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Designing for Thermal Conductivity with Flake Filled Composites

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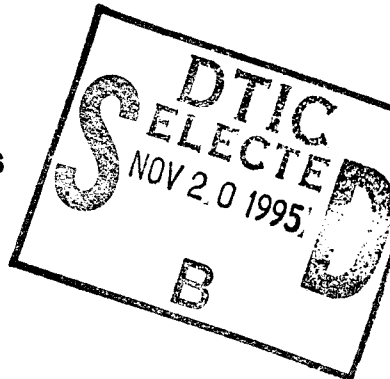
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INTRODUCTION

The topic of solving thermal conductivity problems can be approached from the perspective of the design engineer who needs only the most basic raw material property data to make a choice to solve an existing or anticipated heat problem. Or, it can be approached from the perspective of a polymer engineer who would call upon additional expertise to solve a heat problem within the realm of his specialty—plastics.

In this text the two approaches are considered, and data are contained which will prove useful to both. Traditional materials are covered since they can be used as points of reference to which later developments can be compared. Theoretical evaluations of materials, systems, and designs are made, and are compared and contrasted to case study results.

One goal of this text is the education of the plastic part designer in the considerations needed to make a plastic perform as well or better than the traditional metal and ceramic materials. Thermally conductive plastic composites combine the required heat transfer property of metal and the desired qualities of chemical resistance, light weight, subassembly consolidation, and low cost mass production.

Enlightenment of the design engineer is another goal, that he or she might consider broader options in the choice of part design and raw material alternatives. In addition, the thermodynamicist who specializes in solving heat transfer problems will find the information useful, and based on the principles used in his profession.

Pure metal as a heat transfer medium works admirably, but has limitations in its weight and processing expense. Ceramics offer reasonable conductivity with improved chemical resistance, but suffer from a lack of flexibility and impact strength. Pure plastic resin offers a high degree of design freedom coupled with light weight, chemical resistance, great strength and toughness, and economy in large scale production. It lacks, however, a reasonable degree of thermal conductivity. In many applications modest increases in thermal conductivity can dramatically increase the ability of plastics to transfer heat, making them an ideal raw material in many environments.

Conductive polymer composites formulated with high aspect ratio rapid-solidified aluminum flakes combines a high conductivity filler with an insulating matrix, resulting in the conductivity of the metal being combined with the processing ease of the plastic component. Heat transfer effectiveness is equal to 80 to 95 % that of metal, the composite can still be handled on an unmodified injection molding machine. These composites, although with only a few years of product application, are already solving design problems in the appliance, automotive, computer, instrument, and medical industries.

SECTION 1

THERMAL CONDUCTIVITY BASICS

Thermal conductivity is a property of a material or system, and is measured as the ratio of the time rate of heat flow per unit of area, to the negative gradient of the temperature. It is the speed at which heat can move through a material. Thermal conductance of a material is measured in a method analogous to that used to measure electrical conductance and resistance. Indeed, electrical and thermal conductivity in solids are closely linked.

In metals the free electrons are responsible for the electrical conductivity. The greater the quantity of free electrons the lower the resistance and the higher the conductivity. Thermal conductivity is related to electrical conductivity by the Wiedemann-Franz ratio, wherein at ambient conditions, the conductivity varies inversely with temperature.

In the case of ceramics, plastics, and other electrical insulators where electrical conductance is low, thermal conductivity is effected by lattice vibrations and is again inversely proportional to temperature. However within a typical temperature range of 200 Celsius degrees a single value is sufficient to express this property.

Knowing that the task to be accomplished is heat transfer, and that material effectiveness can be ranked by thermal conductivity, engineers have made metal the traditional material of choice. Designers of heat sinks, heat pipes, and heat exchangers have been sorely limited in options with metal, commonly aluminum, being used nearly exclusively. The other material classes, ceramics and organics, have been typically used as electrical and thermal insulators.

In many applications there are conflicting requirements for thermal conductivity properties. Power tools were often housed in metal. In addition to strength, the metal was used to rapidly dissipate the heat generated by the motor. The tool handle then had to be insulated to prevent its becoming too hot to hold. When the switch to polycarbonate and similiar plastics occurred the hot handle problem was solved, but a whole new problem in heat build up was created.

Although plastics by nature are insulators, there are many application needs which plastics could fill if they were slightly more thermally conductive. These are cases in which the heat transfer mechanism is not purely **conduction**, but takes into account the additional aspects of **convection** and heat **radiation**.

The disadvantages of the low thermal conductivity of plastics are found both in product and in manufacturing of the more sensitive electronics applications. High power semiconductors and their associated transformers generate heat which must be dumped outside the system to avoid thermal runaway.

In existing plastic applications which have inadequate performance due to heat build up, thermal distortion, and heat degradation, an easily implemented solution is now available in the form of thermally conductive metal/polymer composites.

The high cost problem associated with metals is eliminated with these cost effective composites currently available. The engineer can also take advantage of the additional benefits of:

Standard Plastic Processing
Existing Tooling
Reduced Cycle Time
Lower Energy Requirements

Improved heat transfer properties coupled with cost savings are immediate benefits in existing applications. The orientation of high efficiency high aspect ratio fillers in the plane of flow during molding provides the advantage of maximum conduction and convection heat transfer properties. A design capitalizing on the superior thermal conductivity of these composites gives the performance benefits once thought available only in metal.

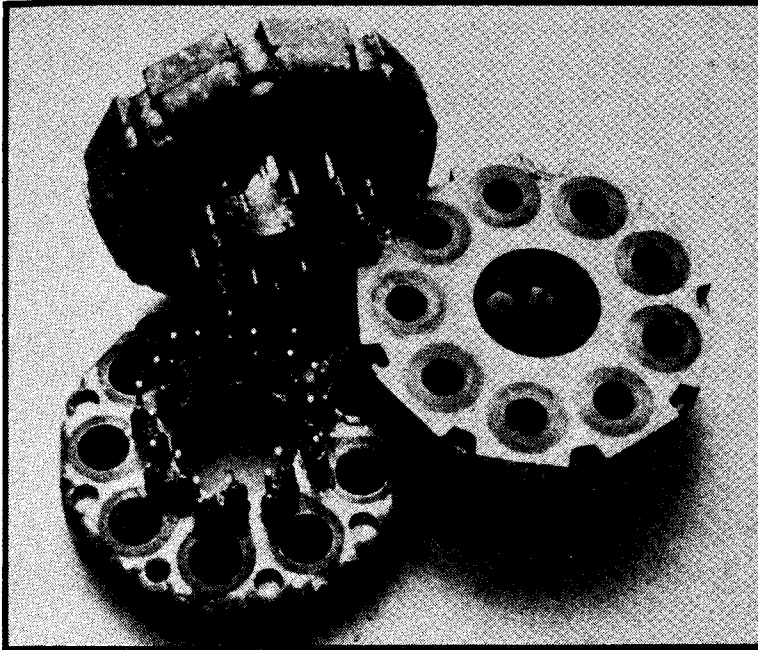


PHOTO 1 - T. C. parts

Although a more detailed discussion of conductivity measuring techniques is left until a later section, it must be covered here in brief to aid in the comparison of materials which follows.

For highly conductive materials like metals a direct method can be used. One end of a test bar is heated by a wire wound resistance coil. The free end is kept at a controlled lower temperature by its being fitted with a water filled cooling coil. The temperature change with respect to distance along the bar may then be measured, and the gradient used in the calculation of conductivity.

A more general test method is that prescribed by ASTM C-177. In this test two flat plaques of the unknown are placed one on each side of a heater. This stack is then placed between two cooling blocks and the total assembly encased in an insulating housing. Temperature measurements are made at the plaque/cooling block interface. The temperature and area of the plaque is then related to the output of the heater which is determined electrically, and the conductivity is calculated.

Using these test methods it is possible to evaluate the intrinsic properties of materials and rank them accordingly. This test alone will not predict whether or not a given design will perform as intended, as part configuration, air or other fluid circulation, and environmental condition also play a large role in the final product performance.

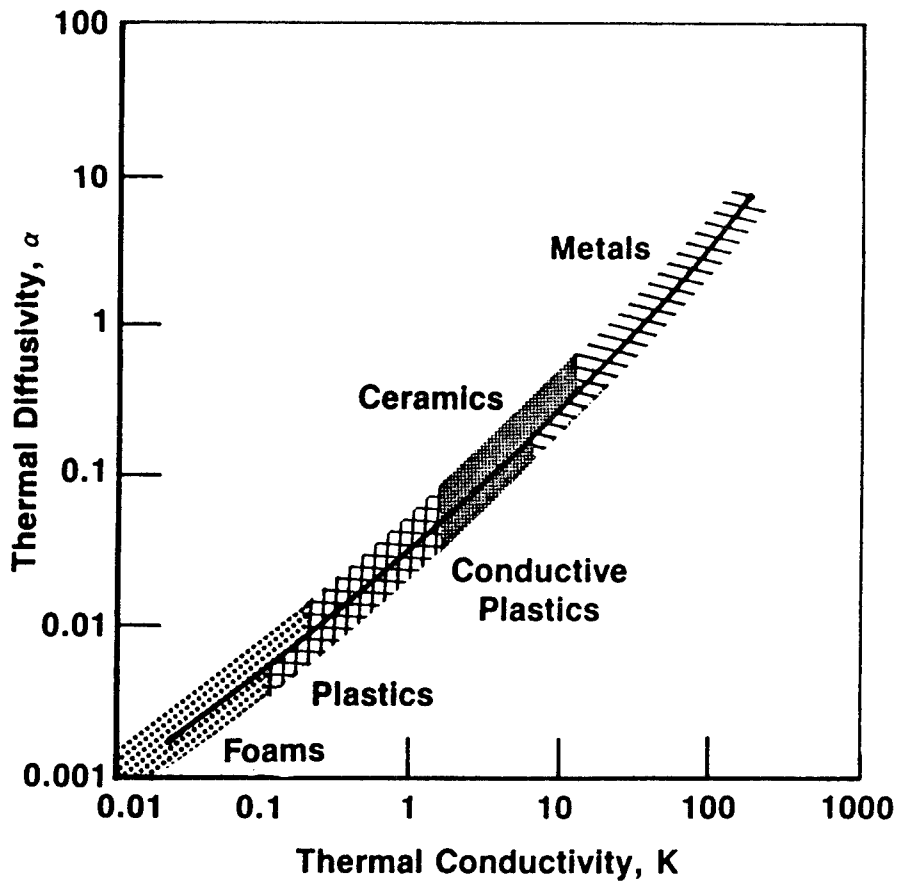


FIG 1 Thermal Diffusivity vs Conductivity

SECTION 2

REVIEW OF CURRENT RAW MATERIALS

Materials in use today for thermal conductivity applications fall into the broad categories of metals, ceramics/glasses, and hybrid structures. By far the most commonly used are metal, with aluminum having the widest acceptance.

Metallics

Aluminum as a heat sink has numerous good qualities: it is lightweight, readily extruded, reasonably high in melt temperature, high in thermal conductivity, low in heat capacity, and fairly inexpensive. However in nearly all cases subsequent machining and grit abrasion is necessary to bring the parts to an acceptable tolerance and surface finish. Then for aesthetic or environmental protection reasons, the parts are coated in an anodizing or chromating process, since aluminum is a very active element and unsuited for use in many environments. Chemical processing plants, refineries, steel mills and their surroundings often have such corrosive contaminants in the air that exposed aluminum is rapidly corroded away. Coastal areas suffer from salt induced corrosion many miles inland where the salt spray mist and salt contaminated dust may blow.

In these environments design engineers often turn to more expensive metals like stainless steel. The ease of fabrication, light weight, and low cost of aluminum is traded for the inert nature and longer use life of these iron chromium alloys.

Ease of fabrication is one reason why copper is typically used in the manufacture of heat exchanger systems. The coil of copper tubing is force fitted into the holes in the stack of metal sheets used to increase the radiator surface area, and brazed in place. Aluminum would be difficult to process in this manner, and stainless steel an unwarranted expense.

CERAMICS

Naturally occurring minerals also find use as heat conductors. Sheets of mica are often placed between a heat producing electronic device and the chassis, giving a reasonably good thermal path while electrically insulating one part from another. The brittleness of the material combined with its tendency to cleave into thinner and thinner pieces has limited its use today, making way for the newer ceramics.

The simple fired clay and glass components in use for years have given way to the more sophisticated alumina, nitride, and boride ceramics. While commonly used as electrical insulators, these are also employed as heat conductors in cases where the electrical conductivity of the metals would cause difficulty. Although not as thermally conductive as metal, experience has shown that ceramics can perform admirably. A few years ago all cookware was metal, but today great inroads have been made in the use of modified glasses. These new products are often modified to enhance their mechanical properties, and minimize the limitations due to their inherent brittle nature. A few formulations are ductile enough for machining, but most are still processed using traditional slow methods.

There is now underway development of metal ceramic hybrids in which the ceramic is strengthened by the incorporation of metal fibers, or the metal matrix is stiffened by the incorporation of silicon carbide or basalt fibers. An example is refractory linings where the metal fibers toughen the composite to prevent spauling.

Concluding the survey of traditional raw materials, one finds little new development of materials for thermal conductivity. The commonly used products are still limited in performance and economy in high volume production. The best hope for an alternative seems to lie in the direction of the more sophisticated organics, plastics and their composites.

SECTION 3 PLASTICS AS RAW MATERIALS

The properties of pure polymers can range from very poor, as in the case of most thermoset materials, to the stronger-than-steel aramid fibers finding use today. Often the polymers never reach the market in the pure state, as they are too weak, too unstable, or too difficult to process in an unmodified form. Others have property profiles that make them suitable for a wide range of applications. Among these applications, however, one rarely finds their use as thermal conductors. The table below lists some of the common plastic resins and their typical properties:

TABLE 1 PLASTIC RESIN PROPERTIES

PLASTIC	TENSILE STR KPSI	FLEX MOD KPSI	ELECT COND OHM CM	THERM COND *
ABS	8.0	400	10^{16}	.10
NYLON	11.8	410	10^{15}	.14
PBT	8.5	340	10^{16}	.10
P/CARBONATE	9.0	330	10^{16}	.11
P/ETHYLENE	4.1	135	10^{16}	.17
P/PROPYLENE	5.0	180	10^{16}	.10
P/STYRENE	7.0	450	10^{16}	.12

* BTU/hr ft² °F/ft

A property profile like one of the resins above, if needed for a heat transfer application, would lead a mechanical engineer to choose such a plastic only for its strength or insulating characteristics, and lead a polymer engineer to search for a method to improve the thermal property desired.

Often if the mechanical, chemical, or processing characteristics of the base polymer are not sufficient for the intended end use, it is possible to alloy or blend polymers together and get some properties better than any of the components alone. The addition of acrylonitrile-butadiene greatly improves the impact strength of styrene, but the thermal and electrical conductivity values remain much the same. True alloys in which the components are mutually miscible and form a single phase also frequently exhibit mechanical property improvements, but again the thermal properties remain unchanged.

SECTION 4

COMPOSITE PROPERTY DEVELOPMENT

For many years fillers and reinforcements have been used to enhance the characteristics of pure plastic resins. Cost, strength, stiffness, heat deflection temperature, and coefficient of friction are just a few of the properties altered. The thermal conductivity of a resin can be modified as well, by the choice of a filler which has a conductivity higher than that of the base resin. Metal and ceramic/glass based particulates have been used, with particle size and shape ranging from the low aspect ratio chunky blocks and spheres to the higher aspect ratio platelets, flakes and fibers.

The four qualities important in choosing a filler are the **aspect ratio**, **chemical compatibility** with the resin, **inherent properties** (tensile strength, flexural modulus), and **processibility**. Additives to plastics which are used in large concentrations, up to 50%, and give little property enhancement are termed fillers. Fillers in general have low aspect ratios, are mineral in nature and thus compatible with most resins, and are readily processible due to their powder or small granular shape. Their strength characteristics play a minor role in the composite performance, since their small size greatly reduces the opportunity for bonding with the polymer and subsequent reinforcement.

Once the aspect ratio of the inorganic component exceeds 20:1, property improvement begins to escalate. Depending on the particle surface chemistry, reinforcement can occur at an aspect ratio as low as 20:1, or with no compatibility require an aspect ratio of as high as 100:1.

Chemical compatibility has two aspects, stability with and adhesion to the resin matrix. A resin and filler system can be tailored to increase compatibility by altering the resin backbone, the metal filler alloy, or the surface chemistry through a coating process.

A compatible system takes advantage of the reinforcing effect of the filler, so the inherent strength of the filler particle becomes important. Not all chemically identical products exhibit equal mechanical or thermal properties, since their strengths are also a function by which the products are made.

Fillers of identical mechanical properties can exhibit different levels of processibility. This is often due to chemical compatibility with the resin or the surface roughness of the particles. Discriminatory evaluation usually demands actual on-line testing.

Plastics can be changed into partially conductive materials, "semi-insulators" with the addition of certain modifiers. Glass, while usually added as a reinforcing agent to improve tensile strength and modulus properties of a composite, also increase the thermal conductivity. The normal range of conductivity for base polymers is 0.1 to 0.2 BTU/hr ft²°F/ft; 20-30% glass reinforced versions increase to 0.15 to 0.25 BTU/hr ft²°F/ft. Talc filled versions, even if chemically coupled to improve mechanical properties, may show virtually no change in thermal conductivity. Metal powders, iron and aluminum, can increase heat transfer through a resin and such materials are used at high loadings, often over 50% by weight, due to their low aspect ratio and high density.

The step beyond the powdered fillers and modified resins is those resins whose property profiles are changed dramatically by the incorporation of high aspect ratio conductive modifiers. This family of particulates includes metalized glass fibers, graphite fibers, and quick quenched aluminum fibers and flakes.

Fibers and flakes are characterized by high aspect ratios (ratio of length to diameter or thickness) which aid in thermal conduction as well as reinforcement of the resin. Flakes tend to orient parallel to the flow of the resin and form layered parts. This gives a high content of filler in minimal thickness. Fibers also orient, but their ends give rise to high stress concentrations leading to warpage and dimensional change due to stress relief in service. Spheres are lower in stress concentration effects but are also lower in conductivity enhancement due to their low aspect ratio.

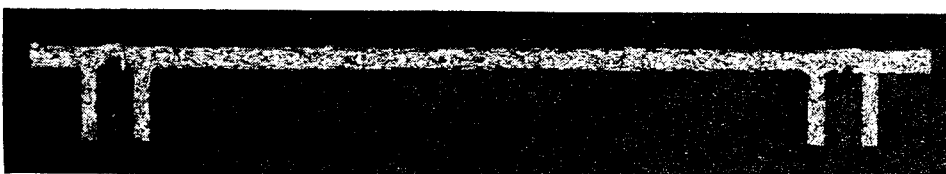


PHOTO 2
ORIENTED FLAKE FILLER IN CROSS SECTION

In order to be used effectively, these reinforcing fillers must be amenable to the process intended. The initial high aspect ratio of a long brittle material is quickly reduced in the tortuous high shear environment of extrusion and injection molding, while other particles, short to begin with, give up the efficiency of greater aspect ratio. In all cases, efficiency of these modifiers is dependent on the aspect ratio of the particle in the final molded part.

Graphite fibers are being used with greater frequency in high performance applications, usually for their reinforcing properties, although a slight improvement in thermal conductivity is a bonus in some applications.

Glass fibers metalized by vacuum deposition or dip coating with aluminum or nickel have been tested for electrical and thermal property enhancement. These products like the carbon fibers need to be processed as little as possible to avoid particle breakup in use. When employed in SMC (sheet molding compound) and some BMC (bulk molding compound) compounds, sufficient aspect ratio remains to give better thermal and electrical conductivity than that seen in injection molding applications.

For levels of improvement beyond what the glass, graphite, and mineral fillers can do it is necessary to confine the composite development to the metal fillers. These typically do not give the high reinforcement values possible with long graphite fibers, but do affect thermal conductivity to an even greater extent.

Properties of some fiber reinforced composites are found in the table below.

TABLE 2 FILLED PLASTIC PROPERTIES

PLASTIC % FILLER	TENSIL STR KPSI	FLEX MOD KPSI	ELECT COND OHM CM	THERM COND *
ABS 30% GLASS	14.5	1,100	10 ¹⁵	0.13
NYLON 30% GRAPH.	35.0	2,900	10 ²	0.58
PBT 40% GLASS	22.0	1,400	10 ¹⁶	0.29
P/CARBONATE 30% GLASS	18.5	1,200	10 ¹⁶	0.21
P/ETHYLENE 30% GLASS	10.0	900.	10 ¹⁶	0.22
P/PROPYLENE 40% TALC	5.0	620	10 ¹⁶	0.19
P/STYRENE 30% GLASS	13.5	1,200	10 ¹⁶	0.17

* BTU/hr ft² °F/ft

Data supplied by LNP Corporation, Malvern, PA.

For comparison, the property profile below of an aluminum flake filled composite will show increases in both electrical and thermal conductivity, with similiar mechanical strengths.

Nylon 6,6 35% FLAKE	10.0	1.1	10 ⁻¹	1.07
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SECTION 5 METALLIC FILLED COMPOSITES

The use of metal particulates as additives is not new to the polymer industry. Fine aluminum and copper powders, ball milled until a flat platelet form is achieved, are commonly blended into the plastic at 1% to 5% levels to obtain a metallic appearance. At the lower concentration there is no noticeable change in physical properties, while at the higher loading some reduction in impact strength may be experienced. However no increase in thermal conductivity will be seen.

Aluminum, iron, and ferrite powders are added to plastic resins to enhance or develop specific properties. A 60% by weight loading of a ferrite will give the compound magnetic properties. 40% aluminum powder will increase the heat conductivity of a formulation nearly as much as a 70% loading of bronze or steel powder. Even at these high levels, the increase in conductivity is limited due to the low aspect ratio of the spherical powder.

To achieve the high aspect ratio needed for property increase, the metal must be either drawn into a wire or formed into a flake. In both cases it is necessary to reduce the thickness of the particle to a range below 100 microns (2 to 3 mils). This serves the dual purpose of improving processability and allows a high aspect ratio to be achieved without unmanageable particle length.

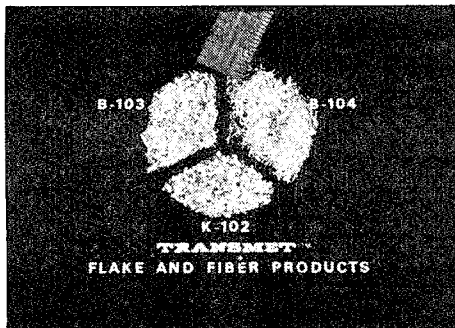


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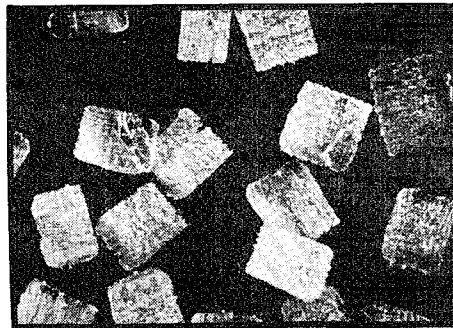


PHOTO 3B

FLAKES AND FIBERS

Long fine metal fibers are produced by bundling together fine wires, drawing them through successive dies, re-bundling them, and so on, until they are of the required thickness, and then cut to the required length. A newer process called melt extraction makes the fibers in one step directly from the melt. This involves a spinning chilled wheel being dipped into a pool of molten metal. The sharp edge picks up a thin layer of the melt, freezes it in a fraction of a second, and casts off the fiber.

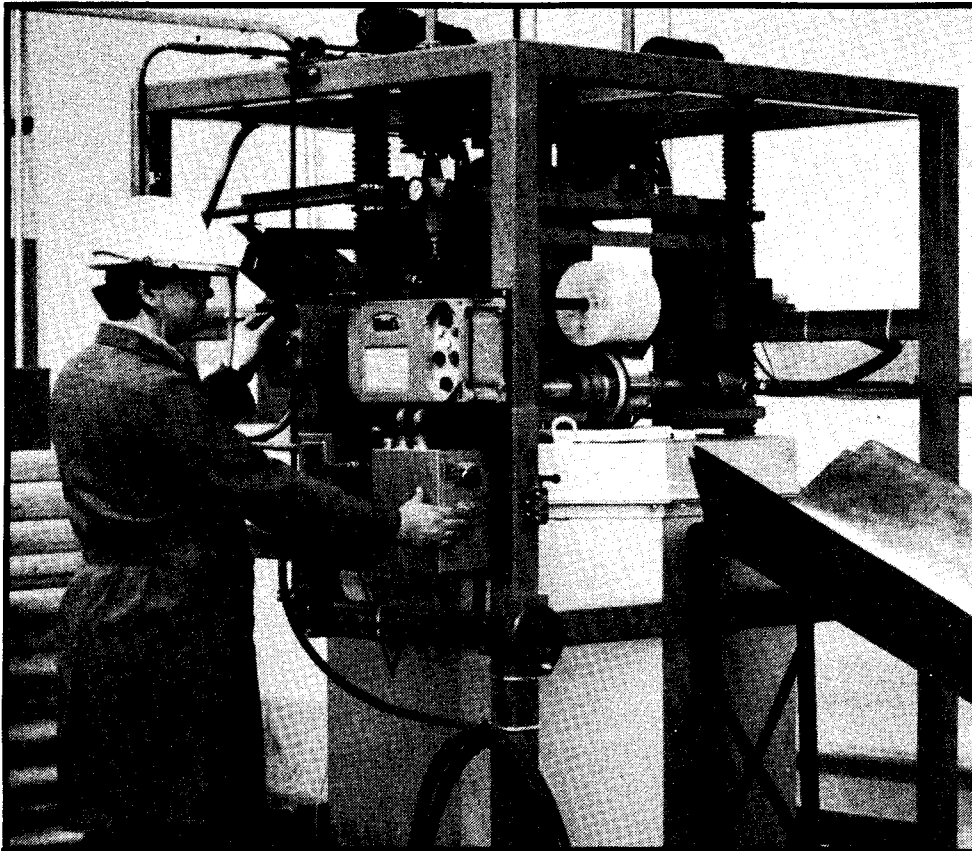


PHOTO 4 MELT EXTRACTION

The aspect ratio of these fibers can be varied by changing the thickness or the length. Although efficiency increases in direct proportion to the increase in aspect ratio, processability tends to decrease. Commonly used aluminum fibers are 90 microns (3 mils) thick and 3mm (.125") long. Steel fibers this thick could destroy a plastic injection molding machine, so the commonly used products range from 4 to 15 microns (0.5 mil).

Metallic flake fillers for plastics are today made by a unique rapid solidification process called "melt spinning". When compounded into a typical resin system these flakes cause an increase in flexural modulus, in electrical conductivity, and a significant increase in thermal conductivity. The table below compares the effects of similar loadings of aluminum powder and aluminum flake on the conductivity of a phenolic resin.

TABLE 3 ALUMINUM FILLERS vs CONDUCTIVITY

FILLER SHAPE	COMPOSITE SPEC. GRAV.	ELECT. RESIST. OHM CM	THERMAL COND. BTU/hr ft ² °F/ft
POWDER	1.85	» 10 ⁶	0.25
FLAKE	1.85	0.1	1.05

The rapid solidification process used to produce the aluminum flakes was developed at Battelle Memorial Institute in 1978 with two goals in mind. First, that the technique would produce a high quality metal particle at a low cost. Second was to employ the basic concept of the quick quenching process which would make possible strong stable metal particles with an extremely fine microstructure.

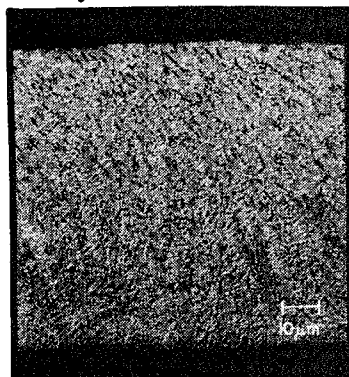


PHOTO 5

This second factor gives the flake a greater ductility and stiffness, allowing them to retain their high aspect ratio while being compounded into the plastic matrix, and during the subsequent extrusion or molding process. In addition, the process causes a dense but very thin stabilizing oxide to form on the flake surface. Once formed, this layer remains intact, protecting the particle from the effects of aggressive polymer matrices and the effects of long term aging.

The manufacturing process involves the spraying of a stream of molten aluminum through a small orifice and onto a flat, notched, chilled wheel spinning at a high rate of speed. The melt freezes in a fraction of a second with a quench rate measured at over one million Celsius degrees per second.

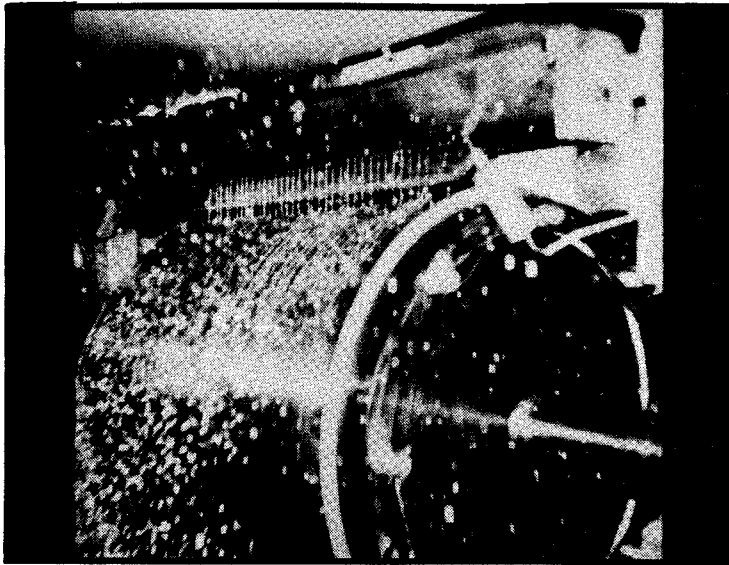


PHOTO 6 MELT SPINNING MACHINE

By altering the configuration of the wheel, its speed, and the flow of metal it is possible to produce flat particles in a wide range of sizes. Those used today in conductive composites are as small as 0.5mm (20 mil) square and include larger sizes which are nearly square- 1 x 1.3mm (40 x 50 mils), and those with a higher aspect ratio- 0.5 x 1.5mm (20 x 60 mil). The thickness in all cases is approximately 30 microns (1.2 mils).

The melt used can be altered to achieve a desired end result, but typically is a high purity alloy. Minor additions of other metals are made to improve particle integrity and processability.

SECTION 6

RESIN/FLAKE COMPOSITES

In the development of a thermally conductive composite, the choice of plastic resin is based on chemical resistance, heat deflection temperature and processability. The choice of flake or other filler is based on the degree of conductivity needed. What remains is the choice of a means to blend the two components together. Because the conductivity is a function of the aspect ratio, the mixing process must be carried out to ensure that no significant degradation of the flake occurs.

There are two methods to incorporate the conductive additive in a resin for the injection molding of a conductive part. The first involves a tumble blending of pelletized resin with flake and directly injection molding the mixture. Experiments have shown that there is flake segregation in the hopper resulting in a great non-uniformity in the parts. A modification of this process involves the use of a powdered plastic tumble blended with the flake. This method, used now with styrenic, polycarbonate, and polyolefin resins has yielded good homogeneous parts. There are limitations and in most cases the molder does not want the added responsibility of formulation quality control or the problems of effectively drying the blend. However speciality blends of resin and metal flake are now being marketed in Australia, and are finding use in heat conduction applications in the appliance and foodware industry.

The most common technique is the preparation of a precompounded product in which the base resin supplier or a custom compounder adds conductive flake to the desired resin matrix and produces a composite pellet which then can be molded or extruded under typical conditions. In compounding, not only must the shear be kept as low as possible to avoid flake degradation, but the compounding time itself must be reduced. If the rapid solidified flake modifier is added to the compounding extruder through a secondary downstream addition port, it is possible to minimize the time the flake is actually being worked in the melt. This technique has been used with single screw (Egan), twin screw (Leistritz, Werner and Pfleiderer), and reciprocating screw (Buss Co-Kneader) extruders and all have been found suitable once the proper processing conditions have been determined. Loadings of 35 vol %, about 50-55 wt %, have been achieved, and in some cases higher loadings are possible.

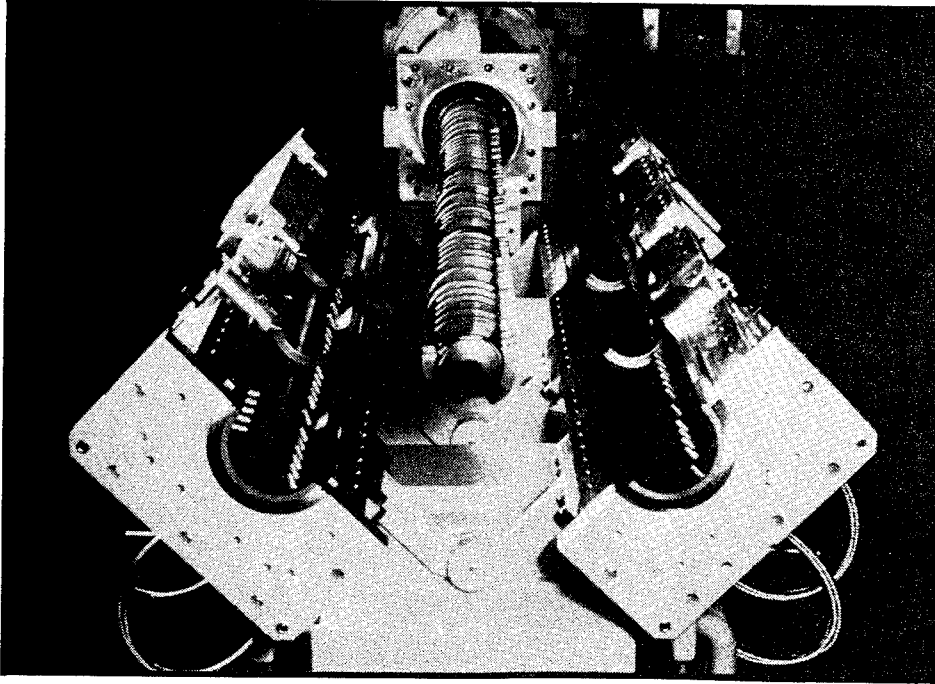


PHOTO 7 BUSS CO KNEADER

Because the effect of a filler on a resin is based on its volume loading, not weight loading, the same effective volume loading of flake in several polymers will be several different weight percents. A 22 vol % (for reasonable thermal conductivity) would be 45.8 wt % in polypropylene, 42 wt % in ABS, 38.8 wt % in polycarbonate, and 36.9 wt % in PVC. See Table in Appendix B.

TABLE 4 CONDUCTIVE PLASTIC PROPERTIES

RESIN BASE	SPECIFIC GRAV	TENSILE STRENGTH KPSI	NOTCHED IZOD FTLB/IN	FLEXURAL MODULUS KPSI	DEFLECTN @264KPSI °F	APPROX COST \$/LB	FILL RATE WT%MAT'L	THERMAL CONDUCTIVITY BTU/hr ft ² °F/ft
ABS	1.54	3.3	1.4	600	190	3.50	40/AL FLK	1.11
ABS/PC	1.54	5.2	1.2	910	217	2.85	40/AL FLK	1.12
PC	1.54	6.4	1.3	950	285	3.60	40/AL FLK	1.14
NYLON6,6	1.48	9.5	1.0	1,200	485	3.35	40/AL FLK	1.34
PBT	1.63	7.8	1.5	1,150	390	3.30	40/AL FLK	1.17
ABS	1.33	5.3	1.2	330	185	5.00	7/SS FIBR	0.11
PC	1.27	10.0	1.3	450	285	5.00	7/SS FIBR	0.13
ABS	1.20	13.0	1.0	1,300	205	12.00	20/NIPAN FB	0.33
PC	1.40	15.0	1.5	1,100	300	12.75	20/NIPAN FB	0.46
NYLON	1.38	18.5	1.0	1,400	495	15.75	30/NIPAN FB	0.58

SECTION 7

THERMAL CONDUCTIVITY CALCULATION

The thermal conductivity of filled plastics can be determined either through theoretical estimation or by direct experimental measurement. The experimental method is more accurate if care is taken in setting up the experiment, but generally more time consuming than the theoretical estimation technique. However, given experimental verification of the theoretical techniques can then be accurately applied to other plastics provided the same filler is used. The following are parameters to be considered:

- a) filler conductivity
- b) shape/aspect ratio
- c) resin conductivity
- d) volume loading
- e) packing/orientation
- f) bonding

In addition, it is possible to estimate the thermal conductivities for various shaped modifiers, although with less confidence. There are two other main properties of the modified resin which change as a function of the modifier and its volume fraction, density and specific heat. These two quantities are required in some methods of determining thermal conductivity, and in solving transient heat transfer problems.

The thermal conductivity of the particulate filler is very important in its effect on the composite thermal conductivity. However, when the filler conductivity reaches a "breakover" point, continued increases have little benefit. For metal fillers whose thermal conductivities are appreciably (100 to 2000 times) higher than that of the base resins, variations in thermal conductivity of the alloy have a surprisingly small effect on the conductivity of the composite. In comparing conductivity (K) of copper, $K=226 \text{ BTU/hr ft}^2 \text{ }^\circ\text{F/ft}$ to a filler of carbon steel $K=42$, there is a change in K of 500%. A change of only 5 to 6% in the relative conductivity factor is produced. Thus, for metal modifiers, their thermal conductivities are not as important as their other properties; e.g., corrosion resistance, ease of forming/manufacture, density, bonding, and aspect ratio.

Rather than alter the composition of the metal filler, consideration should be given to a change to a base resin with a high thermal conductivity. This could produce a much greater increase in the overall conductivity of the composite plastic.

Thermal conductivity of the filled plastic varies parabolically with percent of loading by volume. The upper limit of fill percentage depends greatly on particle shape and ability to process, as well as the point of degradation of other desirable properties with loading. For high aspect ratio modifiers like flake or fiber loading volumes up to 30-35% are achievable, while with spheres a maximum of 50% can be obtained with little problem.

For any given volume loading and particulate shape, the packing and orientation of the particles can be varied to achieve different conductivities, especially directionalized conductivities. If the particulate modifier is randomly oriented, then the thermal conductivity would be equal in all direction. However, if all the particles are preferentially oriented; e.g., the major plane of all flakes are parallel, then the thermal conductivity in the plane will be much greater than through the plane. Further, the thermal conductivity in the plane for this case would be higher than that for the randomly oriented case at the same volume loading, which in turn would be much higher than through the plane. The manner in which the flakes, are packed; i.e., positioned relative to one another, will further affect the thermal conductivity. A layering tendency is relatively easy to obtain through processing control in molding, but uniform packing is greatly dependent on the part geometry and flow during molding and is more difficult to achieve.

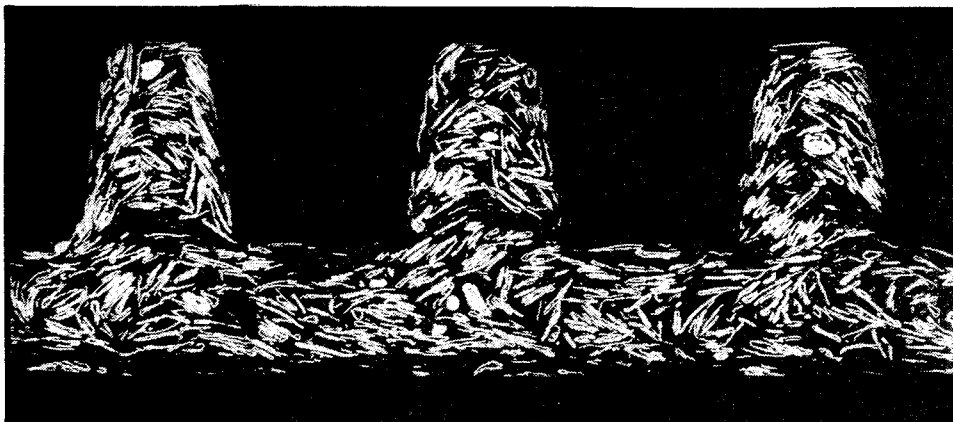


PHOTO 8 FILLER DISPERSION in FLAKE FILLED PART

The foregoing assumes that good adhesion exists between the resin and the modifier. If not, and a thin gas layer exists around the filler particles and is prevalent throughout the composite, then the thermal conductivity of the composite could actually decrease. Taken to the limit this would simulate a plastic foam. Often the lack of good adhesion will become a problem at high loading values even though it is not experienced at lower ones. This is related to processing parameters, poor wetting factors, and voids between closely packed particles not being filled with resin.

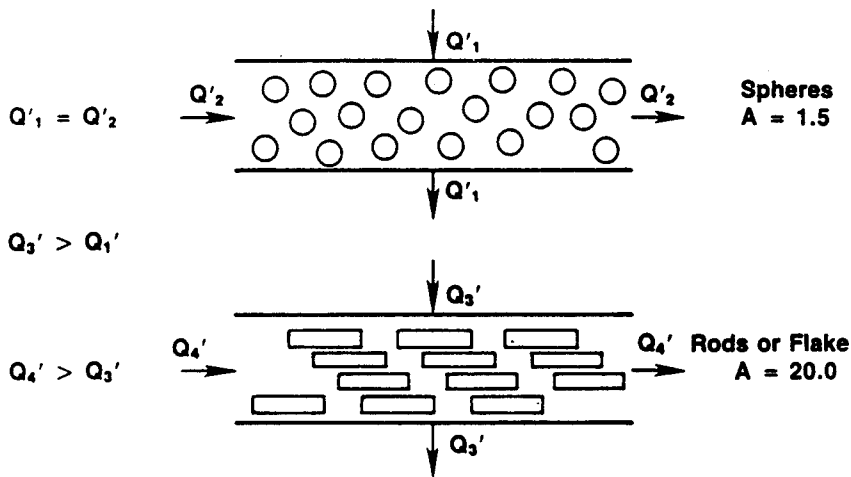
The geometric shape of the modifier particles has a very pronounced effect on the thermal conductivity of the resultant composite. Three, two, and one dimensional shapes-spheres, flakes, fibers- can be added alone or in combination to obtain various properties. The most prominent change is the increase in both electrical and thermal conductivity. An upper limit of the aspect ratio is on the order of 30 - 40 to 1 for flake after which processing and other limitations are experienced at high loading volumes. There is a tendency for the fibers and other high aspect ratio fillers to bend and clump, defeating the effect of their initial higher aspect ratio.

The mechanisms of heat transfer from source to sink involves the combination of conduction and convection, either free, forced, or a combination. Heat dissipation through radiation will also occur if temperatures are sufficiently high, as will heat absorption from radiation. To properly treat and apply the science of heat transfer to practical situations it is necessary to have a working knowledge of the interactions of these three modes of heat transfer, but of greatest significance is conduction, treated here in detail.

The determination of thermal conductivity is made by measuring the quantity of heat energy per unit time that passes through a given area of material of given thickness for a given temperature difference. The converse of this calls for the solution of a heat transfer problem given the conductivity but not one of the other quantities like thickness or temperature on one side, etc. In actuality, the determination of thermal conductivity consists of the experimental solution of a heat transfer problem from which the conductivity is then inferred.

For modified resins in which the modifier is in the form of flake or fibers, the resulting composite usually exhibits thermal anisotropy. Generally for thin cross sections the in-plane conductivity of the part is the same in all directions but quite different from the through-thickness conductivity. Thus, a minimum of two conductivity determinations must be made to describe the thermal conductivity of the composite.

FIGURE 2 ASPECT RATIO vs HEAT TRANSFER



Among the factors needed for these calculations, are the density of the composite and the specific heat.

In its simplest form, the density of a filled plastic can be determined by carefully measuring the dimensions and weight of a representative solid specimen, calculating its volume, and dividing its weight by its volume.

The densities of a filled plastic may also be calculated given the "Percentage by Weight" W (in fractional form) of the filler desired:

$$\gamma = 1[(1 - W) / \gamma_1 + W / \gamma_2]$$

where γ , γ_1 & γ_2 are the density of composite, base resin and filler respectively, and W = weight fraction of filler.

Likewise, the "Percentage by Volume" in fractional form of the filler in the composite can be calculated:

$$\phi_2 = \frac{\gamma - \gamma_1}{\gamma_2 - \gamma_1}$$

The use of the formula assumes complete wetting of the filler by the resin, and no voids or air bubbles entrapped. See table in the appendix for conversion of volume to weight loading.

The specific heat, c' , or c/g , can easily be determined experimentally by a calorimetry method. The basic principle consists of heating the spec-

specimen to a given temperature, rapidly transferring it to a known weight of water at a given temperature, and balancing the heat lost by the specimen to that gained by the water and associated apparatus. If thermocouples and a urethane foam container are used to hold water, then the heat capacities of these items is negligible. Using this simplified process, the specific heat over gravity is found by:

$$c' = c/g = \frac{c'_w \gamma_w (t - t_w)}{\gamma (t_c - t)}$$

where c = specific heat of specimen

g = gravity

c' = c/g of specimen

$c'_w = c/g = 1$ for water

γ_w = density of water

γ = density of composite

t_c = initial temperature of composite

t_w = initial temperature of water

t = equilibrium temperature of water and composite.

Theoretically, the specific heat over gravity for the composite is given by:

$$c' = c/g = 1/[1 - w] /c'_1 + w/c'_2]$$

where c'_1 and c'_2 = specific heats/gravity of the resin and filler respectively and W = weight fraction of composite.

Theoretical quantification of the thermal conductivity of a filled plastic serves two purposes, the estimation of the thermal conductivity and identification of the variables which influence the thermal conductivity. Then knowing the influential variables permits the composite to be tailored to meet given thermal as well as electrical and mechanical requirements.

Progelhof in his review of prediction methods for the thermal conductivity of composites states that the Lewis & Nielson correlation for two phase systems best fits experimental data for the range of conductive flake, fiber, and spherical fillers being investigated here. The equations are:

$$K = K_1 \frac{1 + AB \phi_2}{1 - \beta \psi \phi_2}$$

where $A = k_e - 1$

$$B = (K_2/K_1 - 1) / (K_2/K_1 + A)$$

$$\psi = 1 + \phi_2 (1 - \phi_m) / \phi_m^2$$

and K = thermal conductivity composite, BTU/hr ft² °F/ft

K_1 = thermal conductivity base resin, BTU/hr ft² °F/ft

K_2 = thermal conductivity modifier, BTU/hr ft² °F/ft

A = shape constant, $A = f(L/D)$ or $f(L/t)$, nd

$f(L/D)$ or $f(L/t)$ = function of length to diameter or length to thickness

k_e = Einstein coefficient, nd

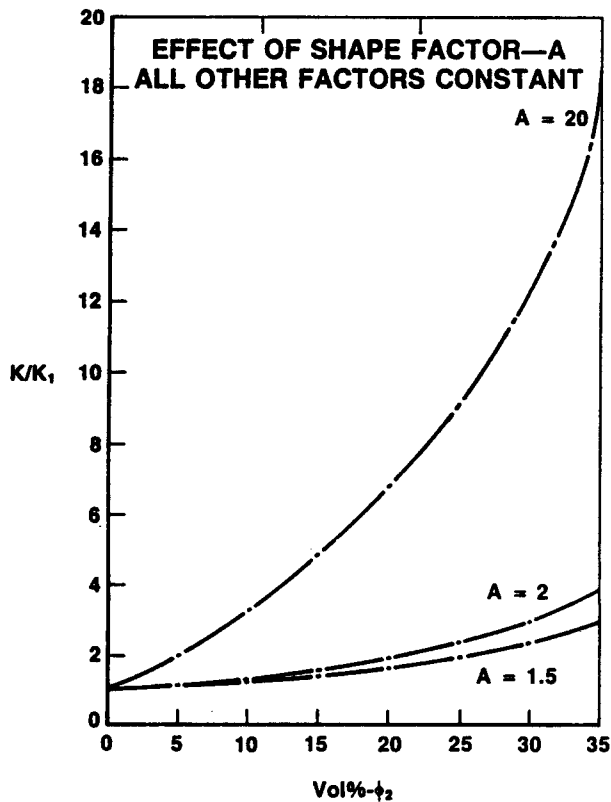
B = relative conductivity factor, nd

ψ = packing factor, nd

ϕ_2 = volume loading fraction, nd

ϕ_m = maximum packing fraction, nd.

FIGURE 3 SHAPE FACTOR vs CONDUCTIVITY



The constant A depends primarily upon the shape and orientation with respect to heat flow direction of the filler in the composite plastic. Presented in Table 5, generally from Nielson are values of A for various fillers.

TABLE 5 ASPECT RATIOS FOR VARIOUS SHAPE FILLERS

The constant ϕ_m is defined as the true volume of the particles divided by the volume they appear to occupy when packed to their maximum extent. Shown in Table 6 are the packing factors for various particle shapes and packing orientations.

Filler Orientation	L/D	Heat Flow	A
Spheres	1	Any	1.5
Random Fibers	2	Any	1.58
Blocks	1	Any	2.0
Random Fibers	4	Any	2.08
Random Fibers	6	Any	2.8
Irregular Particles	—	Any	3.0
Random Fibers	10	Any	4.93
Random Fibers	15	Any	8.38
Uniaxial Fibers	—	=	2 L/D
Uniaxial Fibers	—	⊥	0.5
Flake, Layered (A)	40	=	15-20
Flake, Layered (B)	40	⊥	5-7

A = unbent B = bent during molding

All of these materials give some increase in thermal conductivity, but their main usage has been mechanical property enhancement.

TABLE 6 MAXIMUM PACKING FACTORS

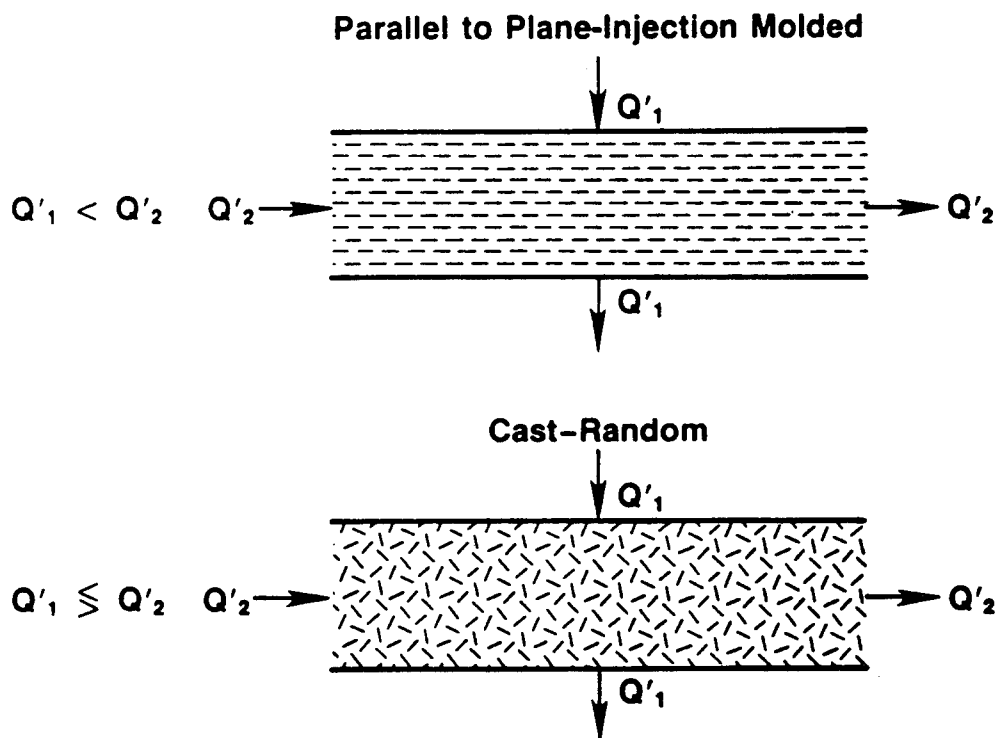
These values are the theoretical values for orientated packing. Obtaining these in practice are quite difficult, so the values for random orientations are the best values for estimation. The factor used was considerably lower than the theoretical values when used to fit the data to a curve.

TABLE 6 MAXIMUM PACKING FACTORS

Particle Shape	Type of Packing	ϕ_m
Fibers	3D Random	0.52
Spheres	Simple Cubic	0.524
Spheres	Body Centered Cubic	0.60
Spheres	Random Close	0.637
Irregular	Random	0.64
Spheres	Hexagonal Close	0.7405
Spheres	Face Centered Cubic	0.7405
Fibers	Uniaxial Simple Cubic	0.785
Fibers	Uniaxial Random	0.82
Fibers	Uniaxial Hexagonal Close	0.907

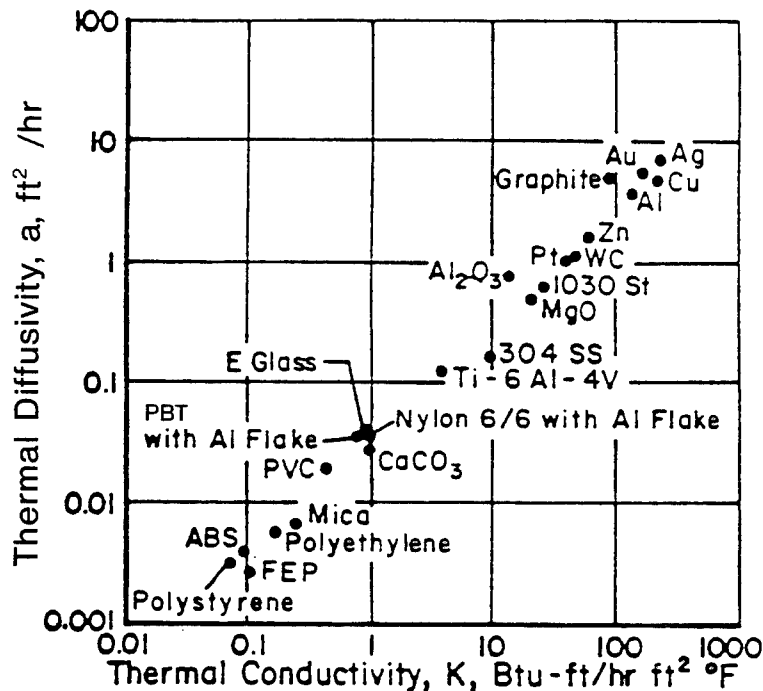
FIGURE 4 ORIENTATION vs CONDUCTIVITY

ANISOTROPIC HEAT FLOW



The thermal conductivity value of most base resins fall in the range of 0.05 to 0.2 BTU/hr ft² °F/ft. Except for plastic foams (which go as low as 0.01 due to the void/gas spaces) the resins are at the lower end of the range of conductivities for solid materials at room temperature (RT). This range for various solid materials is shown in Figure 5. The upper end is 242 for silver and is only exceeded by diamond. Temperature excursions from RT can increase or reduce the conductivities for these materials.

FIGURE 5 THERMAL PROPERTIES

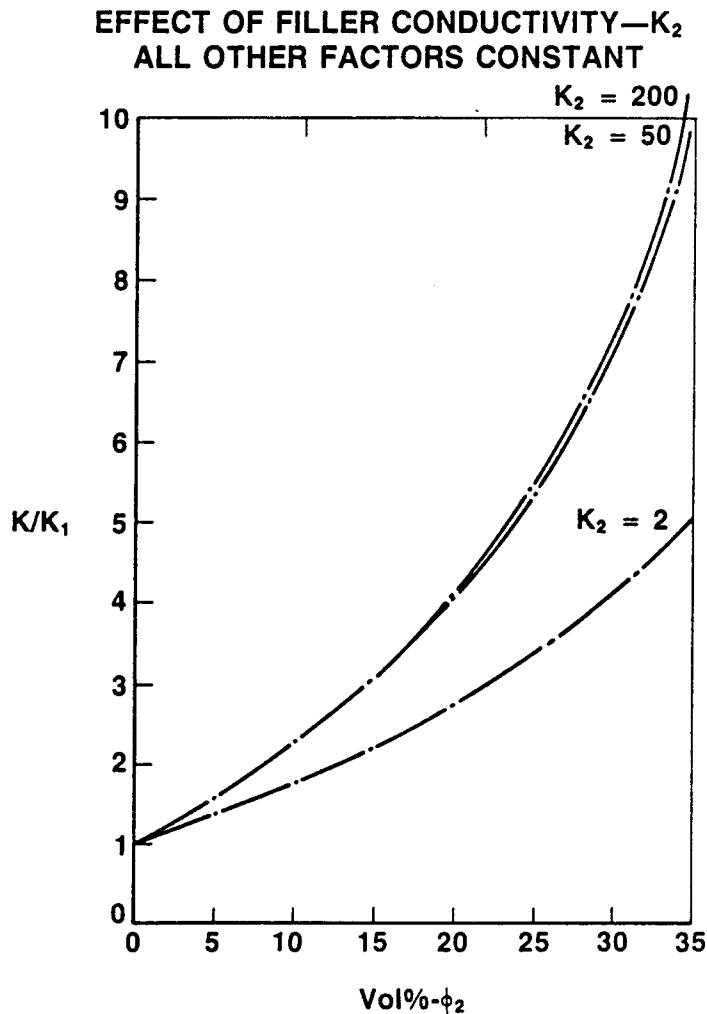


Any material having a conductivity greater than the resin can be used as a conductivity enhancer. Some common materials for filling plastics are:

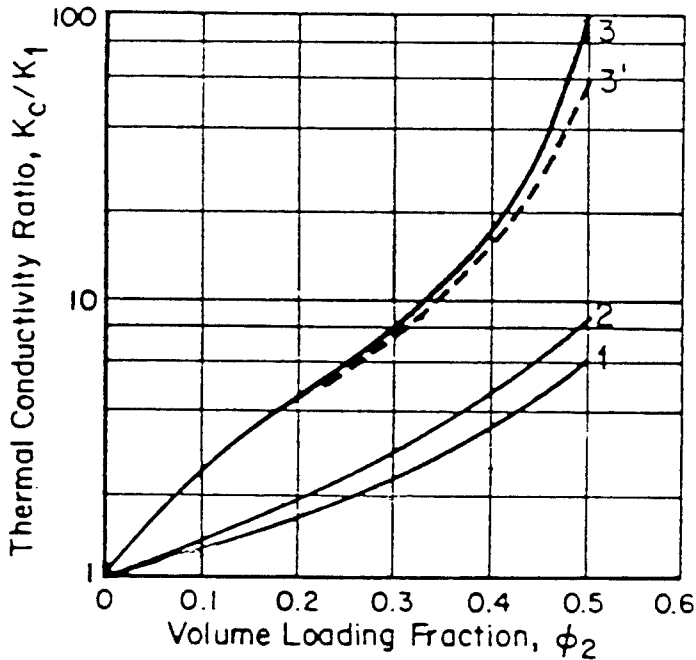
- glass — sphere, fiber, mat
- brass — powder, fiber
- graphite — fiber, powder
- aluminum — powder, fiber, flake
- st. steel — fiber
- mica — flake
- CaCO — powder

However within each family of fillers—the minerals, the glasses, the metals — the variations in conductivity have only a small effect on the thermal conductivity of the composite. To demonstrate this Figure 6 is drawn depicting the conductivity of a system filled with a mineral ($K_2=2$) and with two different metal fillers ($K_2=50$ and 200).

FIGURE 6 FILLER vs COMPOSITE CONDUCTIVITY



Once the high level of conductivity of the metals is achieved, varying this level by a factor of four or more has little effect on the overall composite conductivity.



Presented in Figure 7 are theoretical curves from Equation 1 for an increase in relative thermal conductivity as a function of the volume loading. The base cases used are listed in Table 7. Curves 1-3 illustrate the effect of going from a spherical shape to fibers. Curve 3' illustrates the small effect of lowering the thermal conductivity by 5 times. The effect of this difference is so small that it cannot be shown on curves 1 and 2 at the given scale.

TABLE 7 THEORETICAL THERMAL CONDUCTIVITY DATA

VARIABLES	#1 SPHERES	#2 IRREG.	#3 FIBERS	#3' FIBERS
K_1	0.1	0.1	0.1	0.1
K_2	100	100	100	20
A	1.5	3	12	12
ϕ_m	0.637	0.640	0.52	0.52
L/D	1	—	20	20

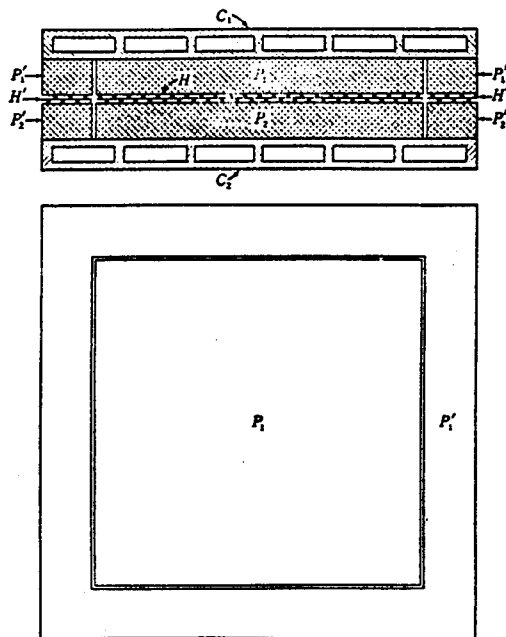
Although approximations of thermal conductivity can be made using the foregoing formulas, relationships, and calculations, the results should be used with an ample safety factor during initial product design. When experience has been gained with a given composite through field testing or property determination by experimentation, this over-design can be reduced. The following sections describe in detail standard test methods and case studies.

SECTION 8 MEASUREMENT TECHNIQUES

There are several testing techniques used to determine the thermal characteristics of a homogeneous material, and they have varying degrees of sophistication and accuracy. The testing of a composite is even more difficult, complicated by the anisotropy of the sample. Complete evaluation of the thermal conductivity of a laminate or macroscopically blended flake filled composite requires testing in at least two directions (through-plane and radially in the plane). Fiber containing systems must be dealt with in the transverse, longitudinal, and through-the-plane directions.

A common method of measuring the through-the-thickness conductivity involves placing a flat electrical heating plate H between two equal plates P_1 and P_2 composed of the material to be tested. These three plates are stacked between two cooling plates C_1 and C_2 .

FIGURE 8 GUARDED PLATE TEST METHOD



C_1, C_2 Cooling plates	P_1, P_2 Plates of material to be tested
H Electrical heating plate	P_1', P_2' Guard ring plates
H' Electrical ring heater	

The heat energy produced by the heating plate travels equally in two directions, half through each test plaque, to the water cooled plates. Temperature measurements are made by thermocouples at the interfaces of H and P₁, at H and P₂, and P₁ and C₁, and at P₂ and C₂.

Because the plaques are of equal thickness (L), in area (A), and thermal conductivity, the temperature difference (Δt) should be the same for both. Using the average value if a difference is detected, and assuming the power output of the heater ($P = I^2R$) is q, a one dimensional heat transfer solution is:

$$q/2 = KA \Delta t/L$$

which solving for thermal conductivity is:

$$K = 0.5qL / (A \Delta t)$$

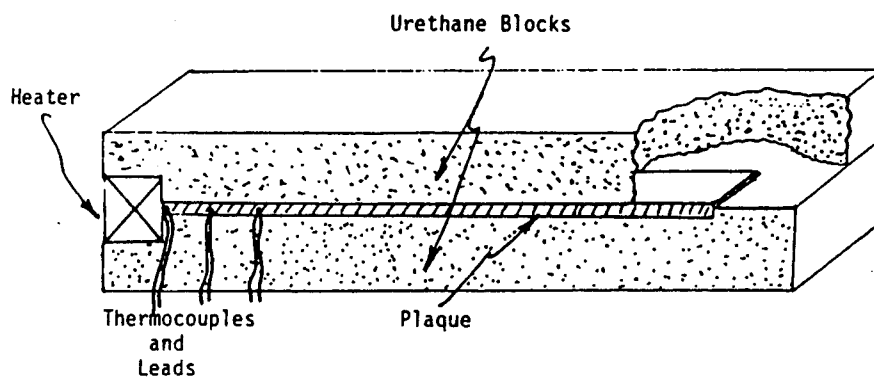
Heat energy would be lost from the edges of the sample plaques if they were in contact with the ambient air. Guard rings are used to minimize the effects of these losses. In figure 8 a ring heater H' surrounds the plaque heater. Similarly guard rings P'₁ and P'₂ of the test material surround the test plaques. By proper regulation of the guard ring heater the same temperature drop across the composite guard ring occurs as across the test plaque itself. With this balanced heat flow, there is no interaction or heat transfers among the heaters and composites. To further stabilize the system, the heat loss from the guard rings is minimized by the enclosure of the test apparatus in an insulated housing.

Instead of arranging special guard rings, a single heater only as large as H and test plates only as large as P may be used. In this case, however, particular care must be taken to avoid errors; for instance, thermocouple readings close to the edge must not be used. Again the edges P and H regions may be replaced with urethane foam insulation to reduce the edge losses.

The most important factor that must be controlled in this method is the thermal contact resistance between the heater and the plates P₁ and P₂ and these plates and the cooling plates C₁ and C₂. Appreciable resistance will affect the accuracy of the determination.

An uncommon but quick method of measuring the in-plane conductivity consists of sandwiching the plaque of material between two blocks of very low conductivity material, raising or lowering the temperature of one edge to a set value instantly, and determining the transient time for temperature changes at other points in the plaque. Inducing a temperature increment on one edge with the other three edges and both faces of the plaque insulated essentially insures one dimensional heat transfer. A sketch of this configuration is shown in Figure 9.

FIGURE 9 TRANSIENT TEST METHOD



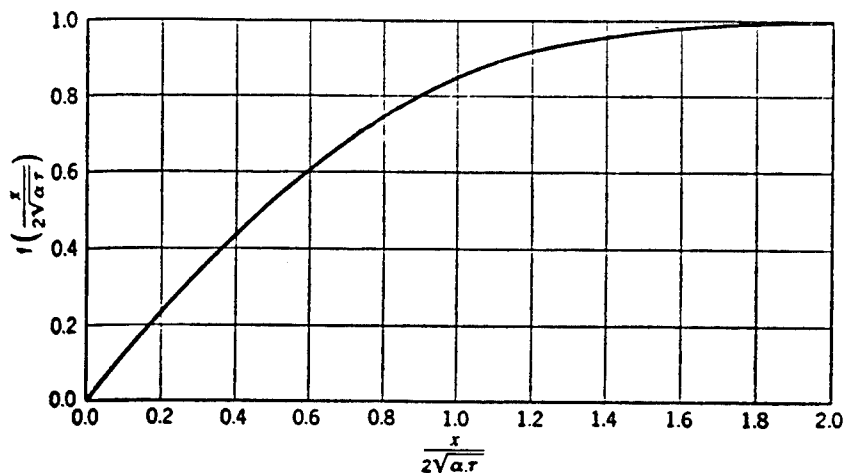
If t_i is the initial temperature of the plaque and t_s is the temperature to which the edge surface is instantly changed, then the temperature, t , at any other point a distance from the edge is given by:

$$t = t_s + (t_i - t_s) f(x/2\sqrt{\alpha\tau})$$

where $f(x/2\sqrt{\alpha\tau})$ is Gauss's error integral. In this function:

- $\alpha = K/\rho c =$ thermal diffusivity
- $K =$ thermal conductivity
- $\rho =$ density
- $c =$ specific heat
- $\tau =$ time

FIGURE 10 GAUSS'S ERROR INTEGRAL



The Gauss error integral may be found by entering the abscissa of Figure 10 with the value of $0.5x/\sqrt{\alpha\tau}$ or vice versa. If for a given t_i , t_s and x both t and τ or a set of t 's and τ 's are determined from experimentation then the thermal conductivity is determinable. First, the function $0.5x/\sqrt{\alpha\tau}$ is determined from the previous equation. Second, Figure 10 is entered with this function and the value of the argument, $0.5x/\sqrt{\alpha\tau} = \theta$, is found. Third, the thermal diffusivity $\alpha = K/\rho c$ contains the thermal conductivity. Finally, the conductivity is determined:

$$K = 0.25x^2\rho c / (\tau\theta^2) \text{ where } \rho c = \gamma c/g$$

In the British and cgs systems the units of these terms and conversions are shown in table B.

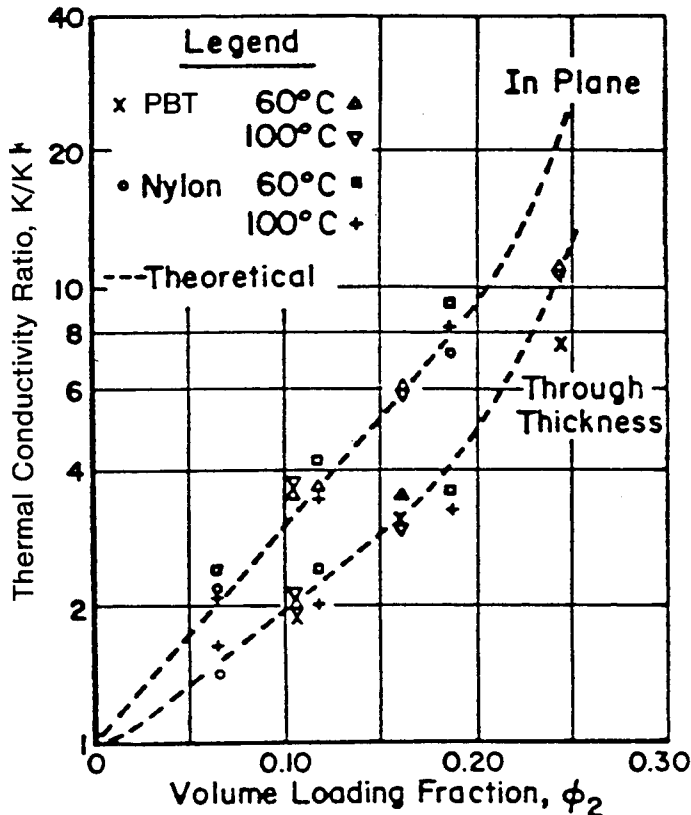
TABLE 8 SYSTEM CONVERSION AND UNITS

Term	British	Mult. Factor	cgs
c/g	Btu/lb °F	1	cal/g °C
γ	lb/ft ³	0.0160	g/cc
θ	nd	1	nd
τ	hr	3600	sec
x	ft	30.480	cm
K	BTU/hr ft ² °F/ft	0.004136	cal/sec cm ² °C/cm

Thermal conductivity determination by the transient method requires that both the density and specific heat be known. These should be determined for the composite resin experimentally, or by mathematical estimation if necessary.

If we now return to the example cases discussed earlier, a comparison between the theoretical and the experimental solutions to the problems can be made. In Figure 11 the thermal conductivities for two aluminum flake modified resins, at two temperatures, and for four volume loadings are plotted. The experimental data denoted by the symbols \diamond , v , \square , N were developed using a laser pulse technique at the specified temperatures for PBT and Nylon 6/6. Those experimental points denoted by x's and o's were determined from a transient in-plane heat transfer experiment involving temperature gradients over the range of 20°C to 100°C.

FIGURE 11 VOLUME LOADING vs CONDUCTIVITY



Using the above theoretical development, the constants which best fit these data are listed in Table 9.

TABLE 9 THEORETICAL CONSTANTS FOR TWO FLAKE FILLED COMPOSITES

Term	In-Plane	Through-Plane
A	15.5	6
ϕ_m	0.28	0.28
K_2	90 BTU/hr ft ² °F/ft	90 BTU/hr ft ² °F/ft
K_1 PBT	0.11 "	0.11 "
K_1 nylon 6/6	0.14 "	0.14 "

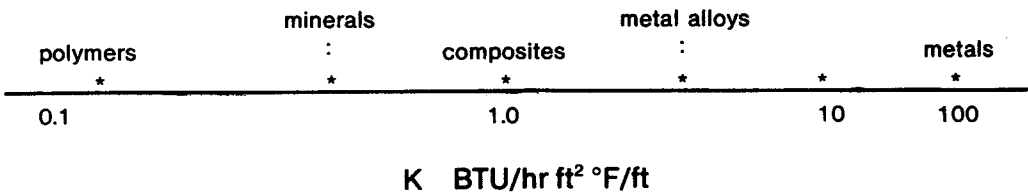
The in-plane shape constant "A" was selected lower than that value which would normally be chosen for this constant, because on injection molding the flakes were bent and did not lie perfectly in a plane. The through-thickness shape constant for the same reasons was selected higher than theoretical. These constants are valid only over the packing factor range of 0 to 0.25. Above that, the calculated K / K_1 ratio would probably be invalid.

The PBT in-plane data points as determined from these transient experiments fall on the through thickness line as determined by the laser pulse technique. Examination of the PBT specimens shows that the flake modifier there was more deformed and nonlayered than in the nylon specimens, accounting for the seeming discrepancy in data. This once again points out the need for careful analysis if a problem solution is to be attempted on a theoretical basis, and the advantage of direct property testing.

SECTION 9 HEAT TRANSFER vs CONDUCTIVITY

In the preceding sections the topic was thermal conductivity, or the K of the materials. If we were to employ either theoretical calculations or the experimental method a range of values could be seen. Pure plastic falls on the low end and pure metal on the high end. The ranges of conductive composites, metal alloys, and minerals overlap and fall between. This is expressed below on a logarithmic scale.

FIGURE 12 CONDUCTIVITY RANGE



We see that there is one order of magnitude increase in thermal conductivity in the change from a pure polymer to a conductive flake filled composite, while there is a three order of magnitude difference between the polymer and the pure metal. Yet in field testing the conductive composites perform as well as a pure metal. Part of the explanation is that unlike electrical conductivity, thermal energy is transferred by molecular vibration as well as free electron transfer. Part of the explanation is in the nature of heat transfer.

Heat energy can be transferred by conduction, by convection, and by radiation — three separate but related phenomena. The mechanism is different in each case, and different aspects of design become important in each. Examples are: part color in radiation, part density in conduction, and the film coefficient in convection. Oftentimes these ancillary design aspects have an overriding consequence on the effectiveness of the total heat transfer. Since most thermal transfer problems involve the conduction of heat away from one location and its subsequent dissipation, to the air or other fluid medium, an analysis of the limitations to dissipation is justified.

In Figure 13 there is a limitation to the heat being transferred from the air or other fluid on the left to the conductor, and then from the conductor to the fluid on the right. This limits the capability of the system to dissipate heat. On testing it was found that the temperature of the fluid just above the surface of the conductor was lower than the main stream fluid on the hot side, and higher than the main stream fluid on the cool side. The interaction of fluid and the barrier wall gives rise to a phenomenon called the film coefficient.

EFFECT OF FILM COEFFICIENT—H

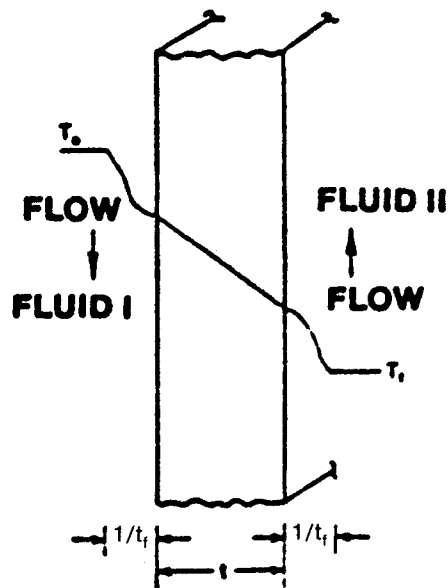
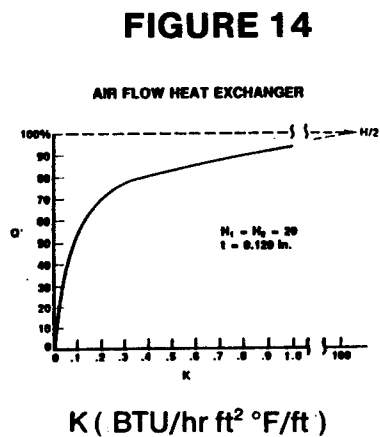


FIGURE 13 FILM COEFFICIENT

In this example t_0 , the temperature of the fluid on the hot side, decreases slightly as it begins to interact with the thin layer of fluid hugging the conductor wall. The temperature then falls more rapidly as the heat is conducted to the cooler wall, where it again goes through the transitional film coefficient before the uniform cooling fluid temperature is reached. The magnitude of the coefficient H is a function of many variables, such as: nature of the fluid, rate of flow, surface geometry, and roughness. The lower the fluid velocity the greater the influence of the film coefficient, and the less critical the actual conductivity of the barrier wall.

The calculation of heat transfer below shows that since the denominator of the equation is the sum of the inverse of the film coefficients and the conductivity, the film coefficient on each side of a conductor is equally as important as the conductivity of the conductor.

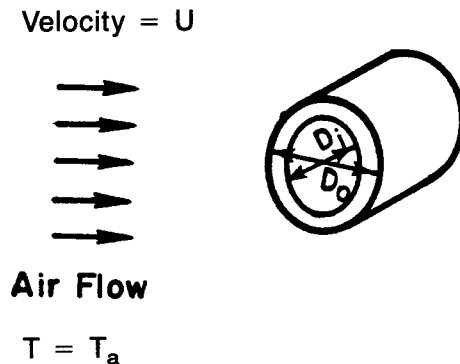
As K becomes large t/K becomes quite small, thus after some point additional increases in K become inconsequential. The turning point will vary with the specifics of each case and the magnitude of H . The better the thermal transfer through the boundary layer the more important the conductivity of the barrier wall becomes. Figure 14 is a graph of the percentage heat exchange to be expected with thermal conductivity of the barrier ranging between 0 (a perfect insulator) and 100 (a good metal conductor).



As K increases from a good foam insulator value of 0.01 to a plastic of $K = 0.1$ to a composite of $K = 1.0$, the efficiency increases from 5% to 50% to 95%. Thereafter a 100 fold increase in K to the realm of metals improves the efficiency a few percentage points until the limiting factor H , short of 100%, is approached. The effect of increasing the plate thickness is also shown.

SECTION 10

A common example of a combined heat transfer mechanism is a heat exchanger where the heat is conducted through a tube wall and dissipated by free or forced convection. These mechanisms will be demonstrated for the three materials with various thicknesses of wall for a heat exchanger with constant internal temperature and forced air convection as shown in the sketch.



The governing equation for this combined case is:

$$q = \pi (T_i - T_a) \left[\frac{1}{HD_o} + \ln \left(\frac{D_o}{D_i} \right) / 2K \right]$$

Where q = heat flow rate BTU/hr per unit length of tube

T_i = temperature inside tube, °F

T_a = flowing air temperature, °F

H = forced convection coefficient, BTU/hr ft² °F (this is a complex term and is dependent on the air properties and Reynolds Number of the flowing stream)

D_o = outside diameter of tube, ft

D_i = inside diameter of tube, ft

K = thermal conductivity, BTU/hr ft² °F/ft

U = Free air velocity, ft/sec

Of interest is the change in the heat transfer rate q rather than q itself or the outside wall temperature, etc. Consequently, all that needs be computed for the various materials and the tube diameters is the term:

$$Z = 1/[1/HD_o + 0.5 h (D_o/D_i) / K]$$

This term was evaluated for air velocities $1.2 < U < 200$ and the three cases shown in Table 10. A plot of the Z's for each case as a function of air velocity is shown in Figure 15.

TABLE 10 HEAT EXCHANGE TUBE PROPERTIES

Property	Aluminum	Flake	Base Resin
Thermal Conductivity, K, BTU/hr ft ² °F/ft	100.00	2.0	0.1
Outside Diameter, D _o , inches	.20	0.2	0.2
Wall Thickness, t, inches	.02	0.05	0.05
Inside Diameter, D _i , inches	.16	0.1	0.1

Comparison of the Z's for each material in this figure with increasing air velocity shows that the heat transfer for the base resin is conductivity limited almost over the entire range. At low velocities, there is little difference between the aluminum tube and the flake modified resin tube. For small ratio increases in conductivity to the base resin 1/20/1000 the ratio of heat transfer is 1/4.5/5.6. Thus, even for a high velocity of 200 ft/sec, the flake modified tube is 75 percent as effective as aluminum.

FIGURE 15 FORCED AIR HEAT CONDUCTION

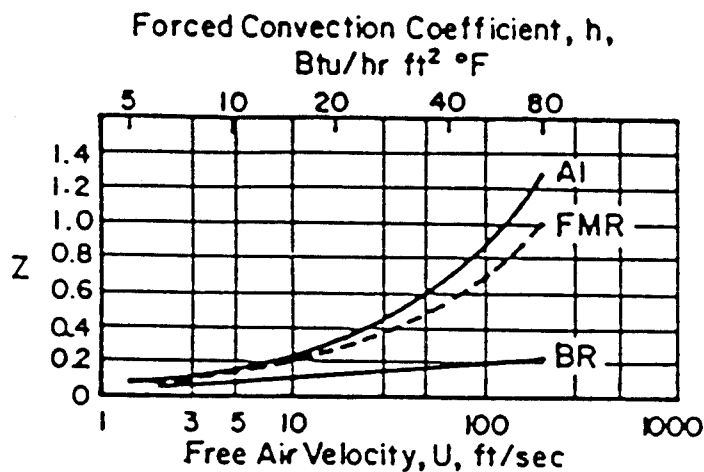
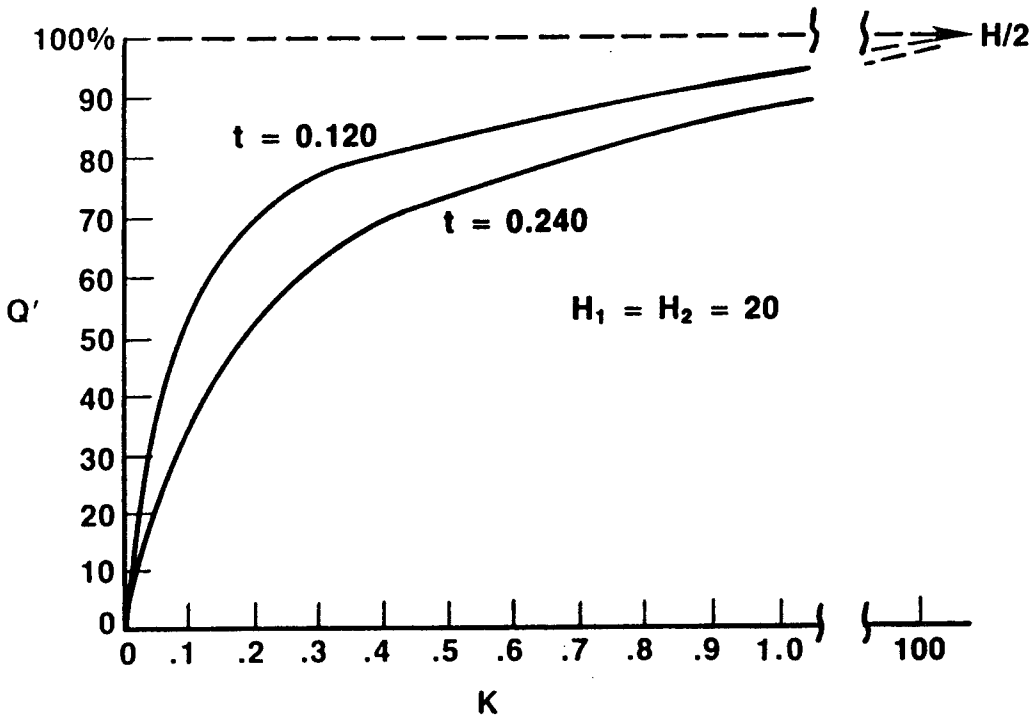


Figure 16 is a plot of the formula in which the two film coefficients H_1 and H_2 are equal to each other and both equal to 20. This is an air flow that would be found in an environment with a small fan blowing, such as in an electronic enclosure. The wall thickness separating the two temperatures is 120 thousandths of an inch or 0.01 ft. The 0/0 point at the intersection of the graph is not obtainable because that is perfect insulation, nor is the 100 percent of heat transfer obtainable.

FIGURE 16 HEAT EXCHANGE vs WALL THICKNESS



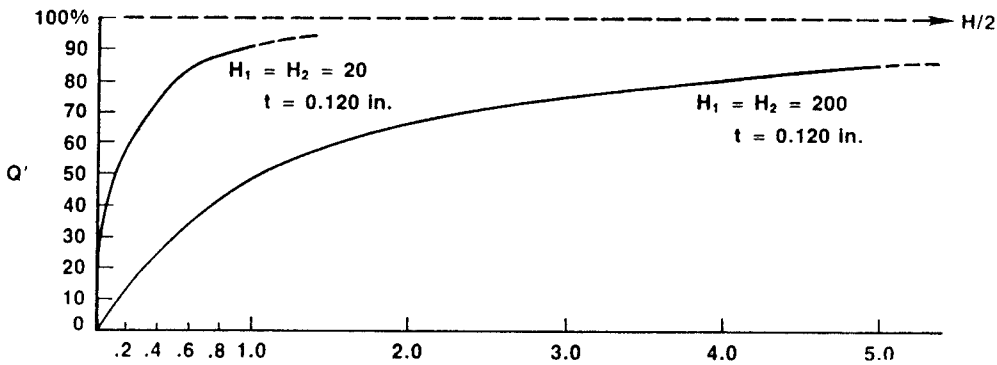
For very small changes in the conductivity of the material between the two temperatures, very significant changes in the ability to transfer heat occur. For instance, standard plastic unmodified resin with a K factor of .1 will conduct about 40% of the heat from one side of the barrier to the other. With a thermal conductivity of 1.0, (which is readily obtainable with an aluminum flake filled composite), you are obtaining a heat flow of 90.9 percent through the barrier. At this stage, by improving the thermal conductivity a 100 times such as shown with aluminum at a 100 you only reach a 99.9 percent of heat flow efficiency. In other words, for a 100 times improvement in the K value of the barrier material, you only achieve an additional 9 percent efficiency in heat flow.

The two curves in Figure 16 compare an air flow heat exchanger with wall thickness doubled and film coefficient constant at 20. This shows the effect of the wall thickness of the barrier as it relates to the K value of the barrier and the ability to efficiently transfer heat. The lower line shows the effect of a wall thickness of .24 inches versus the line from the previous slide at .12 inches or half as thick. With a K value of 1.0 the heat flow efficiency of the thicker wall is 84 percent versus 90.9 percent.

To better understand the major effect of the film coefficient or H we have in Figure 17 increased H by a factor of 10 which at H= 200 would be typical in a fluid flow heat exchanger situation rather than an air flow heat exchanger. The upper curve as we have seen has a 90+ percent efficiency with a K factor of 1 and the lower or fluid flow heat exchanger curve shows only a 50 percent heat flow efficiency.

FIGURE 17 FLUID HEAT EXCHANGER

FLUID FLOW HEAT EXCHANGER



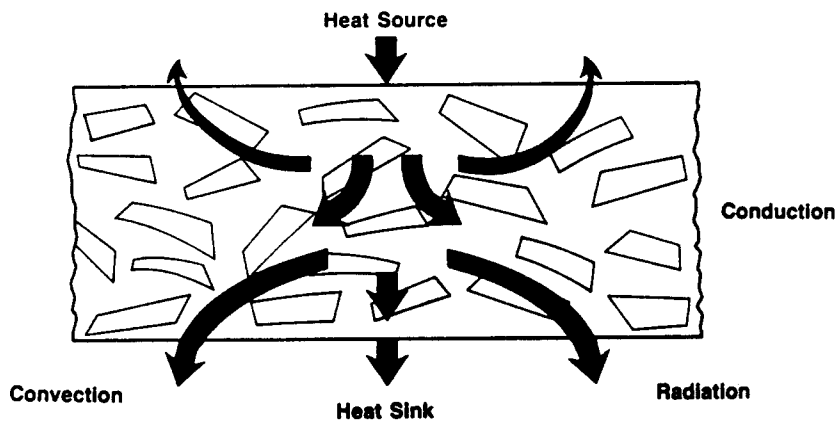
Even by increasing the K value by a factor of 5 we still only reach an 80+ percent efficiency rate and while some materials modified with the aluminum flake can reach a K value of 5, it may be necessary to consider only metals in this type of application.

SECTION 11 HEAT SINK APPLICATIONS

A common heat transfer situation in the electronics industry is the mounting of heat producing devices on thermally conductive/convective materials (heat sinks) to limit the temperature rise of the device. The heat is conducted away from the device and dissipated from the conductive mount by convection, either free or forced from both sides. The empirical approach is presented in the following solution.

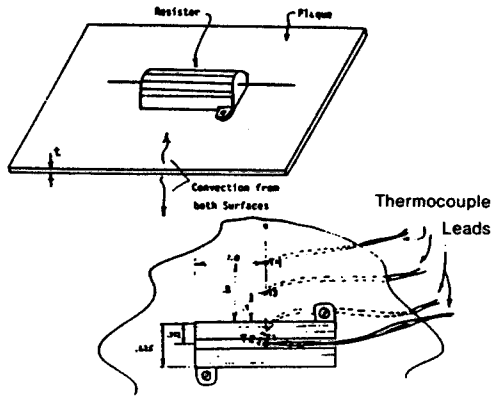
FIGURE 18 IN-PLANE HEAT TRANSFER

HEAT TRANSFER—IN PLANE EFFECT



The problem consists of determining the steady state temperature rise of a power transistor mounted on a heat sink. In this case, the heat sink is a 4x6 inch plaque approximately $\frac{1}{8}$ inch thick. The comparison of temperature rise among the three materials: aluminum, flake modified resin, and base resin is desired.

FIGURE 19 HEAT SINK TEST



The theoretical solution of this problem by manual means is difficult. However, mathematical formulation of the problems involves hyperbolic/bessel functions containing the term $(h/Ka')^{0.5}$ (let it equal) m where h is the free convection film coefficient, K is the thermal conductivity and a' is the plaque thickness. Physically this term or characteristic value is the root of the ratio between heat loss by convection per unit length for a unit area of plaque to that of conduction through that length. A plot of the temperature rise of the transistor for a range of m 's would permit the temperature rise to be determined for a plaque of known K and thus m falling within this range.

FIGURE 20 TEMPERATURE RISE vs M

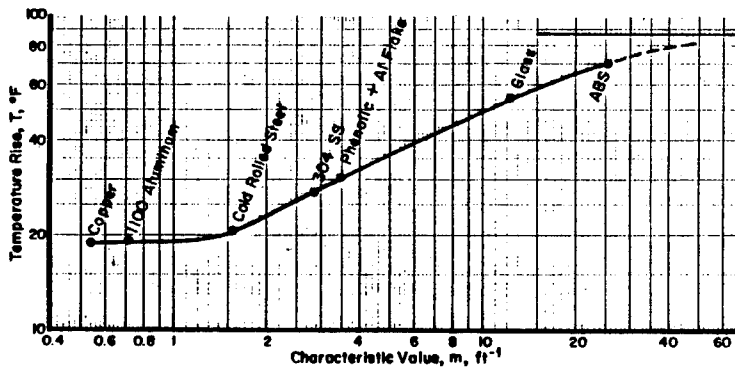


Figure 20 is a plot of m versus T developed for a conductivity range $0.1 < K < 226$, (conductivity of ABS plastic to copper) for the materials listed in Table 11. The characteristic value m is defined as:

$$m = h/Ka'; \text{ ft}^{-1}$$

$$h = h' \frac{(\Delta T)^{0.25}}{\Delta T_o}, \text{ BTU/hrft}^2 \text{ } ^\circ\text{F}$$

$$h' = 1 \text{ at } T_o = 71 \text{ F}$$

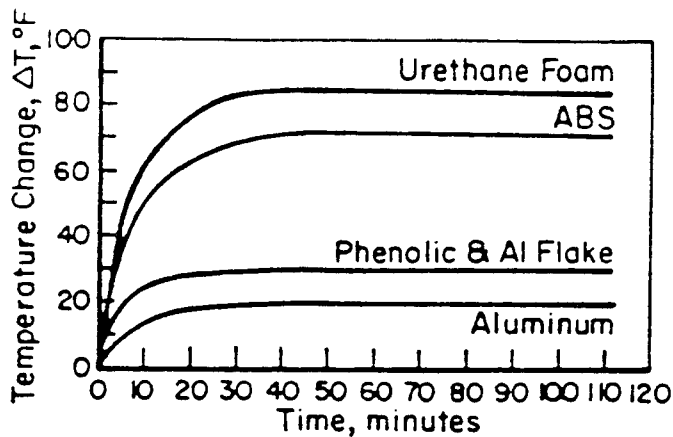
ΔT = temperature rise of the transistor, $^\circ\text{F}$

K = thermal conductivity, $\text{BTU/hrft}^2 \text{ } ^\circ\text{F/ft}$

a' = plaque thickness, feet

The asymptote of 86°F in this plot was determined by attaching the transistor to a plaque of urethane foam having a $K = 0.01$. A plot of temperature rise for this and three other plaque materials is shown in Figure 21. Now for determining the temperature rise for a material, the characteristic value m is calculated for the given K and a' and an assumed h_i . Then an initial T_i determined from the plot, a new $h_n = h' (\Delta T/\Delta T_o)^{0.25}$ is calculated and compared with the initial h_i or a new ΔT_n is computed and compared with the initial ΔT_i , and so on until the differences between the h 's or ΔT 's are sufficiently small.

FIGURE 21 TIME TEMPERATURE RISE



For the flake modified resin:

First Iteration

$$K = 2$$

$$a' = 0.125/12$$

$$h_o = 0.9$$

$$m_1 = 6.57 \cdot \Delta T_1 = 40.3 \cdot h_1 = 0.868$$

Second Iteration

$$h_1 = 0.866$$

$$m_2 = 6.44 \cdot \Delta T_2 = 40.2 \cdot h_2 = 0.867$$

The two iterations are sufficiently close for this approximation. For the aluminum and base resin, the temperature rises are:

	T	h	K
Aluminum	20.0	.73	100
Flake Modified Resin	40.2	.866	2
Base Resin	75	1.01	0.1

The accuracy of most of the temperatures is on the order of $\pm 1^\circ\text{F}$. In addition, the accuracy of computing m which depends on ΔT as well as a reference book value of K is probably on the order of $\pm 5\%$ of m . Thus, values for low ΔT 's or relatively low m could vary considerably when determined from the graph. However, this graph does give a reasonably good estimate of temperature rise and/or conductivities as function of the other.

TABLE 11 HEAT SINK MATERIALS

MATERIAL	a	K	T	h	m
ABS	0.166	0.11	71*	1.0*	25.6
Phenolic+ Al flake	0.137	5.76**	30	0.806	3.5**
#1100 aluminum	0.127	128	20	0.728	0.73
Urethane foam	0.5	0.01	86	—	—
Free air	—	—	74	—	—
Glass	0.125	0.58	55	0.938	12.5
304 stainless steel	0.122	9.40	27.5	0.788	2.9
Cold rolled steel	0.124	27	21	0.737	1.6
Copper	0.125	226	19	0.719	0.55

a = plaque thickness, inches

a' = a/12 ft

K = thermal conductivity in BTU/hr ft² °F/ft

h = h' (T/T_o)^{1/2} = corrected film coefficient

h' = film coefficient for free convection, in BTU/hr ft² °F/ft

ΔT = temperature change, °F

$\Delta T_o = 71^\circ\text{F}$

m = (h/Ka')^{0.5}/ft

*h' = 1 assumed at T = 71 °F

**derived K

Generally, this empirical determination at present is limited to the case at hand, i.e.:

4x6 inch plaques

Thin plaques typically 0.125 inches

Transistor of the type used

Power dissipation of 2.84 watts, 9.7 BTU/hr

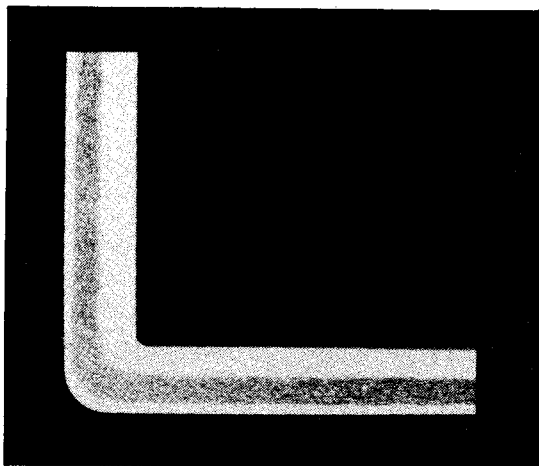
SECTION 12 DESIGNING FOR HEAT TRANSFER

There are three basic considerations that must be asked when approaching a heat transfer design problem.

1. What is the heat source?
2. Where is the heat sink?
3. How is the heat transferred from source to sink?

Generally, the heat transfer characteristics can be estimated from general heat transfer equations adapted to the specific geometry. However, in specific instances, it may be necessary to perform experimental trials for complex geometrics and in those instances where two or more heat transfer mechanisms are involved. These examples will be shown using an aluminum flake filled plastic.

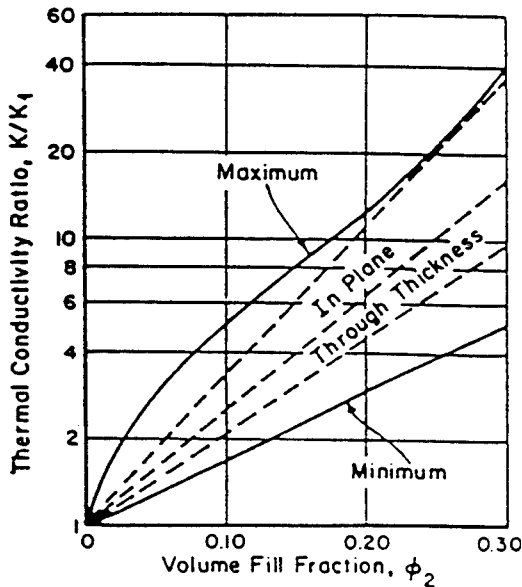
PHOTO 9 CROSS SECTION OF ELECTRONICS HOUSING



For Rapid Solidified Aluminum flake modified resins, the main change in thermal properties is the increase in thermal conductivity, 1 : 10 or 20, with lesser changes in specific heat, 1 : 2/3 or 1/2, and density, 1 : 1-1/2 or 2. Emissivity and absorption effects could be expected to change with the degree of modification as well as convection coefficient due to changes, in resin color, surface aluminum flakes, and surface texture, but the greatest change is in thermal conductivity.

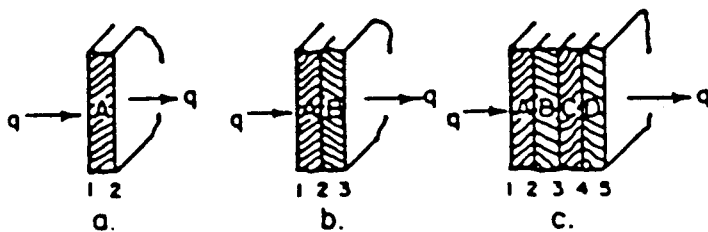
Figure 22 depicts the range of thermal conductivity ratio that can be achieved at present for flake modified resins. Conductivity increases higher than 30x and/or fill volume greater than $\phi_2 = 0.3$ are probably not attainable due to degradation in other properties as well as increase in void space at higher fills. Also, a reduction in aspect and packing factors occurs at higher fill volumes. In this figure are denoted typical ranges of ratios for in-plane and through thickness thermal conductivity ratios for flake modified resins. However, other ratios are possible depending on the processing techniques utilized. Using the range of thermal conductivities for common plastics and the multiplier at a loading $\phi_2 = 0.3$ give a range of conductivities for the modified resins of $K = 1$ to 3 BTU/hr ft² °F/ft give an average of $K_{avg} = 2.0$. This value will be used in the following heat transfer examples. These examples will show the improvement in heat transfer between the flake modified resins and base resins as well as between the modified resin and metal; e.g., aluminum.

FIGURE 22 THERMAL CONDUCTIVITY vs FILL



Probably the simplest heat transfer case is that of the steady state heat flow rate through a plane wall of a given thickness, x , and thermal conductivity, K , having a temperature difference from one side to the other.

FIGURE 23 HEAT TRANSFER THROUGH LAYERS



The governing equation for this case is:

$$q = K_A A (T_1 - T_2) / (X_2 - X_1) = K_A A \Delta T_A / \Delta X_A = A \Delta T_A / (\Delta X_A / K_A)$$

Where \$q\$ = the flow rate, BTU/hr

\$K\$ = thermal conductivity, BTU/hr ft² °F/ft

\$A\$ = area of wall, ft²

\$T\$'s = temperatures, °F

\$\Delta T\$ = Temperature difference, °F

\$X\$'s = distances, ft

\$\Delta X\$ = wall thickness, ft

\$A, B, C\$,

etc = subscripts referring to wall layers

Likewise for two layers

$$q = -AK_A (T_2 - T_1) / X_A = -AK_B (T_3 - T_2) / X_B$$

or

$$q = -A [(T_3 - T_1) / (X_A/K_A + X_B/K_B)]$$

and for many layers (\$n\$ number)

$$q = -A(T_n - T_1) / (X_A/K_A + X_B/K_B + X_C/K_C + \dots + X_n/K_n)$$

From this equation it is seen that the thermal resistance to conduction for each layer per unit area is its thickness divided by its thermal conductivity, \$R = \Delta X/K\$, with units of hr °F/BTU (this assumes that the area \$A\$ is constant for each layer). Thus, it is realized that the total resistance is the sum of the individual resistances.

Consider an egg poacher in which the cup and egg act as a two layered wall. However, rather than determining the cooking time or transient thermal gradients directly, the problem is to determine a satisfactory material for the cup. Assuming that the cup can be made of one of the following three materials: aluminum, flake modified resin, or base resin, having the

properties and thickness as shown in Table 12. Using these values, we can determine:

- a. Resistance, R , of each material.
- b. Relative temperature drop, ΔT , to that of an equivalent thickness of egg across each material for a constant flux.
- c. Equivalent wall thickness for a given ΔT again using egg as reference.

First, the resistance $r = \Delta X/K$ by definition for a unit area.

Second, the differential temperature, ΔT , is found from the equation $q = KA \Delta T / \Delta X = 1$ and solving for $\Delta T = \Delta X/K = R$ and the relative value then is just its resistance R divided by that for the egg; R/R_{egg} .

Third, the equivalent wall thickness were the cup made of egg is given by multiplying the actual ΔX by R/R_{egg} .

These terms are listed along with the material constants for the three materials in Table 12.

The significance of these terms are:

- a. Resistance, R , the case for which heat is transferred is given by the reciprocal of this value. Thus, the lower the value, the higher the heat flow rate will be for a given ΔT .
- b. R/R_{egg} indicates the relative resistance of the various materials and given thickness in relation to the egg material. For example, the pure resin is some 5.6 times more resistant to heat transfer than the egg. Conversely given a constant heat flow the temperature drop across this layer would be 5.6 times that across an equal thickness of egg, and only .28 times that for the conductive resin.
- c. KR_{egg} or the equivalent thickness of egg indicates the additional layer of egg material surrounding the egg through which the heat must pass to cook the egg. The thinner this layer, the shorter the time required to cook the egg.

TABLE 12 EGG POACHER VALUES

MATERIAL	THERMAL CON- DUCTIVITY THICKNESS		R	R/R _{egg}	KR _{egg}
	*	INCHES	hr °F/BTU	—	INCHES
Aluminum	100	0.02	0.000016	0.0014	0.000028
Flake/resin	2	0.08	0.00333	0.28	0.0224
Base resin	0.1	0.08	0.0666	5.60	0.488
Egg	0.35	0.08	0.0119	1.0	0.08

*BTU/hr ft² °F/ft

In summary, the increase in the thermal conductivity of the resin, while only 1/50 that of aluminum, is quite sufficient in this application for effective heat transfer.

PHOTO 10 FLAKE FILLED EGG POACHER



The ability of flake modified plastic composites to conduct thermal energy gives designers the freedom to take advantage of the savings possible with the cost effective high production volume oriented plastics. Engineers who require the high thermal conductivity of metal plus the flexibility of designing with plastics are encouraged by these new laboratory and field test results which are now proving their benefits in metal replacement. The commercial success of this egg poacher application is

just one example. Additional uses include:

Pulleys—to improve wear characteristics

Electronic housings—eliminate fans

Lamp reflectors—reduce warpage

Coil bobbins—longer life

Motor housings—bearing stability

Heat exchangers—eliminate corrosion

With conductive flake modified plastic composites heat transfer is combined with corrosion resistance, light weight, longer part life and lower production cost. Photos 11 and 12 are examples of current applications.

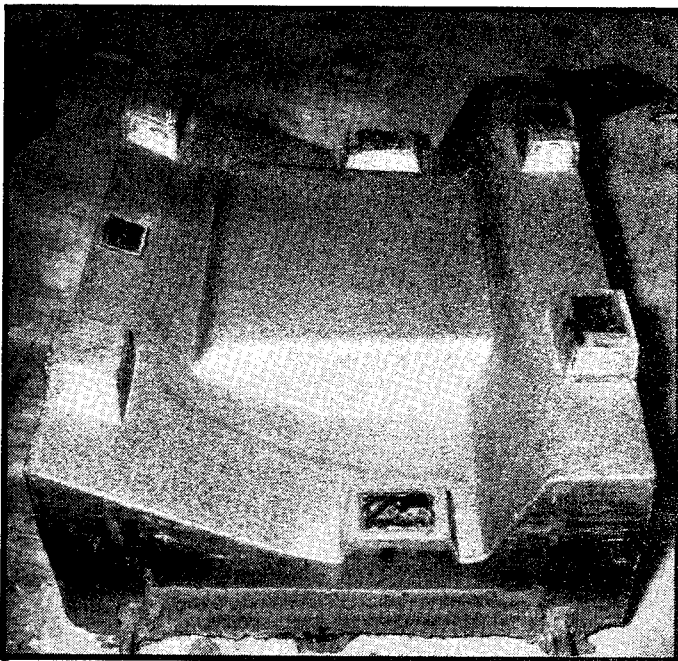


PHOTO 11

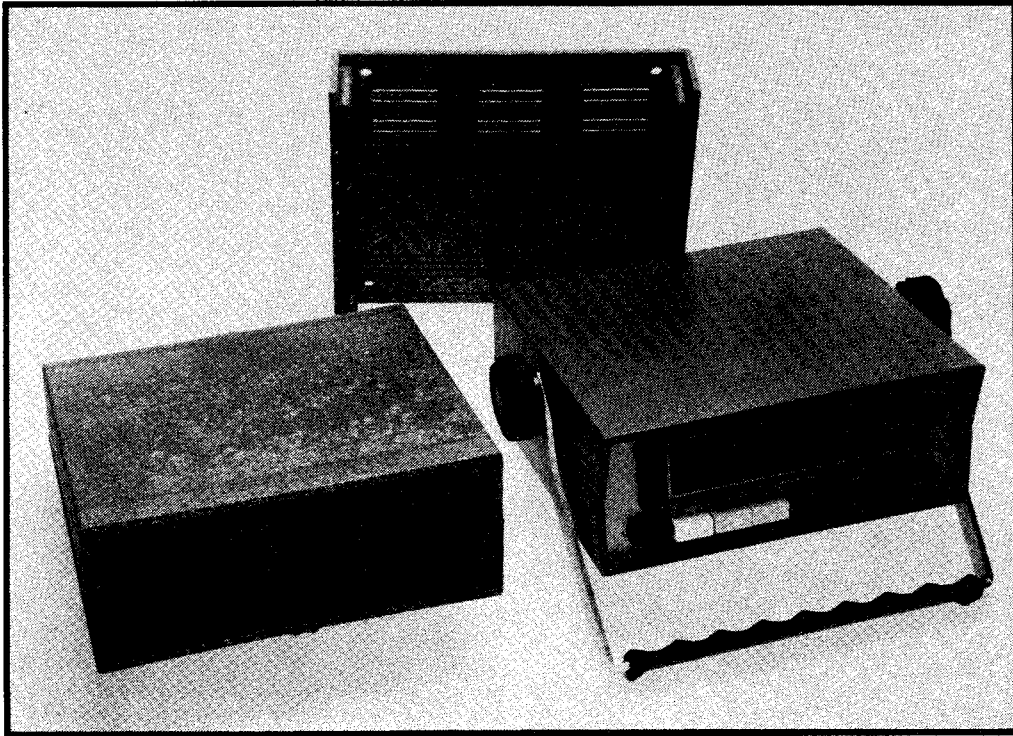


PHOTO 12

APPENDIX A MOLD AND PROCESSING GUIDE

Design—Plastic Considerations

The following information can be applied to most plastic parts. It specifically addresses part design parameters for reinforced plastics such as the Rapid Solidified Aluminum Flake conductive composites, but does not depart from the current practice of good plastic design.

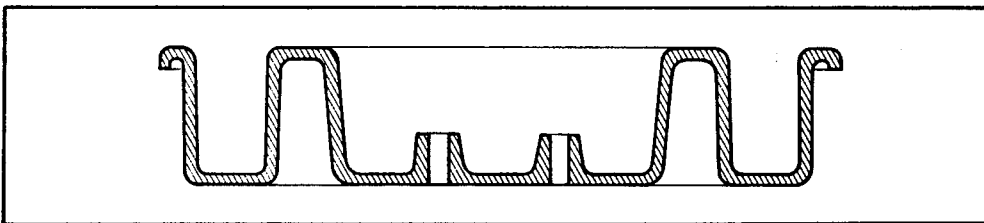
The addition of a relatively high percentage of modifier will reduce the mold shrinkage of the base resins, giving excellent reproducibility from shot to shot. The areas of draft and taper should be noted with care in their respective areas of consideration.

Uniform Wall Thickness

Uniform wall thickness is important, as it is in any plastic part design. Two things that should be considered is that the reinforced conductive composites will have a higher rigidity and therefore may be designed with a thinner wall, and if the enclosure must pass the UL flammability of V-O (which most units operating on 110 volts AC must) the minimum wall thickness for V-O as shown on the "UL-listed" yellow card must be taken into consideration. Figure 1A.

UNIFORM WALL THICKNESS

FIGURE 1A



The designer can maintain nominal thickness throughout an intricate part by designing hollow ribs, bosses, and elevation changes. This will not only minimize warpage but will save molding material and cycle time as well.

Draft

Draft is a slight angle on the part relative to the direction of opening and closing of the mold. Parts should be designed so that all side surfaces, both interior and exterior, have draft. This is necessary for easy removal of the part from the mold and to avoid damage to the surface.

Surfaces parallel to the mold movement should have a minimum draft angle of 1-1½ degrees. This includes all part details such as ribs, bosses, elevation changes, and holes. A draft angle of 1-1½ degrees on standing ribs and bosses will result in a thickness change of 0.017-0.0255 inch for each inch of length.

Minimum Radius

In plastic parts and their tooling design, the term radius is used to define the curvature established between two intersecting surfaces. The larger the radius, the better the flow of molding material. Both exterior and interior plane intersections should have a minimum radius of 0.0625 inch. Radii should be designed so as to maintain relatively uniform part thickness. Properly designed radii improves part abuse resistance and facilitates easy removal from the mold (see Figure 2A).

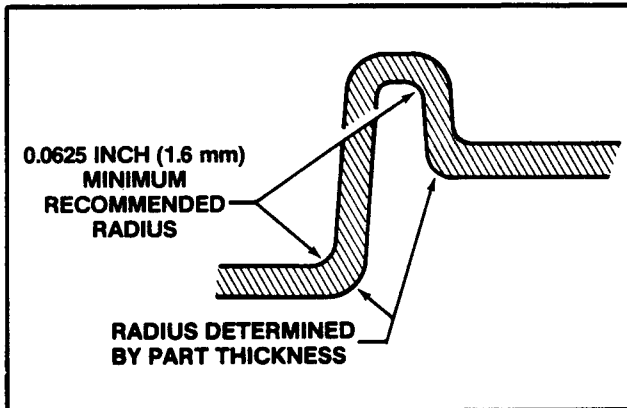
At the base of ribs and bosses, especially those located opposite appearance surfaces, radii should be held to a minimum. This will reduce the mass of material where radii meet adjacent surfaces and reduce the likelihood of warpage or surface depression on the surfaces opposite the ribs and bosses.

TYPICAL RADIUS DESIGN

0.0625 INCH (1.6 mm)
MINIMUM
RECOMMENDED
RADIUS

RADIUS DETERMINED
BY PART THICKNESS

FIGURE 2A RADIUS DESIGN



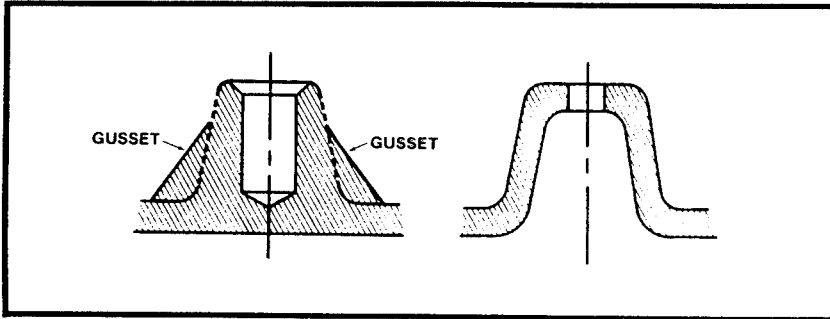
Ribs

Ribs are defined as linear projections from the adjacent plane surface of a part. They are used to add strength and rigidity to a part and to prevent warpage or bowing of large plane surfaces. This allows a considerable reduction in mass and bulk, thereby saving material and reducing mold cycle time.

Nominal thickness should be maintained when designing ribs. They should be dimensioned so that the outer end thickness is between 75 and 90 percent of nominal, allowing the draft angle to gradually increase thickness to nominal (or slightly over nominal) thickness at the point where the rib joins the flat surface. The use of tall ribs should be avoided since they tend to make molded parts difficult to remove from the mold. When wide ribs are required, they should be hollow or cored so as to maintain nominal thickness.

Ribs should have at least 1-1.5 degrees of draft per side (2-3 degrees total).

FIGURE 3A



Bosses

Bosses are defined as projections from a plane surface of a part to provide for the attachment and support of related components. They may be solid or hollow. Bosses, like ribs, should be designed to maintain the nominal thickness established for the part. Large diameter bosses should be hollow or cored to maintain nominal thickness.

Bosses should have at least 1-1.5 degree of draft all around.

Melt Temperature. Consult your supplier of Transmet™ flake modified plastic resin for starting conditions and zone temperature settings. The following are suggested maximum stock melt temperatures for various base resins (see Table 1A).

TABLE 1A

Material	Temperature	
	°F	°C
P/P	550	290
Modified PPO	620	325
Nylon 6/6	600	315
Nylon 6	580	305
ABS	490	255
ABS/PC Alloy	520	270
ABS/PVC Alloy	415	215
PVC	390	200
PBT (polyesters)	540	280
PET (polyesters)	590	310
PC	650	345
PPS	650	345

MAXIMUM PROCESSING TEMPERATURE

MOLDS AND MOLDING EQUIPMENT

Since most electronic enclosures are made from thermoplastic materials, this section will not cover information available for thermoset plastics. Similar information has been generated for thermosets however.

Injection Mold Considerations

Mold Materials

For low to medium production volume, P-20 steel is recommended. If an etched grain or detailed surface is required, the mold surface should be flash chromed or nickel plated. H-13 to S-7 steel is recommended for high volume production.

Sprue

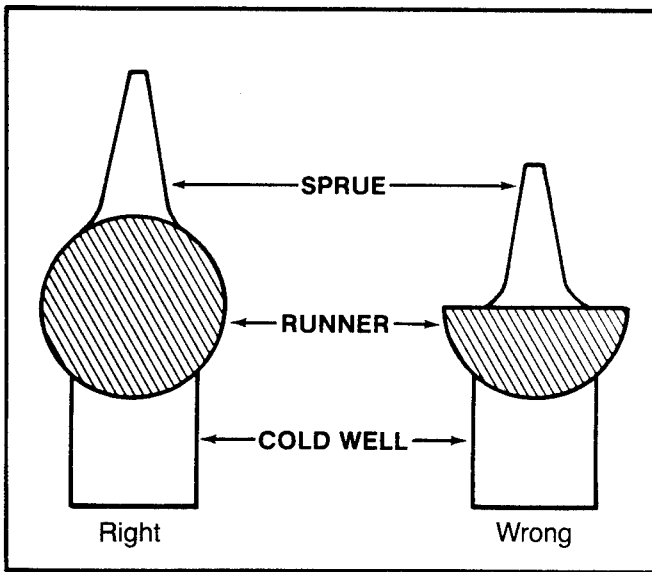
The sprue size should be as large as possible within the limits of the part. The diameter at the small end should be slightly larger than the nozzle opening and have a taper of 3 to 5 degrees for good release.

Runners

Full round runners are recommended to minimize heat loss and maximize flow. Trapezoidal runners, though not preferred, can be used (see Figure 4A). The size will depend on the part, but it should not be less than 0.250 inch (6.0 mm) in any direction.

TYPICAL SPRUE AND RUNNER

FIGURE 4A



Gates (Other Than Center Sprue Gates)

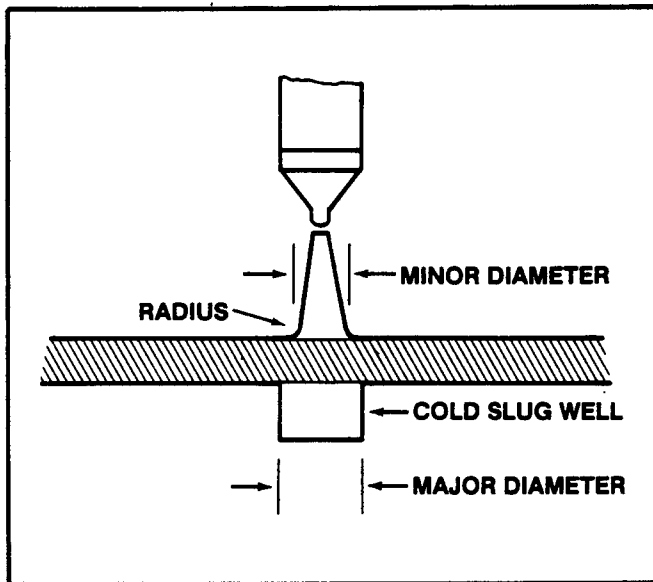
As in all filled materials, gates should be large to avoid jetting and tearing of the modifier. The size and shape of the part will dictate gate design, but fan gates with a minimum thickness of 0.080 inch (2.0 mm) are recommended. Maintain a minimum land length. Submarine and tunnel gates can be used, but may adversely affect the final conductivity of the part.

Center Sprue Gating

Many electronic housing parts are natural for sprue gating. As is recommended with the runner system, the sprue should be kept short with a generous cold slug well at the far end. See Figure 5A.

CENTER SPRUE GATING

FIGURE 5A



MINOR DIAMETER
RADIUS
COLD SLUG WELL
MAJOR DIAMETER

The major diameter of the sprue should be at least twice the part wall thickness with the minor diameter less than $\frac{3}{4}$ of the major. A generous radius at the intersection of the sprue and the part will help eliminate blush marks in that area.

Temperature Control

It is important to be able to maintain tight control of mold temperature for proper fill and warpage control. Since Transmet flake and carbon fiber modified plastics have higher thermal conductivity, the need to avoid premature surface freeze off is best controlled by even heating of the mold. To some extent the resin-rich surface desired for finish painting is obtained through mold heating. Any extra cost involved in this facet of mold building is generally justifiable.

Surface Finish

Textured surfaces can be produced in plastic parts by various types of etch treatments and mechanical tooling applied to the mold cavity. Textures applied to surfaces opposite projecting ribs and bosses can disguise localized surface depressions or discolorations in pigmented parts. Molded-in styling lines or changes in contour are also effective in masking surface depressions. When parts are textured, draft must be increased. For every 0.001 inch (0.025 mm) of texture depth, draft must be increased 1 degree.

Numbers, letters, and symbols can be molded into the part. Characters should be smooth and rounded. They should, where possible, be positioned on surfaces parallel to the parting line; otherwise movable mold inserts are required.

Injection Equipment Considerations

Best results are obtained on standard reciprocating-screw injection molding machines where near maximum rated shot capacity is used.

Screws

Screws with a lower compression ratio (1.5:1 to 2:1) allow the molder greater latitude in the use of back pressure and screw rpm. By working the material more gently, there is less chance of destroying the integrity of the conductive modifier.

Nozzle

Short nozzles which are free of any sharp internal corners and which have separate temperature-controlled heater bands are recommended. This will avoid cold slugs which restrict the flow path to the mold.

Clamp

While part design and tie-bar clearance will frequently dictate the equipment to be used, a good rule is to plan a minimum 2.5 tons of clamp for each square inch of surface perpendicular to mold movement.

Drying

No plastic resin should be processed at a moisture content above that recommended by the supplier. Parts molded from modified plastics not only have to satisfy the appearance and physical requirements, but must be conductive as well. Therefore qualified molders should have

dehumidifying dryers and hopper dryers with a maximum Dew Point of 0 degrees F (– 20 degrees C).

For those materials that are not hygroscopic (P/P, P/S), the preheating provided by a hopper dryer is beneficial.

PROCESSING AND QUALITY CONTROL FACTORS

Processing Considerations

It is well known in the plastics industry that all plastic resins require proper handling before, during and after the molding process to produce parts which are acceptable. To this end, each resin producer has a published set of recommended molding parameters for each product.

As resins are alloyed, blended, or filled with modifiers, the need to follow the suppliers molding recommendations becomes greater. The plastic parts molded from these materials must be acceptable dimensionally and cosmetically, but they must be structurally sound as well.⁶

The objective of molding *conductive* plastic parts from *any* conductive plastic composite is to obtain an acceptable, structurally sound, thermally conductive part at an efficient cycle. This is achieved by maintaining the integrity and aspect ratio of the modifier. Since each plastic part and injection molding machine has its own personality, the following information should be considered as starting points.

Melt Temperature

Depending on the filler used, these temperatures could range from 10 to 40 degrees F above those for a comparable unfilled base resin. Consult your supplier of the conductive modified plastic resin for starting conditions and zone temperature settings.

Mold Temperature

Again the resin suppliers recommendations should be followed. However a rule of thumb of 50 to 100 degrees F. above the neat base resin mold temperatures can be used. Surface finish, cycle times, and warpage are affected by mold temperature control.

Screw Speed

Speed can vary depending on the material and part configuration, but should be in the medium range of 80 to 120 RPM.

Injection Pressure

The part design, weight and rating of the machine generally controls this parameter, but medium injection pressure is a good starting point.

Note: The next two parameters have the most rapid and drastic effect on the final conductivity of the part. This is because they both have a direct bearing on the final aspect ratio of the conductive modifier and its relationship with itself and the overall part.

Back Pressure

Back pressure should be as low as possible and still maintain good injection molding practice of getting a homogeneous melt without relying totally on barrel heat. High back pressure will tear and cut a flake or fiber filler, thereby decreasing its aspect ratio immensely.

Injection Speed

To avoid jetting and high speed shear at the gate, which can be detrimental to the dispersion and integrity of the conductive modifier, a slow initial injection speed should be used. Obtaining a full part with reasonable cycle times while preserving its conductivity is still the primary objective.

Note: Highly crystalline composites with improved thermal conductivity may require higher injection speeds with hot molds to produce highly conductive parts.

Finishing/Decorating

External components such as business machine enclosures, must meet high standard for appearance. Surface treatments may be produced by the mold or they may be applied after molding. Since the conductive modifier is embedded in the plastic matrix, post molding operations are no more complex than those encountered with an unmodified resin.

For cosmetic painting, no special preparations are necessary. The paint system should be chosen to be compatible with the base resin and can be applied by standard painting procedures.

Quality Control Considerations

Any quality control program should be based on the end use requirements of the molded parts and assure that the resulting unit (enclosure) operates to the design specifications. A number of these QC checks are fairly standard such as dimensions, cosmetics, and secondary operations.

The UL flammability testing does not require an expensive laboratory apparatus. In order to obtain a go/no-go status on a lot of resin or throughout a production run, a break-off tab is frequently added to the mold and this is then tested periodically to assure that the material and the part are remaining within the specification.

Impact testing or passing the UL 746C impact test is a direct responsibility of the end part manufacturer. The testing is done on a completed unit by a vertical ball drop or swinging pendulum impact. A periodic check on individual plastic parts is simply done with a specified ball dropping a specified distance onto the part and the resultant fracture/no fracture area is examined per the specification. If individual parts pass the ball drop test, indications are good that the final unit will as well.

Thermal conductivity quality control is not of major concern, since any variation in processing sufficient to adversely affect the best conductivity capability would dramatically reduce mechanical properties as well.

If testing is desired, a fast non-destructive method involves a known heat source and a thermocouple or infrared heat sensor. The time for the top surface to achieve a target temperature, when the part is placed on the heat source, is measured and compared against a standard. A major discrepancy is reason to cross section a part to inspect for excess flake degradation, or to perform an ash analysis to ensure sufficient filler has been used in the formulation.

Volume To Weight % Conversion

VOL%FLK	16	18	20	22	24	26
S.G.						
RESIN		WEIGHT PERCENT FLAKE				
0.90 (PP)	36.4	39.7	42.9	45.8	48.6	51.3
0.95	35.1	38.4	41.5	44.5	47.3	50.0
1.00	34.0	37.2	40.3	43.2	46.0	48.7
1.05 (ABS)	32.9	36.1	39.1	42.0	44.8	47.5
1.10	31.9	35.0	38.0	40.9	43.7	46.3
1.15	30.9	34.0	37.0	39.8	42.6	45.2
1.20 (PC)	30.0	33.1	36.0	38.8	41.5	44.2
1.25	29.1	32.2	35.1	37.9	40.6	43.1
1.30 (PVC)	28.3	31.3	34.2	36.9	39.6	42.2

THERMAL CONDUCTIVITY OF COMMON MATERIALS

$$K = \text{BTU/hr ft}^2 \text{ } ^\circ\text{F/ft}$$

Plastics	0.08 to 0.19
Micas	0.3
E Glass	0.7
Graphite Fiber — 34m	0.8
Stainless Steel	15.1
Carbon Steel	27.0
Nickel	36.0
Aluminum	135
Copper	226

**Effect of various fillers/reinforcements
on physical/mechanical properties
(as exemplified by nylon 6/6)**

Property	Unreinforced	Glass fiber	Carbon (graphite)	Mineral	Carbon/ glass fiber	Mineral/ glass fiber	AIFI
Reinforcement content (% by wt.)	0	40	40	40	20C/20G	20M/16.5G	40
Specific gravity	1.14	1.46	1.34	1.50	1.40	1.42	1.48
Tensile strength (psi x 10 ³)	12	31	40	15	34	17.5	10
Flexural modulus (psi x 10 ⁵)	4.0	16	34	11	28	9.5	12
Impact strength, notched/unnotched (ft-lb/in.)	0.9/6	2.6/19	1.6/13	0.7/8	1.8/16	1/13	1.2/7
Heat deflection temperature @ 264 psi (°F)	150	500	500	440	500	470	465
Thermal expansion (10 ⁻⁵ in./in./°F)	4.5	1.4	0.8	3.0	1.15	2.5	2.0
Mold shrinkage (10 ⁻³ in./in.)	15	4	—	9	—	7	8
Water absorption, 24 hr. (%)	1.6	0.6	0.4	0.45	0.5	0.5	0.55

COMPARISON OF MATERIALS

CONVERSION FACTORS

$K, BTU/hr ft^2 F/ft \times 14.8815 = \text{cal/hr cm}^2 C$
 $\times .004136 = \text{cal/sec cm}^2 C$
 $\times .017305 = \text{watt/cm}^2 K$

Thermal Conductivity

Material	High	Low	Material	High	Low
Diamond	320	—	Nitriding Steels ^b	30	—
Silver ^a	242	—	Malleable Irons	29.5	—
Copper	226	196	Alumina Ceramics ^c	29	—
Chromium Copper	187	—	Silicon Carbide ^d	29	—
Gold ^e	172	—	Tin Bronzes (cast), Lead	28	—
Aluminum & Its Alloys	135	67	Carbon & Free-Cutting Steels ^b	27	—
Plain Brasses	120	70	Alloy Steels (cast) ^b	27	—
Graphite ^f	120	29	Tin Bronzes (cast), High Lead	27	—
Phosphor Bronzes	120	29	Cupro-Nickels & Nickel Silvers	26	—
Beryllium Copper	110	100	Thorium	21.4	—
Lead Brasses	104	67	Martensitic Stainless Steels ^b	21.2	11.7
Tungsten ^g	96.6	—	Nodular or Ductile Irons ^b	20	18
Aluminum & Its Alloys (cast)	92.5	51.0	Lead & Its Alloys ^b	19.6	16.0
Beryllium ^h	87	—	Cobalt-Base Superalloys ^b	18.0	11.9
Molybdenum & Its Alloys	84.5	67.1	High Temperature Steels ^b	17.3	15.8
Magnesium Alloys	80	24	Boron Nitride ⁱ	16.6	—
Tin & Aluminum Brasses	67	58	Ultra High Strength Steels ^b	16	—
Zinc & Its Alloys	65.3	60.5	Boron Carbide ^d	16	—
Tungsten Carbide Cermet	50.1	25.7	Heat Resistant Alloys (cast) ^b	15.1	12.1
Rhodium ^b	50	—	Feritic Stainless Steels ^b	15	12.2
Columbium & Its Alloys	42	31.5	Cr-Ni-Fa Superalloys ^b	15	9.5
Platinum ^b	42	—	Nickel-Base Superalloys ^b	15	8.2
Palladium ^b	41	—	Stainless Steels (cast) ^b	14.5	—
Alloy Steels ^b	38.5	21.7	Uranium	14.5	—
Tin & Its Alloys	37	34	Tin-Lead-Antimony Alloys ^b	14	—
Nickel & Its Alloys ^b	36	8.7	Tantalum Carbide	12.8	—
Wrought Irons ^b	34.5	—	Age Hardenable Stainless Steels ^b	12.1	—
Iridium ^b	34	—	Zirconium Carbide	11.9	—
Aluminum Bronzes (cast)	33	22	Alumina Ceramics ^c	10.7	6.2
Tungsten-Titanium Carbide Cermet	32.9	16.5	Low Expansion Nickel Alloys ^b	10.3	7.8
Tantalum	31.5	—	Titanium Carbide	9.9	—
Silicon Bronzes	31	20	Titanium & Its Alloys ^b	9.8	4.3
Gray Irons (cast) ^b	30	28	Zirconium & Its Alloys ^b	9.6	8.1

A XIX

Material	High	Low	Material	High	Low
Beryllia ^d	9.52	—	Nyons 6, 11, 66 & 610	0.14	0.10
Austenitic Stainless Steels ^b	9.4	8	Syrene-Butadiene & Nitrile Rubber	0.14	—
Columbium Carbide	8.2	—	TFE Fluorocarbons	0.13	—
Carbon ^b	5	3	Acetal	0.13	—
Calcia ^e	4.1	—	Cellulose Nitrate	0.12	0.08
Zircon	3.6	2.9	ABS Resins	0.12	0.10
Cordierite & Forsterite	2.4	0.9	Acrylics	0.12	—
Polycrystalline Glass	2.1	1.1	Nylon, Glass-Filled	0.12	—
Electrical Ceramics	1.84	1.45	Polyesters (cast)	0.12	0.10
Magnesia ^f	1.6	0.9	Silicone Rubber	0.12	0.11
Wood Comp Board	1.5	—	Polypropylene	0.11	—
Wood Felts (1 in.), Sheet	1.5	0.08	Neoprene Rubber	0.11	0.05
Silicon Nitride ^g	0.9	0.30	Polycarbonate	0.10	0.07
Epoxy (cast)	0.8	0.1	Polyvinyl Chloride	0.097	0.089
Silica Glasses ^h	0.8	—	Polyvinyl Formal	0.09	—
Silica, Vitreous ⁱ	0.8	—	Natural Rubber	0.08	—
Borosilicate Glasses ^b	0.7	—	Polystyrenes, GP	0.08	0.06
Alkyls	0.60	0.20	Modified Polystyrenes	0.07	0.02
Wood Comp Board, Softboard	0.6	0.3	Buyl Rubber	0.05	—
Lead Silicate & Soda-Lime Glasses ^b	0.5	—	Vinylidene Chloride	0.05	—
Zirconia ^j	0.5	—	Urethane Foamed-in-Place, Rigid	0.03	0.01
Polyvinyl Alcohol	0.46	—	Neoprene Foams	0.029	0.021
Melamins	0.4	0.17	Prefoamed Cellulose Acetate, Rigid	0.027	0.025
Phenolics (molded)	0.39	0.10	Butadiene/Acrylonitrile Foams	0.025	0.021
Wool Felts (1 in.) Roll	0.39	0.24	Natural Rubber Foam	0.025	—
Phenolics Laminates, High Pressure	0.29	0.17	Silicone Foams, Rigid	0.025	—
Plastics Laminates, High Pressure	0.24	0.17	Phenolic Foamed-in-Place, Rigid	0.02	—
Ureas	0.19	0.10	Polystyrene Foamed-in-Place, Rigid	0.02	—
Cellulose Acetate & Propionate	0.19	—	Prefoamed Epoxy, Polystyrene, Rigid	0.02	—
Polyethylenes	0.17	—	Butadiene-Styrene Foams	0.018	—
Ethyl Cellulose	0.17	0.09	Thoria ^k	0	—
CFE Fluorocarbons	0.145	—			

^aValues represent high and low sides of a range of typical values at room temperature except where noted.

^bAt temperatures between 20 and 212 F. ^cAt temperatures between 212 and 1800 F. ^dAt temperatures above 1800 F.

CONVERSION FACTOR: To obtain cal/sec cm²/cm, multiply by 0.004

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