

The rise and fall of electrical beam trawling for shrimp in the East China Sea: technology, fishery, and conservation implications

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Since the 1980s, shrimp beam trawling has flourished in inshore waters of the East China Sea (ECS) off Zhejiang Province. By 2000, there were more than 10 000 beam trawlers operating in the area. The fishery targets several species of shrimp, including *Parapenaeopsis hardwickii*, *Solenocera crassicornis*, *Parapenaeus fissuroides*, and *Trachypenaeus curvirostris*. In the early 1990s, electrical beam trawls using pulse generators, powered either from the vessel or from underwater battery packs, became popular in the fishery. As a result of this new technology, the catch rates of shrimp, especially the burrowing shrimp species, increased. At its peak usage, there were more than 3000 vessels using electrical beam trawls in Zhejiang Province and another 500 or more in the adjacent provinces of Jiangsu and Fujian. This technology was also widespread along the Chinese coast, but a lack of regulation resulted in the misuse of electrical pulse parameters that caused damage to juvenile shrimps and other benthic species. In 2001, this fishing method was banned from the waters off Zhejiang Province, and subsequently in other parts of the ECS. This paper reviews the research on electrical beam trawls, the fishery, and fishery-management issues associated with this new technology.

Keywords: beam trawl, electrical stimulus, shrimp, shrimp electrical pulse stimulus apparatus.

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Introduction

The East China Sea (ECS) is the main fishing ground for a variety of species of fish, shrimps, and crabs in China. Severe overfishing in the 1960s and 1970s resulted in the depletion of several major commercial fish species, such as the large yellow croaker (*Larimichthys crocea*) and the little yellow croaker (*L. polyactis*). This depletion of major predators resulted in a boom of a key prey item, shellfish. Consequently, fishing gears and operations have been adapted to harvest the new target species. Shrimp beam trawls were successfully introduced in 1980 (Zhou, 1999), and their use escalated over the next 20 years. At the beginning of the 1990s, an estimated 5500 beam trawlers were fishing in the ECS, with an annual shrimp production of 145 000 t (Song *et al.*, 1991). Since then, the fishing grounds have expanded to include the offshore areas, and both vessels and gears have increased in size. By 2000, an estimated 10 000 shrimp beam trawlers were operating in the ECS.

The use of electricity in fisheries may be more than 200 years old (Polet *et al.*, 2005). Many research and practical applications of electricity in freshwater fisheries were reported at a special symposium held in Belgrade in May 1966 (Vibert, 1967). In the 1970s, several studies investigated the use of electricity in flatfish and crustacean fisheries in the North Sea (De Groot and Boonstra, 1974; Stewart, 1974, 1975, 1977). However, a ban on its use by the European Union in 1988 abruptly ended this research. In the early 1990s, renewed interest in this research centred on the reduction of seabed impact by heavy beam trawls in the North Sea (van Marlen, 1997; van Marlen *et al.*, 1999, 2001, 2005, 2006; Polet *et al.*, 2005).

In China, similar research into the use of electrical stimuli for fishing started in 1974 (Hong *et al.*, 1981), but the research was not applied to the fisheries at that time. Research resumed in 1992, leading to the development of an electrical beam trawl system, powered either through cables or by a battery-pack system, which was adopted by the fishery. By 2000, an estimated 3000 beam trawlers were operating in coastal and offshore areas of Zhejiang Province, using a shrimp electrical pulse stimulus apparatus (SEPSA; Chen, 2001). This device was also tested in Belgium for use in the brown shrimp (*Crangon crangon*) beam trawl fishery (Polet *et al.*, 2005).

The use of the SEPSA system led to increased catch rates and total landings of shrimp, and subsequent overfishing caused a large decrease in biomass. To compensate for this reduction in catch rates, many operators adjusted the electrical output parameters of SEPSA to increase the size range of the shrimp being caught, resulting in further biomass depletion. Faced with the inability to control the manufacture, trade, and use of illegal SEPSA, the fishery management authority in Zhejiang Province, one of the primary provinces using SEPSA in the ECS, decided to ban the use of SEPSA within its jurisdiction on 1 January 2001. This paper reviews the development of shrimp beam trawling in the ECS, the use of electrical pulse stimulus systems, and the management issues that developed with the fishery. We begin with background information on the reaction behaviour of shrimp to electrical stimuli, which led to the development and selection of electrical output parameters for the SEPSA system.

Reaction of shrimp to electric stimuli

Seawater has very low electrical resistance, and using direct current (DC) power in seawater requires a large amount of power. Using electrical pulses instead of DC, power consumption can be reduced. When shrimp are exposed to electrical pulses, they react immediately and strongly, so electrical pulse stimuli, not DC stimuli, were adapted for use in the fishery. Electrical pulses are characterized by shape, amplitude, width, frequency, and duration of bursts. When shrimp are exposed to different pulses, they generally elicit three different reactions: jumping, narcosis, or death. The effect of electrical pulses on shrimp depends largely on the steepness of the rising and falling edges of the pulse (Zhejiang Fisheries College, 1981). The steeper edges cause greater reactions in shrimp, but shrimp are also sensitive to the exponentially declining pulses. Shrimp are also less sensitive to DC stimuli. In laboratory experiments, when 50 Hz AC stimuli were applied to shrimp, they exhibited tetanus reactions and soon became narcotized (electro-narcosis), sinking to the bottom of the tank (Hong *et al.*, 1981). When the strength of stimuli remained high, shrimp mortality increased.

Chen (2001) reported on a detailed laboratory study on the reaction thresholds of four major commercial shrimp species in the ECS, with water temperature at 18°C and salinity at 29 psu, using 5 Hz electric pulses (Figure 1). The species tested were Kuruma prawn (*Penaeus japonicus*), spear shrimp (*Parapenaeopsis hardwickii*), southern rough shrimp (*Trachypenaeus curvirostris*), and coastal mud shrimp (*Solenocera crassicornis*). The main conclusions from these experiments were:

- (i) When the orientation of shrimp was parallel with the electrical field (perpendicular to the electrodes), the shrimp were more sensitive to the stimuli. For example, the threshold electrical field strength (EFS) was 1.8 V m^{-1} when the shrimp body was parallel with the field and 4.2 V m^{-1} when it was perpendicular to the field. Large shrimp were more sensitive to stimuli than smaller ones, regardless of their orientation to the electrical field. For all shrimp species (five length classes), the threshold EFS ranged from 1.8 to 18 V m^{-1} when the

pulsewidth was longer than 0.3 ms, and large shrimp had a higher EFS threshold than small shrimp. In the same electrical field, large shrimp would also react more strongly or earlier than small shrimp. This provided a basis for size selection in fishery applications.

- (ii) To induce a strong reaction in the shrimp, a pulse with sufficient width was required. For all shrimp species, the threshold pulsewidth was 0.1 ms, and anything below that required higher pulse amplitude. However, further increases in pulsewidth did not reduce the threshold pulse amplitude.
- (iii) As power consumption was related to pulsewidth and pulse amplitude, the optimal pulsewidth for the desired reaction was between 0.2 and 0.3 ms for these shrimp species.

These results were used to determine suitable EFS strengths and to determine the orientation of the electrodes when targeting suitable shrimp sizes in fishery applications. When shrimp are buried in the substratum, a higher EFS is required than that used when the shrimp remain on the substratum surface (Chen, 2001). Typically, the buried shrimp feel the first pulse, and a second pulse causes them to jump out of the substratum. The stronger the EFS, the shorter the reaction time. For small, 50 mm total length (TL) shrimp, the threshold EFS for jumping out of the substratum was 38 V m^{-1} when the body was parallel with the electric field, and 58 V m^{-1} when it was perpendicular to the electric field (Chen, 2001).

Fewer bursts were needed to narcotize shrimp when long pulses with higher EFS were used. Table 1 (adapted from Chen 2001) shows the number of pulse bursts required for 90 mm TL Kuruma prawns to become electro-narcotized by 5 Hz pulses. The length of each pulse burst was 1 s. At the threshold EFS, increasing pulsewidth had little effect on the height the shrimp would jump. However, increasing the EFS or pulse frequency increased the shrimp jumping height until it reached its maximum (Hong *et al.*, 1981).

Shrimp electrical pulse stimulus apparatus

The SEPSA system consisted of a power source, pulse generator, electrodes, and power transmission cables. A DC transformer was used to raise the voltage, and output from the pulse generator was passed to the electrodes installed in front of the groundgear. The pulse generator was encased in a 200 mm diameter, 1 m long steel cylinder. Because the power was from a generator aboard the vessel, the electrical fields were stable and not affected by the length of the tow. Transmitting higher voltage DC power through these small-diameter electric cables also reduced power consumption and costs. The cabled high-voltage transmitting method became popular in the fishery in 1992. In 1996, a cableless system was invented, which featured a battery pack installed in a long, steel tube (2.5 m) together with the pulse generator. Cableless systems were much easier to operate during shooting and hauling of the gear. However, the battery pack must be changed and recharged after every tow to ensure that enough power is available to generate pulses of sufficient strength. Because of the residual memory of rechargeable batteries, voltage drops as the tow length increases, and the effectiveness of the system is lowered. Nevertheless, the invention of the cableless system replaced a portion of the cabled SEPSA in the fishery.

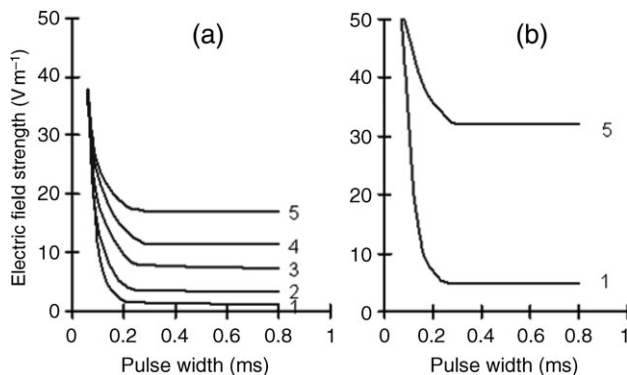


Figure 1. Thresholds of electrical field strength in relation to pulsewidth for different species of shrimps: (a) body axis parallel with the electrical field, and (b) body axis perpendicular to the electrical field. 1, Kuruma prawn (*Penaeus japonicus*) 160 mm TL; 2, Spear shrimp (*Parapenaeopsis hardwickii*) 110 mm TL; 3, southern rough shrimp (*Trachypenaeus curvirostris*) 80 mm TL; 4, coastal mud shrimp (*Solenocera crassicornis*) 65 mm TL; 5, spear shrimp (*Parapenaeopsis hardwickii*) 50 mm TL (after Chen, 2001).

Table 1. The number of bursts and duration required to narcotize Kuruma prawn (*Penaeus japonicus*) of 90 mm TL under different EFSs and pulsewidths (Chen, 2001).

Electrical field strength (v/m)	Pulsewidth					
	0.3 ms		0.6 ms		0.9 ms	
	Number of bursts	Duration (s)	Number of bursts	Duration (s)	Number of bursts	Duration (s)
48	21	42	19	38	14	28
60	19	38	18	36	14	28
70	17	34	17	34	14	28

The operational parameters of a SEPSA were determined according to the shrimps' reaction to electrical stimuli, as discussed earlier, and with consideration for minimizing power consumption. Typical parameters of a SEPSA are listed in Table 2 (adapted from Chen, 2001). The electrodes, made of 7.5 mm copper, were connected to the pulse generator through a short cable. The electrodes were usually strengthened with a steel cable to reduce damage. The steel cable also increased the weight of the electrodes to ensure better bottom contact.

Work in both the laboratory and the field demonstrated that buried shrimp generally jumped out of the substratum to a height above the groundgear within the first 2–3 pulses. Therefore, in setting up the SEPSA, the distance between the electrodes (D , in m) should meet the following condition:

$$D \geq VMf^{-1},$$

where V is the towing speed in m s^{-1} , M the number of pulses required, and f the pulse frequency (Hz). For typical applications, $f = 3\sim 5$ Hz, $V = 1 \text{ m s}^{-1}$, and $M = 2\sim 3$; the distance between the electrodes should be greater than 0.6–1.0 m. In commercial applications, 1 m was the typical distance between the electrodes (Chen, 2001).

Fishing operations

All beam trawlers in the ECS are side trawlers, and those fishing with a SEPSA range in length from 24 to 36 m, and are equipped with 250–350 hp engines. Typical shrimp beam trawls in the ECS have beam lengths of 24–36 m and a net length between 15 and 19 m (Figure 2). Beams are typically made of seamless steel pipes of 180–230 mm diameter. The length of the beam is usually similar to the length of the vessel. Mesh sizes in the body of the net started with 45 mm at the front end, tapering to 25

mm in the codend. Earlier beam trawls had two codends, but now the majority of the trawls have between six and eight codends. Trawls with a large number of codends are generally more stable and result in better catch rates and quality.

A typical electrical shrimp beam trawl had an electrical pulse generator and associated components installed on the middle of the beam. Parallel electrodes were fitted in front of the groundgear to form an electrical field. The shrimp fishing depths in the ECS area ranged between 40 and 100 m, and to fish those depths, warp lengths of 7–12 times the depth were normally used. When the trawl reached the seabed, the power supply for the cable system was switched on or, if a cableless system was used, the power was switched on automatically through a pressure switch at a user-specified depth. The trawl was usually towed at 1.5–2 knots for 3–5 h.

There are 96 species of shrimp in the ECS (Liu, 1963), of which ten or more have commercial value (Song *et al.*, 1991). Different species are available at different times of the year, making shrimp trawling a year-round operation in the ECS (Figure 3, Table 3). The use of SEPSA increased shrimp catches by 40% and those of large shrimps by more than 100%, with a typical catch-per-tow of 80–150 kg. However, with the prevalence of illegally upgraded pulse parameters, greater proportions of small shrimp <50 mm were also being caught. This proportion was greater than before SEPSA was used in the fishery.

Fishery management challenges

Three major issues arose as the electrical beam trawl fishery developed: (i) high settings of the pulse parameters resulted in poor size selectivity and high mortality of juvenile shrimp; (ii) large-scale use of SEPSA technology contributed to overfishing of the resource; and (iii) illegal production, trade, and use of unauthorized SEPSA, together with an unregulated fishery, contributed to the decline in the shrimp resource.

On the basis of the research, pulse amplitudes of >60 V in a cabled system and >45.5 V in a cableless system would cause shrimp >50 mm TL to jump and fall into the net regardless of condition and orientation. Most small shrimp <50 mm TL would also respond to the stimuli. As a consequence of the large catches, the use of SEPSA became popular, which in turn led to a decline in abundance of some shrimp species. In response, some manufacturers and vessel operators, striving to maintain or improve catches, increased power output and reduced the electrode distance to increase the strength of the electrical field. This resulted in the capture of shrimps ranging widely in size, including juvenile shrimp and fish, which proved to be detrimental to the conservation of both shrimp and finfish resources. The cumulative effect of electrical stimuli from repeated encounters may also have resulted in an increase in the mortality of escaping shrimp and fish.

Table 2. Recommended parameters for the SEPSA (Chen, 2001).

Parameters	Cabled	Cableless
Pulse frequency (Hz)	5	4 ± 1
Pulsewidth (ms)	0.3	0.3–0.5
Pulse amplitude (V)	≥60	40.5 ± 5
Power output (kVA)	≥50	31–48
Pulse current (A)	≥1 000	–
Input voltage (V)	24	72
Electrode distance (m)	1	1
Electrode length (m)	30	30
Length of cable (m)	400–700	–
Water depth (m)	≤100	–

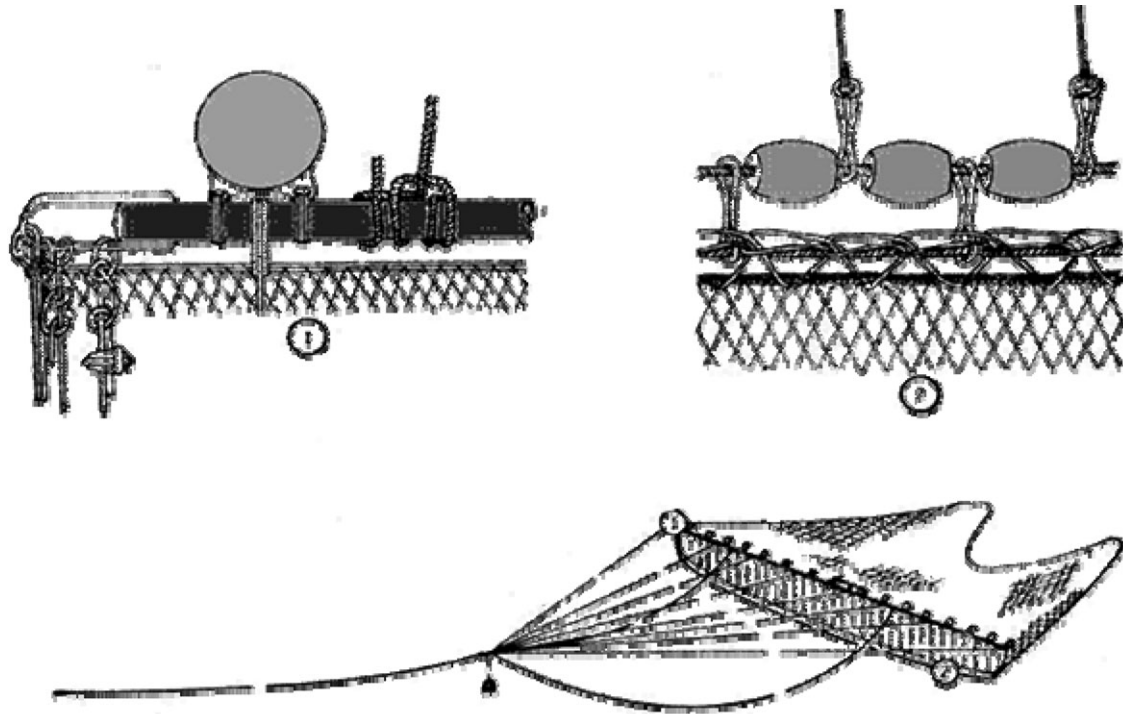


Figure 2. Rigging diagram of a typical shrimp beam trawl in the ECS (from Li *et al.*, 1990). 1, beam and headline rigging; 2, footgear rigging.

The increased efficiency of electrical beam trawlers put greater pressure on the stability of the shrimp resources. At the peak of its use, more than 35% of beam trawlers were using SEPSA. In Zhejiang Province alone, there were more than 3000 vessels using SEPSA on their beam trawls (Chen, 2001). As a result, the

shrimp biomass declined drastically; for example, the biomass in 1995 was 33.5% less than that estimated in 1994. The downward trend in shrimp biomass in the inshore areas continued until 1998. In addition, shrimp biomass offshore fluctuated and declined in the years leading up to the ban (Xu, 2000).

At the height of the fishery with SEPSA, management measures included licensing its use and limiting power output, and other

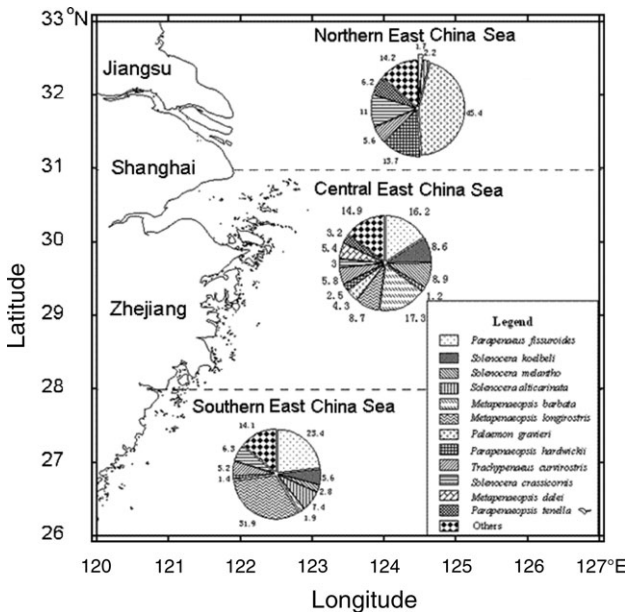


Figure 3. Map showing fishing areas in the ECS and major shrimp species caught (from data in Song, 2005).

Table 3. Fishing grounds, season, and major target species in the ECS.

Fishing grounds	Target species (fishing season: month of year 1–12)
Northern ECS	<i>Parapenaeus fissuroides</i> (12–5), <i>Solenocera alticarinata</i> (6–9), <i>Palaemon gravieri</i> (2–6), <i>Parapenaeopsis hardwickii</i> (10–4), <i>Tachypenaeus curvirostris</i> (5–8), <i>Solenocera crassicornis</i> (8–4), <i>Parapenaeopsis tenella</i> (5–11)
Central ECS	<i>Parapenaeus fissuroides</i> (12–5), <i>Solenocera koelbeli</i> (6–10), <i>Solenocera melantho</i> (6–9), <i>Solenocera alticarinata</i> (6–9), <i>Metapenaeopsis barbata</i> (6–10), <i>Metapenaeopsis longirostris</i> (3–7), <i>Palaemon gravieri</i> (2–6), <i>Parapenaeopsis hardwickii</i> (10–4), <i>Trachypenaeus curvirostris</i> (5–8), <i>Solenocera crassicornis</i> (8–4), <i>Metapenaeopsis dalei</i> (5–8), <i>Parapenaeopsis tenella</i> (5–11)
Southern ECS	<i>Parapenaeus fissuroides</i> (12–5), <i>Solenocera koelbeli</i> (6–10), <i>Solenocera melantho</i> (6–9), <i>Solenocera alticarinata</i> (6–9), <i>Metapenaeopsis barbata</i> (6–10), <i>Metapenaeopsis longirostris</i> (3–7), <i>Parapenaeopsis hardwickii</i> (10–4), <i>Trachypenaeus curvirostris</i> (5–8), <i>Solenocera crassicornis</i> (8–4)

output-parameter settings. Management had no certification processes for device manufacturers to control development, and there was no suitable equipment to monitor and enforce regulations on SEPSA output parameters in the fishery. Because of large profit margins in the sale of SEPSA, many underground manufacturers emerged in coastal regions. The immediate effect of an increase in catch, when higher output SEPSA parameters were used, resulted in many manufacturers producing devices that exceeded the output values set by the management authorities. The SEPSA system was becoming, more or less, an electrical killing apparatus, rather than the intended stimulus device. Fishery management authorities were unable to control and regulate use of the illegal technology because of the large numbers of vessels involved and the wide geographical expanse of coastal communities. As a result, on 1 January 2001, the SEPSA system was banned by the Zhejiang Provincial Fishery Bureau from its coastal waters (Zhejiang Ocean and Fishery Bureau, 2000, 2001). The ban included the manufacture, sale, repair, transport, and use of any SEPSA.

In addition to this ban, other management measures were implemented in an effort to reduce the heavy fishing pressure and restore the shrimp resources. Shrimp fishing permits were issued to limit the number of vessels allowed in the fishery and, in 2005, a 1-month closed season was implemented to protect juvenile shrimp. In 2006, this seasonal closure was extended to 2 months (16 June to 16 August). Although the shrimp resource included several commercial species with different biological characteristics, migration patterns, and spawning times (Song, 2005), existing management and enforcement capacities did not allow for complex management strategies, such as multiple time and area closures to conserve the resource.

Conclusions

Shrimp beam trawls are designed specifically to fish with a lower vertical opening and slow towing speeds that should reduce the finfish bycatch. The gear is low cost, easy to operate, and productive; it has proven itself an important fishing gear in the ECS. The development of electrical beam trawls greatly increased the efficiency of the trawl in catching shrimp and improved economic returns to the industry. When the SEPSA system was used properly, it improved the size selectivity of shrimp catches and reduced disturbance to the seabed and benthic community because a lighter weight groundgear could be used.

The positive aspects of the SEPSA system were negated by the unregulated use of excessive power output and improper settings of pulse parameters, which caused injury to both shrimp and other marine life. The commonly used pulse amplitudes of 60 V in the cabled system and 45.5 V in the cableless system were too high to target large shrimps >100 mm TL. The unregulated use and misuse of the SEPSA system, along with the declining shrimp resources, led to the ban in the Zhejiang Province on 1 January 2001. Should this technology ever be reintroduced into the shrimp fishery, further research on optimal parameters for different species would be necessary. Management of the technology should include: (i) certification procedures for device manufacturers and maintenance and repair agents; (ii) introduction of tamper-proof key settings for the output power parameters during fishing; (iii) introduction of specialized equipment to monitor output power parameters by vessel users and by enforcement personnel in the field; (iv) the use of SEPSA should be strictly controlled relative to total fishing effort and total allowable catch.

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