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Application of Advanced Composites in Tokamak Magnet Systems

C. J. Long

OAK RIDGE NATIONAL LABORATORY
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ABSTRACT

The use of advanced (high-modulus) composites in superconducting magnets for tokamak fusion reactors is discussed. The most prominent potential application is as the structure in the pulsed poloidal-field coil system, where a significant reduction in eddy currents could be achieved. Present low-temperature data on the advanced composites are reviewed briefly; they are too meager to do more than suggest a broad class of composites for a particular application.

INTRODUCTION

One aspect of tokamak-type fusion reactors in which the properties of advanced structural composites, such as graphite-epoxy and boron-epoxy, are especially attractive is the pulsed poloidal-field coil system. The purpose of this paper is to examine tokamak reactor magnet systems, especially poloidal-field systems, with reference to the use of such high-modulus composites.

MATERIALS REQUIREMENTS FOR SUPERCONDUCTING MAGNETS

Because many designers of advanced composites are unfamiliar with superconducting magnets, it may be useful to review certain salient features of such magnets.

The most important aspect of superconducting magnets is that they operate in liquid helium at a temperature of about 4 K (—452°F). This low temperature creates a number of problems, including major changes in the properties of some materials from room temperature. Certain epoxy formulations, for example, which are quite usable at and above room temperature, tend to be excessively brittle at 4 K.[1] Conversely, some epoxies well suited to liquid-helium service soften at temperatures above 25°C, and therefore are seldom used for general purposes. This exemplifies the usual change in materials at low temperatures: toughness and ductility decrease, while strength tends to increase. A great variety of materials show this effect, but its extent varies dramatically from one to another. Certain rules can be formulated to predict trends in cryogenic behavior, but they are no substitute for tests at the temperature of interest.

Devices, including magnets, made of more than one material will generally be subject to thermal stresses when cooled by 300°C or more from their assembly temperature. (This is the approximate difference between room and liquid helium temperatures.) These stresses may present particularly severe problems when two materials are in intimate contact, as in superconductive wire or a structural composite. Another effect of the low temperature is a high coefficient of performance (c.o.p.) (ratio of refrigeration power to heat extracted from the magnet). The ideal c.o.p. is about 70, and the real power factor is several times that. This low refrigeration efficiency demands that heat input to the magnet from all sources, including eddy currents, be minimized by whatever means available.

Superconductor wires as a class are sensitive to mechanical strain. Conductors based on niobium-titanium (Nb-Ti) alloys begin to show a reduction in electrical performance at total strains around 0.20%, while some that use A-15 compounds, such as Nb_3Sn and V_3Ga, may show effects as early as 0.10%. Recent measurements[2-4] indicate that the allowable strain in multifilamentary Nb_3Sn conductors may be several times greater. Because of this limitation in strain, the working stress in a structural material may be limited not by its yield strength but by the product of allowable conductor strain and the modulus of the structural material in the appropriate direction. A stiffer structure can in some circumstances be more valuable than a stronger one.

Magnets are inductors, and large ones store considerable amounts of energy (about 1 GJ for an Experimental Power Reactor Poloidal Field system[5]). The speed with which this energy can be discharged, should that become necessary, is a function of the voltage allowed between the terminals of the magnet. A structural material that is a good electrical insulator, in the sense of high breakdown potential as well as high resistivity, could be advantageous in making a higher voltage possible.

TOKAMAK SYSTEMS

A tokamak (Fig. 1) is a particular type of fusion reactor in which plasma confinement is achieved by two systems of electromagnets: the toroidal field (TF) coils and the poloidal field (PF) coils. The toroidal field system consists of a toroidal array of 16 to 24 identical solenoids of circular, oval or D-shape. At present, it seems quite likely that the TF coils must be superconducting for a commercially viable power plant. Most of the conductor is in this system. The toroidal magnets themselves ordinarily operate at a constant current during a plasma burn; their components thus experience pulsed fields only from other magnet systems, such as the PF system. It appears at present that these pulsed fields will affect TF coil design in choice of conductor but probably not in the choice of support material.

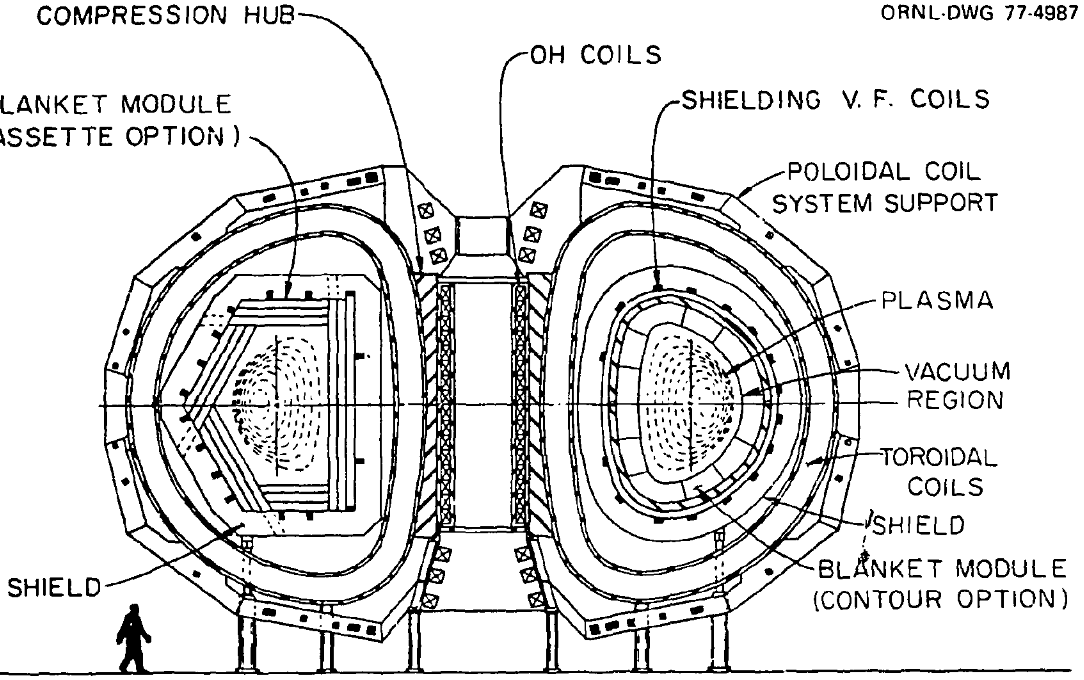

Fig. 1. Schematic Cross Section of a Tokamak. In this design, the OH (ohmic heating) coils form the central solenoid.

The PF system is different in a number of respects from the toroidal system; some of these may dictate use of a different structural material.

The term "poloidal field coils" encompasses several systems whose common feature is that they are coaxial with the major axis of the plasma torus. Their functions include driving the current in the plasma, stabilizing the plasma, and producing local field perturbations for special purposes. The physical arrangement, which does not correspond with the functional divisions, is a "central solenoid" in the center of the torus and various individual coils above, below, and outside the torus. The smaller, individual coils will probably be resistive to reduce engineering complication, but several designers[6–8] have proposed superconducting central solenoids. This is the major part of the PF system in terms of current, and the portion where mechanical stresses are of the greatest concern. This discussion will be directed largely at these central solenoids. One important difference between the PF and TF systems is that the PF system current varies with time during the thermonuclear reaction of the plasma. The field produced by the PF coils is therefore also pulsed. One of the principal heat sources in the PF coils is electrical eddy currents induced by their time-varying magnetic fields. Eddy currents in the structure would be negligible if the structure were made of an electrically insulating material. A mechanically strong and stiff, but electrically nonconductive, structural material is desired. This leads designers to consider advanced (high-modulus) composites. Those interested in the general subject of tokamak design should see refs. 6–8; structural material selection for magnets is discussed in ref. 9. Flux rates of change as high as 7 T/s for short periods have been proposed[6] for the central solenoid; slow flux changes are required during most of the operating cycle of the reactor. The time-varying magnets of a reactor are often referred to as "pulse coils." There may also be some poloidal coils operating at steady state; most of the remarks below do not apply to them. Electrically conductive materials in a changing magnetic field experience eddy currents, which deposit a significant amount of energy. For tokamak pulse coils, this may be a substantial fraction of the heat deposited; the possibility of reducing or eliminating this heat source makes organic-matrix advanced composites interesting for magnet structures. The changing electrical and magnetic states imply a changing state of stress as well. Some of the changes in current are fast enough for strain rate to affect the mechanical behavior of the structure, and fatigue must also be considered. For a commercial electrical plant, the number of operating cycles over the lifetime is of the order of 1 × 10^5. Cooldown stresses must, of course, also be included in any load-cycling tests. Fusion reactors are intended to ultimately be part of the base generating capacity of a utility electrical grid. As such, they must be reliable because unplanned interruption of a plant producing 1 GW of capacity is extremely undesirable. The same demand for reliability is imposed on each major component; this may be the aspect in which aerospace experience with composites is most readily transferred to fusion reactors.

Because of the thermonuclear plasma, all parts of the reactor are subject to a radiation (neutron and gamma) flux that is a function of position and reactor design. In the presence of either copper or iron, in any form, the neutron flux will lead to additional gamma radiation through (n,γ) reactions. Over a 20-year design life, the maximum total neutron fluence to the TF coils is estimated[10] as 1.5×10^{22} n/m^2 ($E > 0.1$ MeV); that to the PF coils is about 3×10^{20} n/m^2. This is the fluence for those parts of the coil nearest the plasma; other parts will experience less. These numbers are only order-of-magnitude estimates; they will be a strong function of plasma wall loading, shielding, and TF coil geometry, among other things. Aside from materials degradation, this radiation will have the effect of limiting access to the coils — all maintenance will probably have to be done remotely. Minimization of maintenance is a strong design constraint.

MATERIAL SELECTION CRITERIA

Because this paper concerns itself with composites, which are most useful in the PF coils, this section will be directed at the PF system. The TF coils will be mentioned only when a significant difference exists. Conventional (metallic) materials are discussed in ref. 9, especially with reference to the TF coils. We wish to identify the material properties that distinguish a good material from a bad one. These may be conveniently divided into mechanical properties and physical properties.

The mechanical properties we are interested in are conventional, except that their values at 4 K are required. Of course, the designer needs to know the material's working strength and, because the conductor is strain-limited, its elastic moduli. Some idea of the crack-propagation stress (which admittedly is ill-defined in composites) is necessary as well. Because the loads in a long solenoid may be significantly triaxial, the mechanical properties in all three directions are required. The designer may wish to exchange stiffness in one direction for another; in this case the relation between gain and loss is important. For strength and crack-growth stress, a good measure of the variability from average is necessary so that realistic design values may be set. It appears at present that the TF coil structural stresses will be less multiaxial. If true, this would make the lateral properties of a composite somewhat less important.

A variety of physical properties will also have to be known for reasonably complete magnet design. Obviously, some of them are highly directional; the values of these must be related not only to direction but to the lay-up geometry chosen from structural considerations. Because the magnet is assembled at one temperature and operated at another, the dimensional change with temperature of each component is required. As a first approximation for comparison of materials, $\Delta l/l$ for the range from 300 to 4 K is reasonably proportional to $(1/l)dl/dT$ (α) at room temperature; but $(1/l)dl/dT$ is not constant at low temperatures, and the only accurate way to determine a particular material's change in length on cooldown is to measure it. Stress analysts usually need $(1/l)dl/dT$ as a function of temperature. The specific heat of a composite affects the cooldown time of the magnet, the amount of coolant consumed, and the stability of the magnet against thermal disturbances. It is also a strong function of the temperature, especially at low temperatures. Thermal conductivity, again a function of temperature, is needed to relate cooldown rate to the stresses produced by spatial variations in temperature. The fact that organic-matrix advanced composites are electrical insulators is our principal reason for considering them in poloidal coils; measurements of electrical resistance and breakdown voltage will let the designer determine whether this nonconductive structure can be relied on for electrical insulation or a separate primary insulation system is required. So far there has been no mention of low specific gravity or high strength-to-weight ratio, the reasons advanced composites are found in most of their present applications. Certainly, a light magnet is preferable to a heavy one; but the advantages given a magnet by low weight do not begin to compare with those in any type of aircraft. Considerations of physical properties are much the same for TF as for PF coils, except that the smaller field changes and different geometry make electrical conductivity less important. It is still a factor, however, and the differences between structural alloys are significant. (Aluminum alloys are about 2 orders of magnitude better electrical conductors than austenitic stainless steels.) Because low electrical conductivity is the driving force for use of composites in PF coils, it is quite easy to conceive of a magnet system with metal structure in the TF coils and composites in the PF coils. The fact that all materials chosen will eventually be part of an electrical power grid increases the demand for reliability and design predictability. Better understood and less variable systems are preferable.

CRYOGENIC PROPERTIES OF ADVANCED COMPOSITES

Information on the behavior of advanced composites is limited for liquid nitrogen and even sparser for liquid helium temperatures. Two reviews[11,12] and a handbook[13] summarize the current data. Extrapolations are risky because of the general novelty of composite materials compared with metals and the greater number of variables required to characterize a particular material. Very little information is available to set design values or even to provide typical values; for some time to come, mechanical properties will have to be measured for each contemplated use. The best use to be made of current information is to identify the composite system most likely to be appropriate in a specific application. Some useful data are summarized in Table 1.

Table 1. Approximate Property Ranges for Unidirectional Advanced Composites. All data are for 77 K unless noted. Based on refs. 12–14

Composite	Elastic Modulus, GPa, (10^6 psi)		Ultimate Tensile Strength, MPa (ksi)		$\Delta \ell / \ell$, 300–77 K		Electrical Conductor
	Longitudinal	Transverse	Longitudinal	Transverse	Long.	Trans.	
Graphite-Epoxy	100–300 (15–45)	3–10 (0.5–1.5)	700–1200 (100–175)	20–40 (3–6)	+2 E-4[a]	−3 E-3	no
Boron-Epoxy	~230 (33)[b]	~40 (5)	~1300 (190)	~60 (9)	−4 E-4	−1.5 E-3	no
Kevlar-Epoxy	180–210 (26–30)		1000–1300 (140–190)		+8 E-4		no
Boron-	200 (29)	120–180 (18–26)	1500 (220)	280 (40)	−7.4 E-4	−3.4 E-4	yes

[a] Read as $+2 \times 10^{-4}$.

[b] At 20 K.

Graphite-Epoxy Composites

In general, these are among the least expensive and best known advanced composites. Prospects for further reduction in cost are good because of use in such consumer products as tennis rackets and golf clubs. Because the density is lower than that of stainless steel (sp.g. ~1.5 versus 7.9) a higher price per kilogram can be tolerated.* This of course neglects fabrication cost; major variations may occur here, but they are extremely difficult to quantify without a specific detailed design.

Unlike that of a metal, the Young's modulus of graphite fibers varies considerably with manufacturing process. In general, there is a trade-off between fiber strength and modulus, but the trend does not hold up

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*For two materials of equal mechanical properties carrying the same load, equal cross sections will be required; if the loads are to be transmitted equal distances, equal volumes are required. Therefore, the price-to-volume ratio is more important than the price-to-mass ratio and a less dense material has a relative cost advantage.

well in the composite, especially at low temperatures. Available data indicate a slight (∼10%) increase in uniaxial longitudinal tensile elastic modulus from room temperature to 77 K; the single data point at 20 K shows a further increase of comparable magnitude. Values for this property lie in the range 100 to 300 GPa ($15–45 \times 10^6$ psi). The transverse elastic modulus, which in uniaxially reinforced composites is governed principally by matrix properties, is of course much lower. Values in the range of 3 to 10 GPa ($0.5–1.5 \times 10^6$ psi) are typical for cryogenic temperatures. Different epoxy formulations could affect this substantially.

Because the composites discussed here have little ductility, yield strength is not ordinarily reported, and ultimate tensile strength is used to set working stresses. For graphite-epoxy, ultimate tensile strength measurements show both increases and decreases from room to cryogenic temperatures, depending on the particular graphite-fiber composite. Low-temperature values typically lie in the range 700 to 1200 MPa (100,000–175,000 psi) along the fiber direction. Lateral strength values are again governed by the matrix; observations of 20 to 40 MPa (3000–6000 psi) ultimate strengths have been reported. Cross-plied material has apparently not been tested at cryogenic temperatures but can be predicted to be inferior longitudinally and superior transversely to the parallel-fiber material. Graphite-fiber composites have low room-temperature impact energies compared with commonly used metals and are expected to behave similarly at low temperatures.

In a magnet, the physical properties of the structural material may be as important as its mechanical properties. One of the more unusual attributes of graphite fibers is a negative coefficient of thermal expansion in the longitudinal direction. In other words, they expand on cooldown to cryogenic temperatures. This behavior carries over in part in uniaxial composites, which display an elongation ($\Delta l/l$) of up to 2×10^{-4} on cooldown to 77 K. Laterally, a *contraction* around 3×10^{-3} may be expected. Both these numbers are sensitive to fiber fraction and layup geometry, especially the lateral contraction. While there are undoubtedly places in a magnet system where dimensional constancy during cooldown is useful, it would seem more practical for most of the structural material to contract along with the other materials in the magnet. If it does not, the conductor will be stressed in tension on cooldown and the operating (magnetic) stresses will be additive to the thermal stresses. Differential thermal contraction will also occur within the composite, placing the matrix in tension parallel to the fibers. (Actually, this is the case with any organic-matrix composite, but the stresses are greatest for fibers of negative thermal expansion.) Both this odd thermal contraction behavior and material anisotropy in mechanical properties present a real challenge to a designer who wishes to use graphite-fiber composites in a magnet.

Other physical properties are less remarkable. The vector properties (those measured in a specific direction) are nearly all anisotropic, so that somewhat more sophistication in analysis is required than with homogeneous metallic structures. Data below 77 K are so limited that design calculations will require measurements on the particular system (fiber, matrix, layup) of interest. The thermal conductivities of the graphite-epoxy composites are low in either direction compared with those of pure metals. At 77 K, the longitudinal thermal conductivity is about 5 W/m K, and the lateral conductivity is of the order of 0.3 W/m K. Specific heat is about 0.3 J/kg at 77 K.

In summary, graphite-epoxy composites are the nearest thing to an industrial material among the advanced composites, but information on their behavior at 4 K is grossly inadequate for design. Even approximate measurements would be most useful in reference designs for pulsed superconducting coils; these might be performed under the ERDA-funded NBS Cyrogenic Materials program.

Boron-Epoxy Composites

Although boron fibers are more expensive than graphite, enough boron-epoxy composite is used near room temperature for it to be considered a real engineering material. Boron fibers are neither better nor worse than graphite, but they have a different set of advantages and disadvantages. The designer has to make a choice with regard to a particular situation. In compensation for their cost, boron composites offer better mechanical properties, especially transversely, and the more usual positive coefficient of thermal expansion. Boron-epoxy composites also have appreciably more reproducible mechanical properties than graphite-epoxy composites.[14] Data below liquid nitrogen temperatures are even sparser for boron- than for graphite-reinforced composites; cryogenic mechanical testing will certainly be necessary before they can be used in a superconducting magnet.

Uniaxial longitudinal tensile elastic modulus is about 230 GPa (33×10^6 psi) at 20 K, comparable to the graphite-reinforced epoxies. Transverse modulus is about 40 GPa (5×10^6 psi), roughly 3 times that of graphite-epoxy. It appears that the boron fiber itself contributes more to the transverse properties than graphite. Ultimate longitudinal tensile strength for the boron composite is about 1.3 GPa (190,000 psi); transverse about 60 MPa (9000 psi). In both respects the boron composites are superior to the graphite.

Most of the physical properties of the boron-epoxy composites are not significantly different from those of graphite-base materials. The boron composites do in fact contract longitudinally on cooling, but when the $\Delta l/l$ of −0.04% for boron-epoxy is compared with type 304L stainless steel's −0.25% and graphite-epoxy's +0.01%, it may be seen that the difference is not all that important. (These values are for the change from 273 to 77 K, the lowest temperature for which data on the composites are available.) The cooldown strain developed by boron-epoxy in contact with copper ($\Delta l/l = -0.27\%$) is only 18% less than that of graphite-epoxy against copper. While this is useful, it is not the critical factor one conceives of when learning that graphite has a negative thermal expansion coefficient. Laterally boron-epoxy contracts about 0.15% to 77 K, governed by the matrix. The thermal conductivity of boron-epoxy is not appreciably anisotropic; it is about 0.18 W/m K at about 10 K. This is roughly one-fifth that of type 304 stainless steel at the same temperature. The specific gravity of boron-epoxy is about 2, depending on the particular system.

Boron has one property that immediately raises questions about its use in the minds of all nuclear engineers: a high absorption cross section for thermal neutrons, about 800 b (0.08 pm^2) for the natural isotopic composition. This raises possibilities of intolerable heat load to the magnet and materials degradation. Detailed calculations are required to settle the issue.

Kevlar-Epoxy Composites

A third fiber that has been used to reinforce organic matrices is Kevlar 49, a DuPont proprietary aromatic polyamide which was formerly known as PRD-49. The use of Kevlar in tire cord, just now beginning, gives promise of large production quantities and low costs. At present, cryogenic mechanical properties data for Kevlar are sparse but give promise that the material will prove useful. Transverse properties in particular are unknown; one would not expect these to be too different from those of the matrix. At 20 K, the longitudinal Young's modulus of uniaxial Kevlar-epoxy is in the range 180 to 210 GPa (26–30 × 10^6 psi). Longitudinal tensile strength for the same composite is 1.0–1.3 GPa (140,000–190,000 psi), at least as good as graphite-epoxy. Kevlar composites expand when cooled to cryogenic temperatures, measurably more than graphite-fiber composites. For Kevlar composites, $\Delta l/l$ from 293 to 20 K is about 0.08%. This again is not the problem brief consideration might suggest, but it does need to be considered in design.

Boron-Aluminum Composites

Aluminum-matrix composites, because of their low electrical resistivity (even compared with austenitic stainless steel) are not usable for pulse-coil structures. They therefore are not alternatives to the various organic matrix composites. They have sufficiently good mechanical properties, however, to be interesting as substitutes for stainless steel or unreinforced aluminum in the toroidal field coil structure. Compared with the other composites their transverse properties are particularly good. Against these advantages we should balance high cost, lack of experience, and difficulty of fabrication relative to the organic-matrix composites. (Hot-pressing and diffusion bonding replace the simpler cure cycle of the epoxies.)

At 4 K, a uniaxial composite of 140-μm (5.6-mil) boron in 6061 aluminum has a longitudinal elastic modulus of about 200 GPa (29×10^6 psi) and a transverse modulus of 150 ± 30 GPa [$(22 \pm 4) \times 10^6$ psi], almost twice that of aluminum. Ultimate longitudinal tensile strength of this particular composite is greater than 1.5 GPa (220 ksi); ultimate transverse strength is about 280 MPa (40 ksi).

From 297 to 4 K, longitudinal $\Delta l/l$ is −0.074%, about a quarter of that for austenitic stainless or copper. Transverse $\Delta l/l$, dominated by the aluminum matrix, is −0.34%.

POTENTIAL APPLICATIONS

It is apparent that the most promising application for advanced structural composites in a tokamak is in the structure of the central solenoid of the poloidal field system. The purpose in this case is, of course, suppression of eddy currents (and the ensuing energy deposition) caused by the changing magnetic field. Since the metal-matrix composites are about as conductive as the pure metal, only organic-matrix composites can reasonably be considered for the PF coil structure. Of these graphite-epoxy is worth the first look because it is the system in most widespread use for other applications. Boron and Kevlar fibers may have particular properties that justify their use. The critical machine parameter affecting the usefulness of composites relative to conventional (metallic) structures is the flux rise time during startup. A long rise time will allow the use of metal structure, but a short rise time is likely to require composites in the PF coils.

Because flux changes at the TF coils are so much less, the composites will not be used unless they possess some advantage in fabrication or mechanical properties. Such advantages are conceivable but not obvious at present. The metal matrix composites' superior mechanical properties (compared with organic matrix) could be used here. Metal matrix composites may not be usable even in TF coils, though, because their electrical conductivity is almost as good as that of unreinforced aluminum, and TF coils do experience some changing fields.

SUMMARY

The properties of advanced composites are good enough to make them worth considering as alternatives to structural metals in those superconducting-magnet applications where a particular advantage may be achieved. The most prominent of these is the structure for rapidly pulsed coils, such as the poloidal-field system in a tokamak. The principal hindrance to use of these composites is lack of data on the properties of well-characterized materials at 4 K. In addition, structural analysts must be aware that they are dealing with anisotropic materials.

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