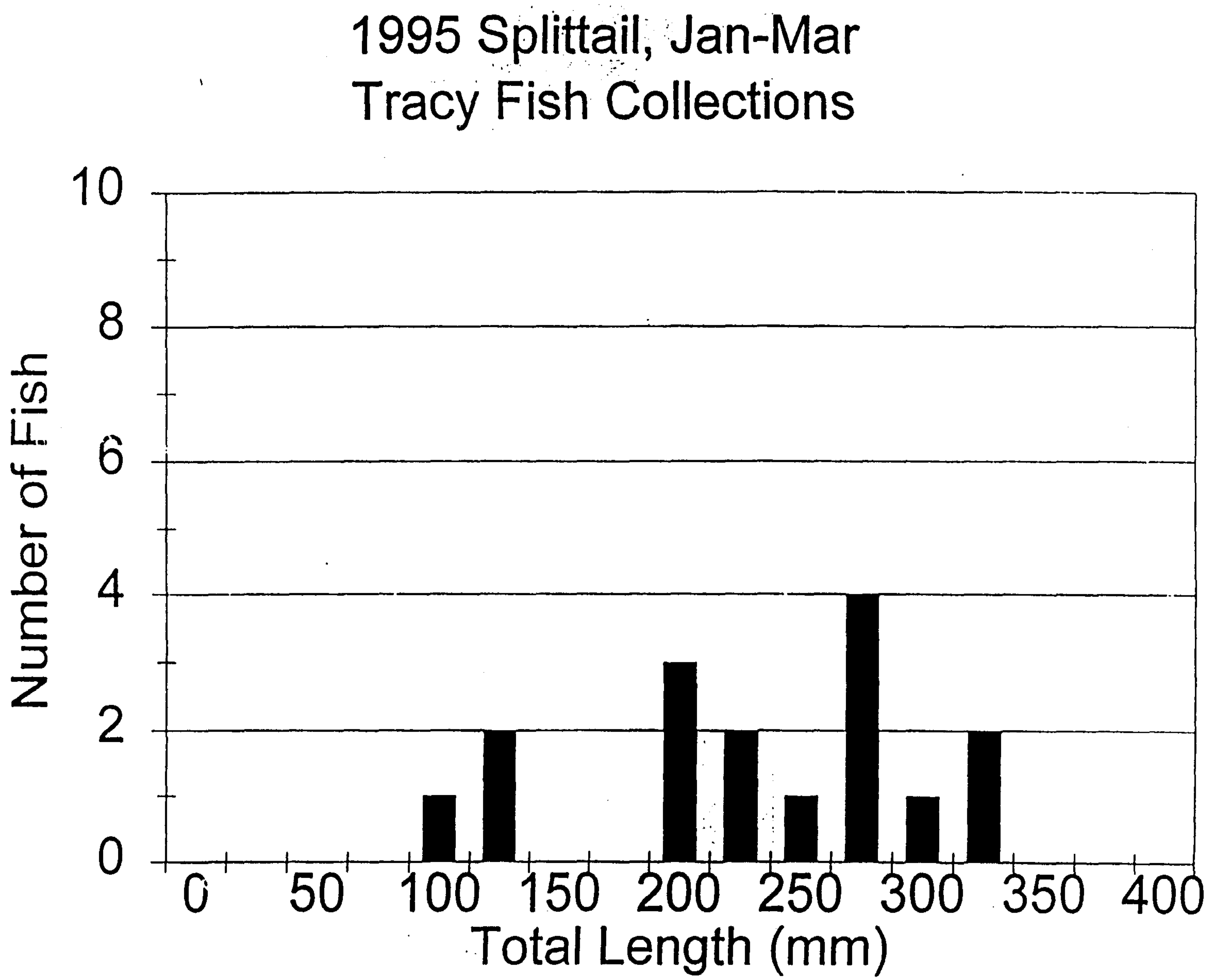


Figure 8. Lengths of splittail reported from 1995 10-minute fish collections during January through March at the Tracy Fish Collection Facility.

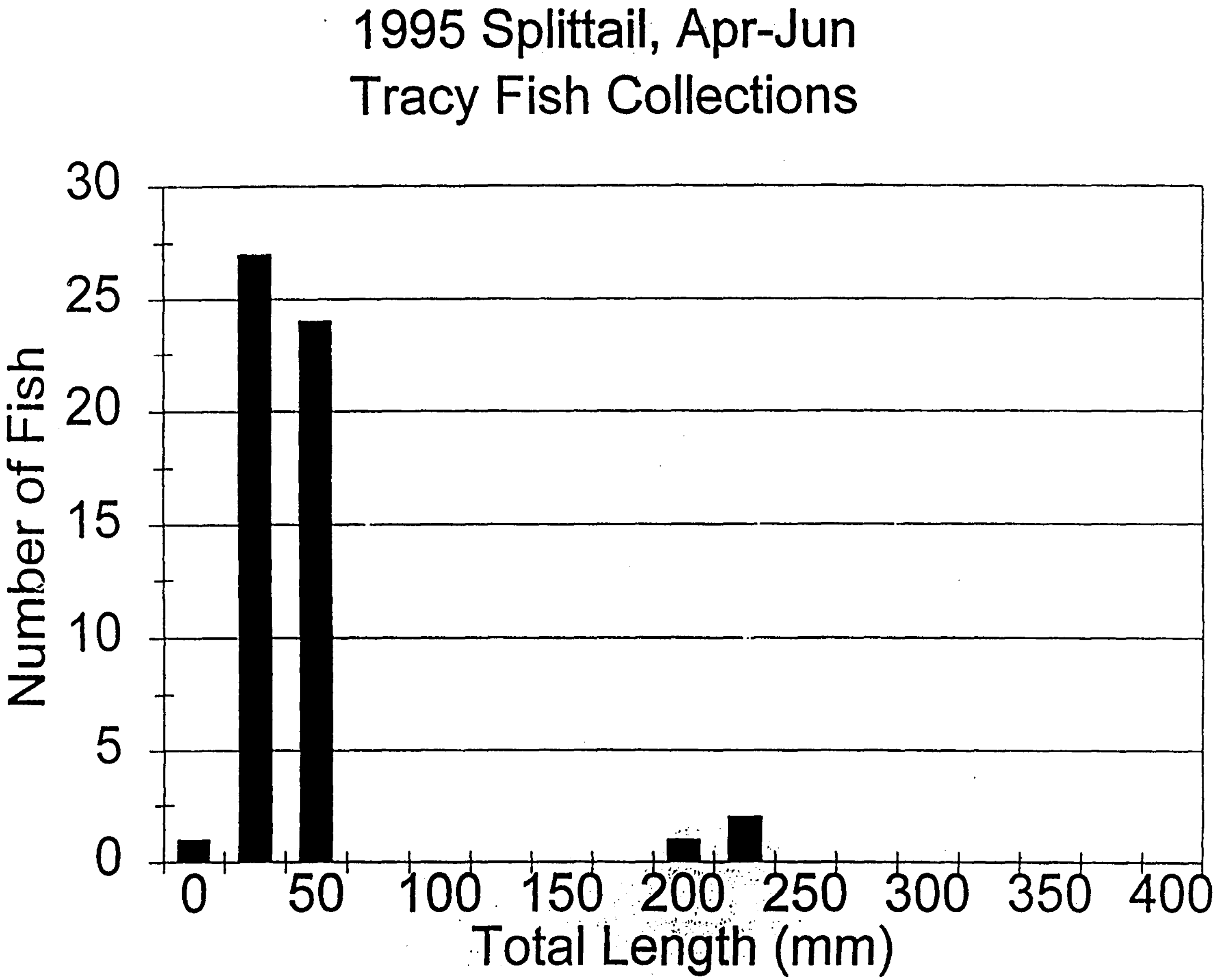
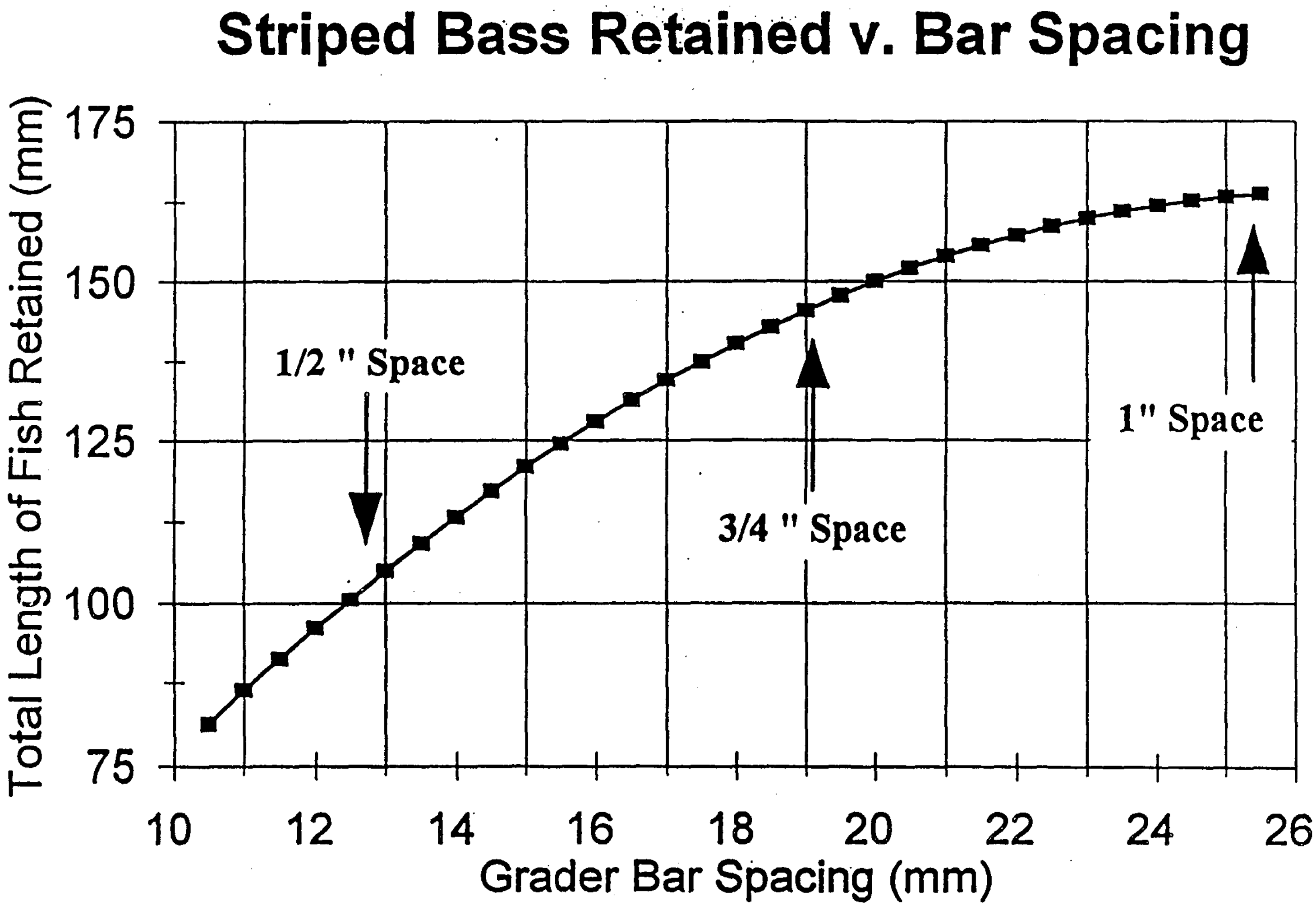


Figure 9. Lengths of splittail reported from 1995 10-minute fish collections during April through June at the Tracy Fish Collection Facility.



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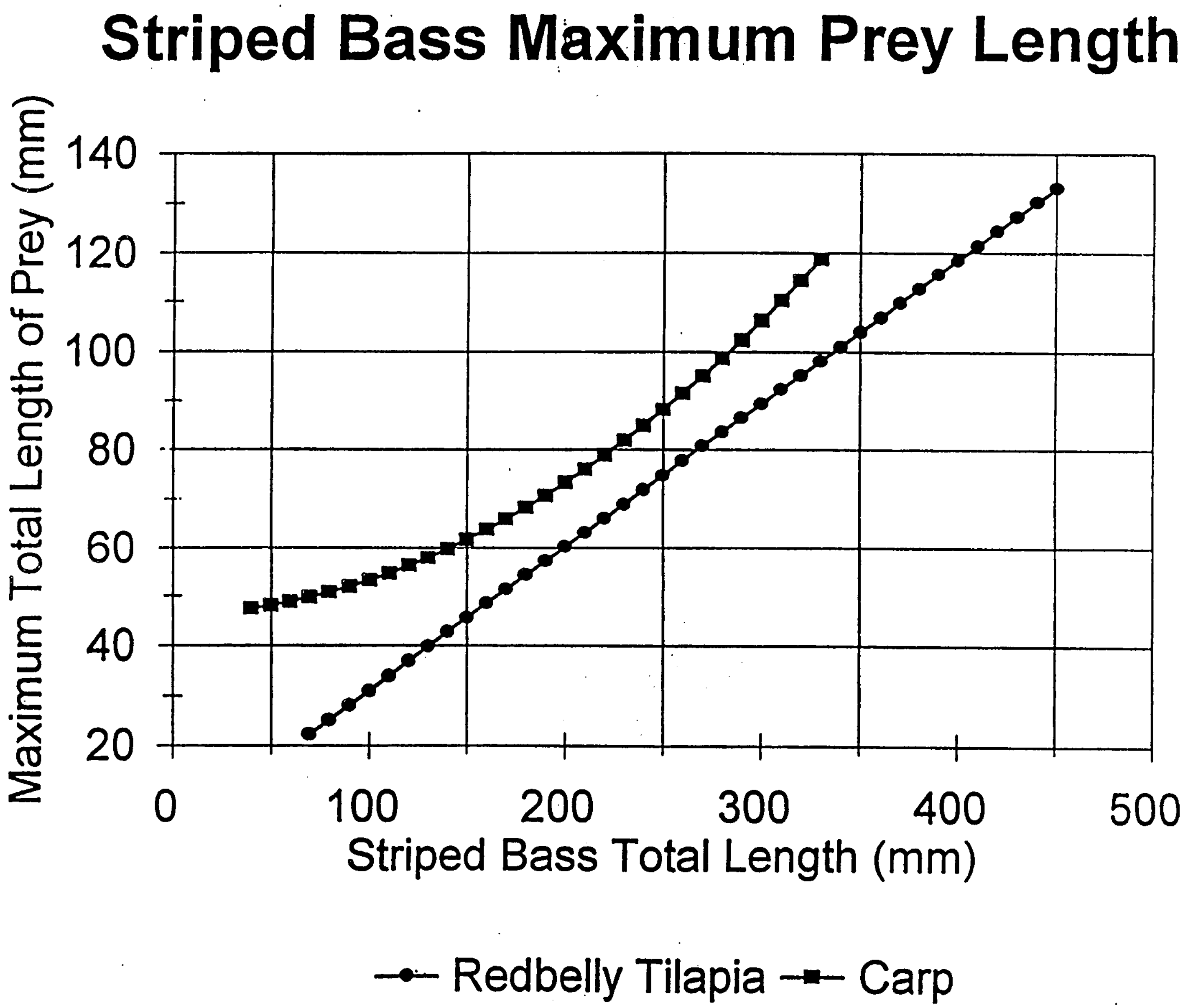

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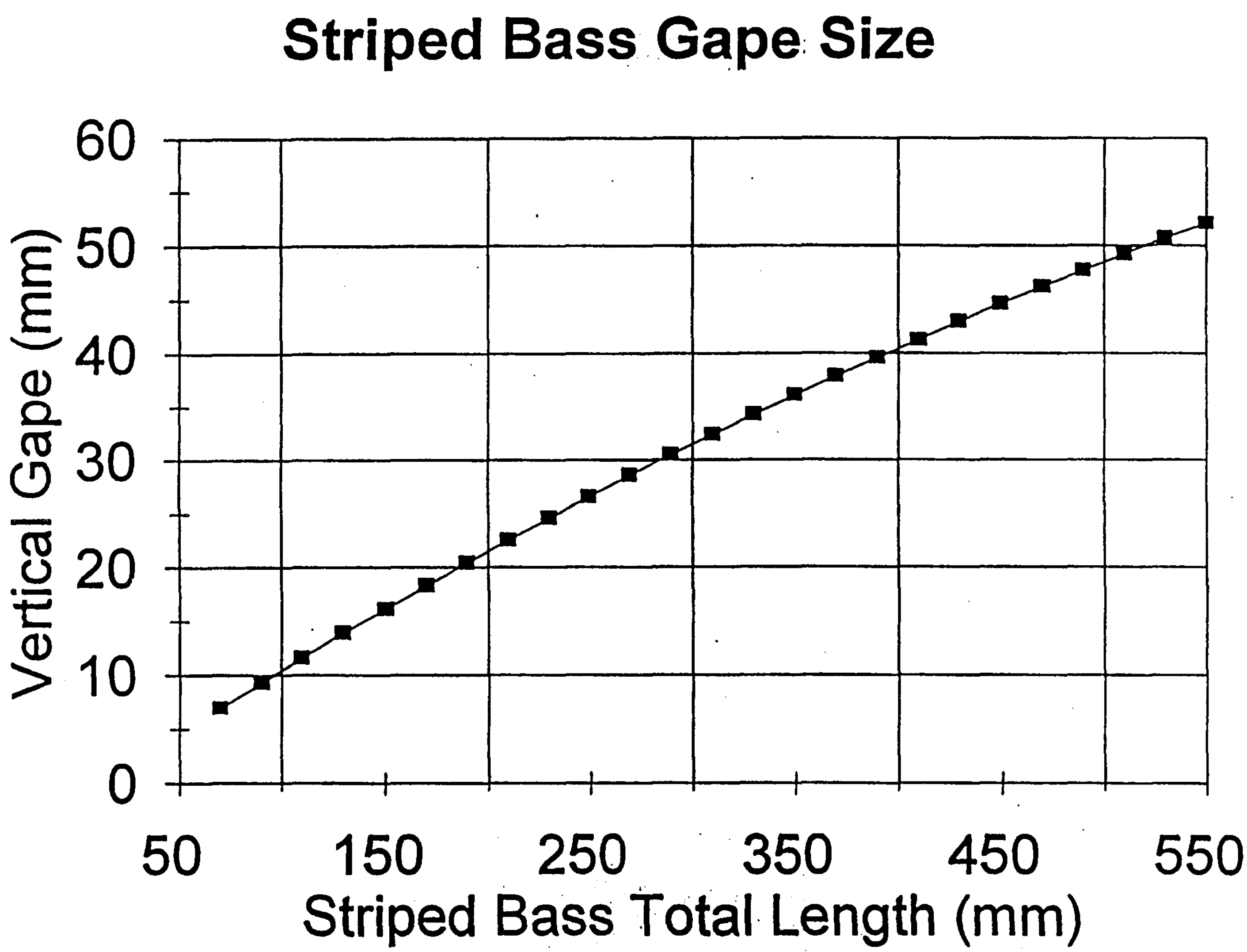

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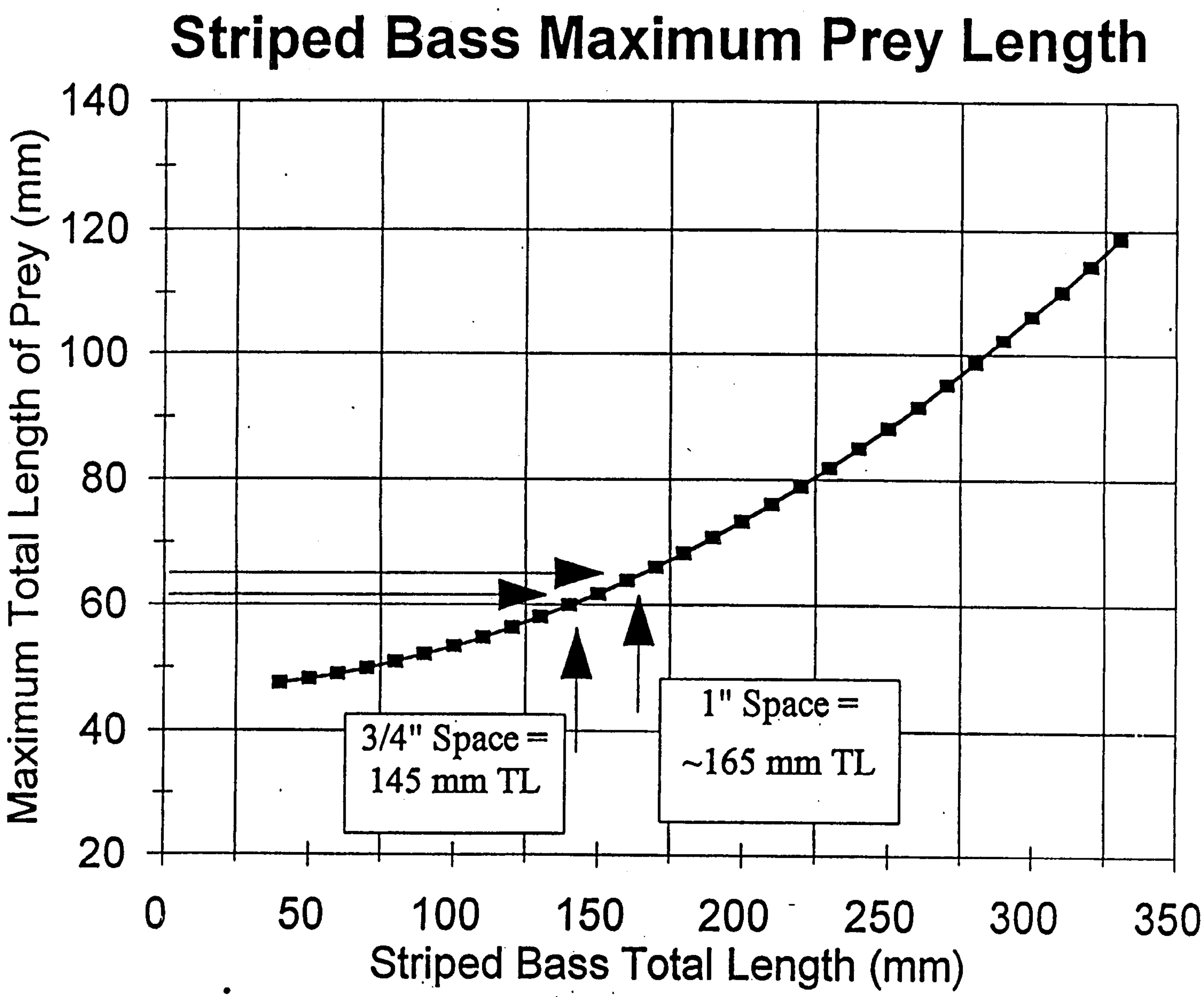

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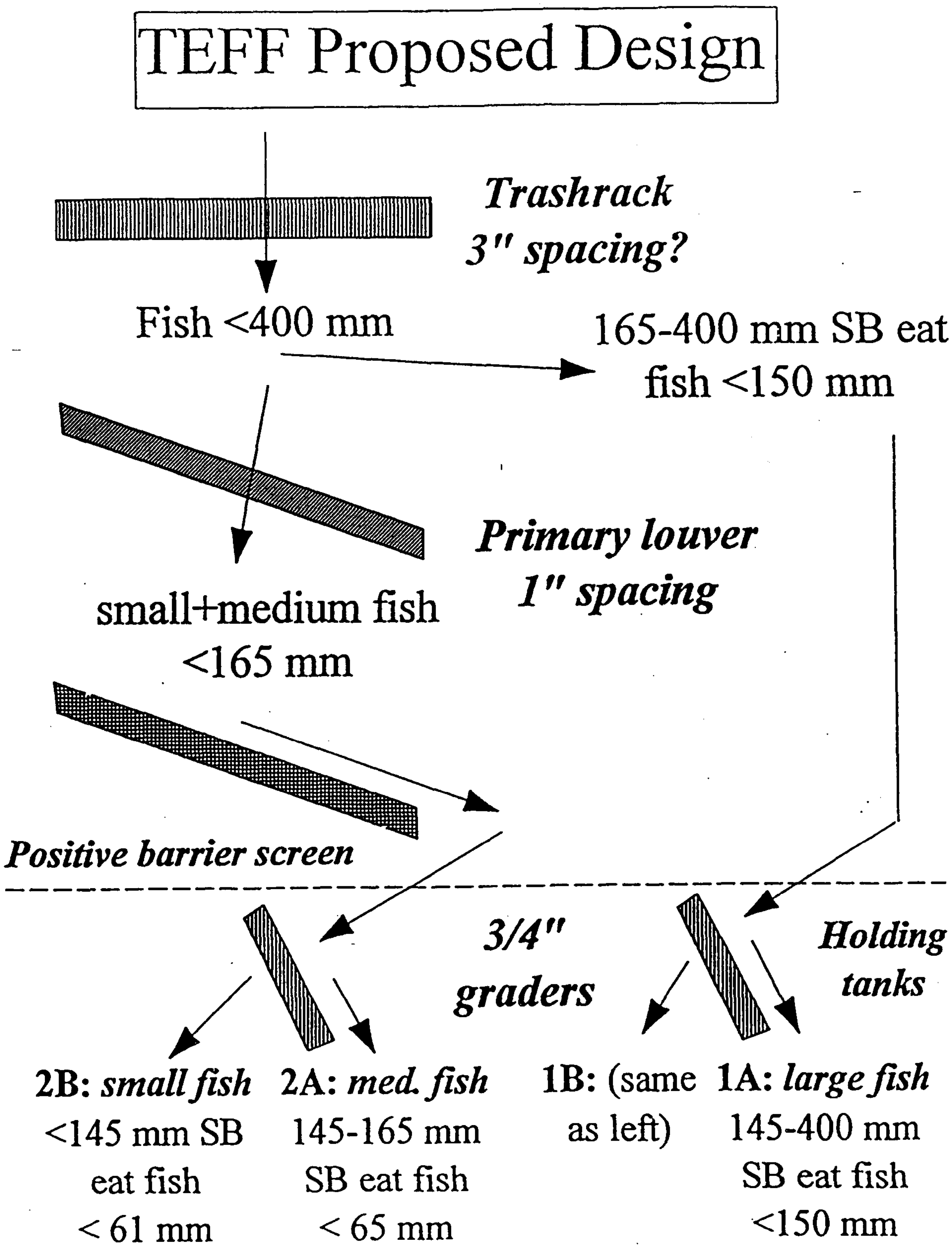

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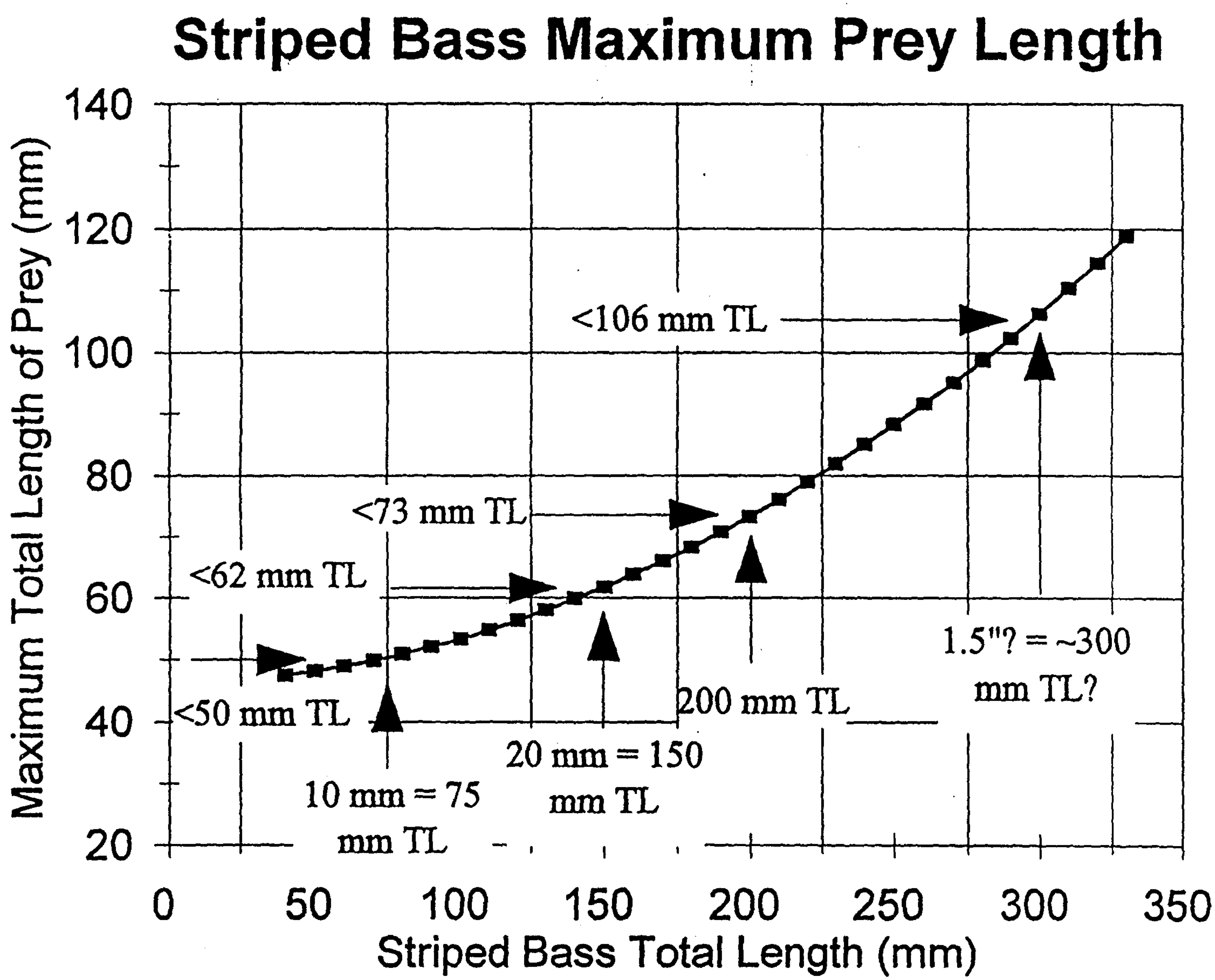

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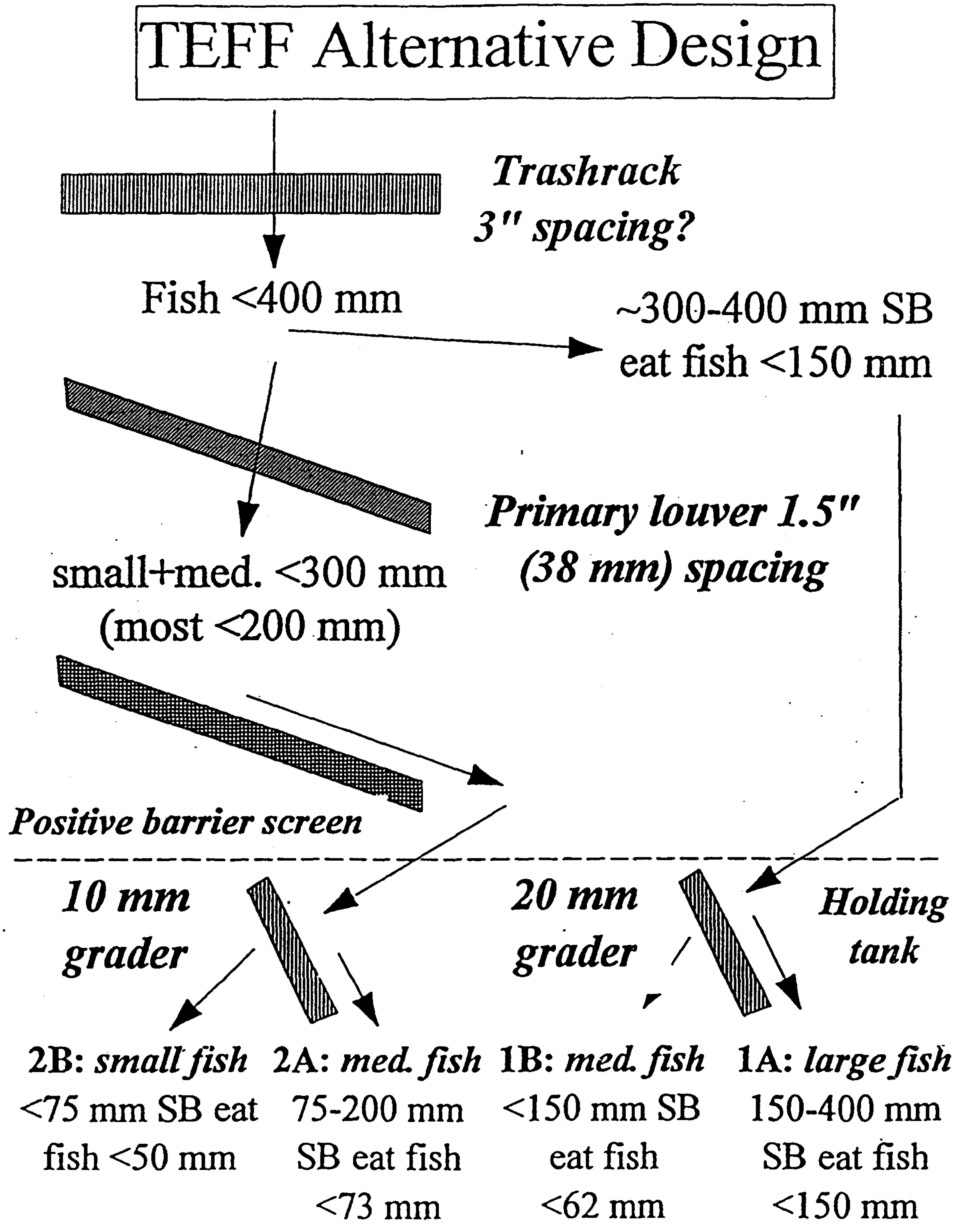

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