Thermal Control Overview

One of NASA's many challenges on the Apollo program was insulating moon walking astronauts from lunar daytime temperatures approaching 130ºC (265ºF) and night time temperatures falling to –110ºC (-170ºF).

Satellites orbiting the earth are subjected to similar extreme temperature variations. The delicate electronics on man-made satellites would not operate efficiently over this temperature range, so it is necessary to insulate the satellite from the space environment.

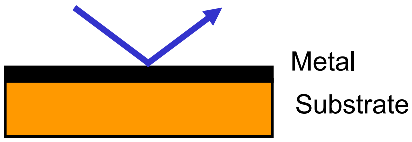
Active thermal control systems such as resistive heaters, thermo-electric coolers, sterling or peltier cycle coolers, and heat pipes are critical tools for managing the temperature in localized areas of the spacecraft. They are of limited value, however, in controlling the mean temperature of a spacecraft. Heating systems consume valuable electrical power. Cooling systems also consume power and actually only concentrate thermal energy in a small volume that must still be passively radiated into space.

In general, there are three modes available for the transfer of thermal energy; conduction, convection, and radiation. Because a satellite is isolated from other objects with mass, the only method available to affect the mean temperature of the satellite is radiation (conduction is important when considering localized temperature within the spacecraft).

All entities radiate thermal energy at a rate depending on their temperature and their efficiency of radiation or emittance. Passive thermal control systems for launch vehicles and spacecraft use engineered materials to control the amounts of energy radiated and absorbed. High emittance materials are used to radiate heat energy into space and cool the spacecraft. These materials may be used to radiate energy that has been concentrated by an active thermal control system. The spacecraft can be isolated from the external environment through the use of multilayer insulation (MLI) blankets consisting of many layers of low emittance materials. The ratio of the solar absorptance to the emittance of the materials illuminated by the sun is chosen to transfer the desired amount of solar energy to the spacecraft.

We manufacture a wide variety of products with engineered absorptance and emittance characteristics for passive thermal control systems. These materials are supplied in large sheets, rolls, and tapes. Our products have been used on nearly every payload and rocket launched since the mid-1960s.

First Surface Mirrors



A first surface mirror consists of a metallic coating (typically aluminum or gold) on a substrate. For multilayer insulation (MLI) blankets the substrate is usually PET or polyimide film, though FEP is used in some applications. Metallic coatings have very low emittance, so films coated on both sides are typically used for the inner layers of insulation blankets to minimize heat transfer.

Aluminum is the most commonly used coating; it combines low absorptance and emittance with low cost. The surface emittance, and hence energy transfer, can be reduced further through the use of gold coatings. Because gold is nearly inert, it has also been used in applications where the MLI blankets will be subjected to moist (salty) atmosphere for extended periods (e.g. space shuttle). As an alternative in this application, the aluminum can be protected with a corrosion resistant AOC coating.

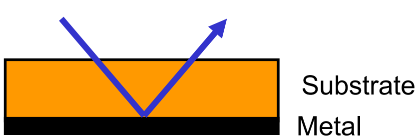
When the internal layers of the blanket will not rise much above room temperature, PET films are used. They form efficient, cost-effective radiative transfer barrier layers. When high temperature operation or burn resistance is required, polyimide is the substrate of choice.

Table 1 gives typical emittance and absorptance values for a variety of metals. The metals in this table are those most commonly used for thermal control. We have the ability to coat films with many other metals including copper, chrome, NiChrome, Inconel™, and Monel™ for other applications.

Table 1 Absorptance and emittance of metal coatings.

Metal	Typical Emittance (ε)	Typical Absorptance (α)	α/ε
Gold	0.02	.28	14
Silver	0.02	.07	3.5
Aluminum	0.03	.12	4

Second Surface Mirrors



When the sun is shining on a surface, it will be heated and reach an equilibrium temperature based on the amount of sunlight absorbed (solar absorptance, α) and the amount of heat energy emitted (emittance, ε). The lower the absorptance to emittance ratio, the lower the equilibrium temperature will be. First surface mirrors have an absorptance ratio of between 3 and 15 as seen in Table 1. To reach lower equilibrium temperatures, another device is necessary with a lower absorptance to emittance ratio.

A second surface mirror uses the bulk of the substrate to provide relatively high emittance and a metallic coating to (usually) provide low absorptance. The lowest ratios of absorptance to emittance are obtained by using a clear FEP (Teflon®) film and a highly reflective silver coating. Polyimide films are used when high temperature operation is necessary or when the stretchy FEP film does not supply adequate structural stability.

The absorptance and emittance characteristics of the second surface mirror can be tuned through the choice of substrate material, substrate thickness, and coating. Table 2 shows the typical absorptance of a wide variety of coatings. Table 3 gives the emittance of FEP and polyimide films as a function of the film thickness.

Table 2 Absorptance of coatings used for FEP second surface mirrors

Metal	Solar Absorptance
Silver	.06-.09
Aluminum	.10-.14
Copper	.20-.30
Germanium	.50-.70
Inconel™	.60-.70

Inconel is a registered trademark of international Nickel Company

Table 3 Emittance of polymer films

Film Thickness		Typical Emittance	
Mils	Microns	FEP	Polyimide
0.5	12.5	0.41	0.52
1	25	0.52	0.64
2	51	0.65	0.76
5	127	0.79	0.85
10	254	0.86	

Special Purpose Coatings

Corrosion Resistant Coating — AOC

The Sheldahl® Brand of corrosion resistant coating was developed specifically to allow aluminum to replace gold in the Space Shuttle's multi-layer insulation (MLI) blankets.

Gold coatings were chosen in the early 1970’s for shuttle blankets and were designed to withstand many launch, mission, re-entry, and mission preparation cycles. When gold reached $850 per troy ounce, a lower cost approach using aluminum was preferred. Because the MLI blanket fills with air upon reentry, salt vapor and pollutants in the air can corrode aluminum coatings.

Sheldahl® Brand AOC “acrylic over coat” was developed to protect the aluminum. The coating is between 2,000 and 4,000 Å thick yet provides environmental protection. Products with AOC protection have passed the following tests:

- 24 hours in 5% salt fog
- 100 thermal cycles between -320° F (-195° C) and +400° F (+205° C)
- 10 humidity cycles
- 25 abrasion cycles per Q000401

Black Coating — Thick Film Black (TFB)

Some thermal control situations require materials with both high emittance and high solar absorptance. In the early days of the space programs there were no commercially available black films that could withstand high temperatures. Sheldahl® Brand Thick Black Film coating was developed to address this application.

Thick Film Black is approximately 0.8 mils ± 0.1 (18µm - 23µm) thick and is composed of a carbon-filled polyester binder. It is typically applied to polyimide substrates to provide both high solar absorptance (≥ 0.85) and high emittance (≥ 0.78). The coating is electrically conductive (≤1,000 Ω/square) and has a matte finish.

Germanium Coating

Germanium coatings offer several unique features when used in thermal control applications. The germanium provides a surface resistivity on order of 10^8 Ω/square for static charge dissipation, an absorptance to emittance ratio of about 0.6, and is transparent in the RF spectrum. Germanium coated polyimide is often used on sunshields to protect RF antennae from solar radiation.

Because germanium is a semiconductor, it is an insulator at RF frequencies. In the thermal IR it is largely transparent (though there can be substantial surface reflection due to its high refractive index). Germanium has some absorption bands near the visible that give rise to a high refractive index and reflection of about 40% of the solar energy.

Silicon Oxide Coatings

Silicon oxide coatings form a clear, insulating layer over substrates or other coatings. The coating provides some protection against atomic oxygen and its thickness can be tailored to provide specific emittance levels. Sheldahl Brand's two main product offerings with this coating are polyimide film coated with aluminum and silicon oxide and FEP films and tapes with silver on one side and silicon oxide on the other.

The radiator panels on the International Space Station and the Space Shuttle are covered with silver coated FEP tape. To assure that the tapes would have a long operating lifetime in the presence of atomic oxygen; these tapes were coated with silicon oxide. This clear coating has minimal effect on the optical characteristics of the tape. The silicon oxide, however, acts as an atomic oxygen absorber and extends the life of the tape.

Some applications require a product with low solar absorptance and an absorptance to emittance ration of less than one. Most metallic coatings are better reflectors in the infrared than in the visible, so metal coatings tend to have an absorptance to emittance ratio of four or more as seen in Table 1. Sheldahl® Brand Materials offer products with a silicon oxide coating over aluminum to raise the emittance substantially. We offer two standard products with this construction; one with an emittance of approximately 0.12, the other with an emittance of about 0.25. We can design coatings to provide other emittance levels as required.

Transparent Conductive Coatings (ITO) For Static Charge Control

Transparent conductive coatings are applied to the front surface of the second surface mirrors to drain static electricity that is typically induced by the van Allen radiation belt. Without the coating, surface charges can build potentials of 20,000 to 30,000 volts.

The most common type of transparent conductive coating is Indium Tin Oxide (ITO). The surface resistance of this coating can be adjusted from as low as 20 Ω/square to as high as about 10,000 Ω/square. As a part of a thermal control system the target surface resistance is a compromise between several competing factors. On the one hand, a thicker, lower surface resistance product is desired to provide a more robust coating. On the other hand, higher surface resistance is desired to reduce surface currents and to maximize the emittance of the product (ITO can be a very good IR reflector).

Our standard product has a target surface resistance of 5,000 Ω/square as a compromise between these competing goals. An ITO coating of this thickness has no measurable impact on emittance and increases the solar absorptance by about 5%. ITO is available in sheets and rolls up to 48 inches wide. We also manufacture tapes with ITO coatings.

Table 4 below provides the key characteristics of our standard ITO coating.

Table 4 ITO coating key characteristics

Parameter	Value
Surface Resistance	2,000 to 10,000 Ω/square
Thickness	<100Å
Abrasion On Polyimide	Resistance remains in specification after rubbing 10 cycles with two pound force on cheesecloth (Q000401)
Coating Adhesion	Passes Scotch® Tape Test (Q000084)
Weathering	U.V/Humidity (ASTM 6 53-77) No Change After 144 Hours

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PERFORATED Interconnects

Connecting ground leads to ITO coated surfaces is difficult. The coating is fragile and many techniques for attaching a ground wire will crack the coating and isolate the ground wire from much of the coating. An alternative is to develop a technique to use the coatings themselves to connect the ITO on one side of the substrate to a highly conductive coating on the other.

Creating an electrical interconnect can be done by perforation a series of holes in the substrate prior to applying the coatings, as seen in Figure 1. When this is done, both the ITO and the metal coatings cover the walls of the perforation hole and form an electrical connection between the top and the bottom of the substrate. This technique provides redundant connections between the two surfaces. Many customers have used this technique successfully with the perforations providing as little as 1% open area.

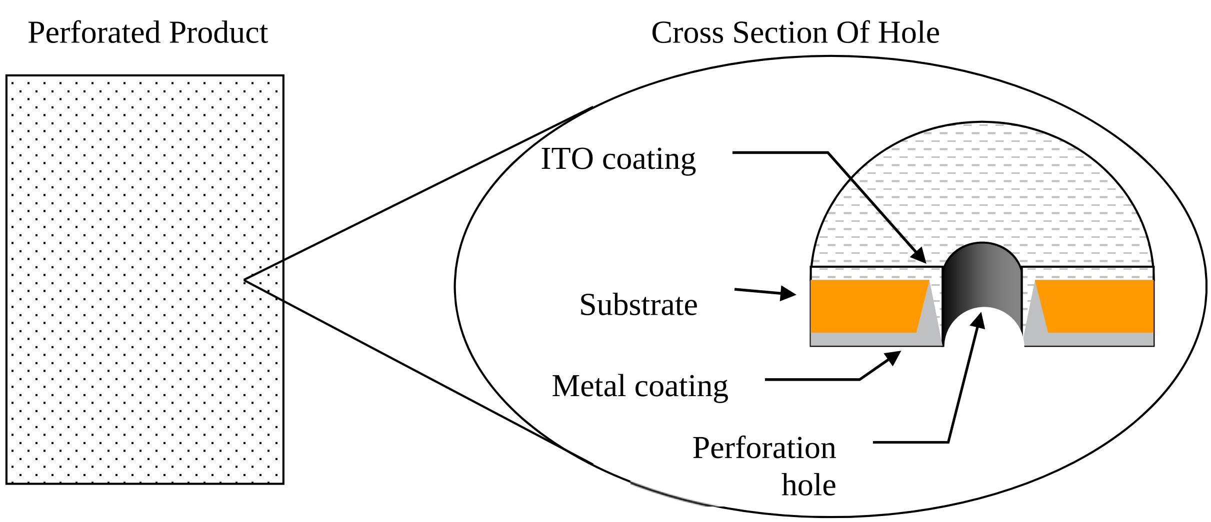


Figure 1 Perforated interconnections

Adhesives & Laminates

Sheldahl® Brand Materials uses many adhesives in its thermal control products. We manufacture thermal control tapes using commercially available pressure sensitive adhesives (PSAs) such as 3M™966, 3M™9460, 3M™9703, 3M™9713, and Adhesives Research AR®8026. Sheldahl® Brand Materials also offers a wide variety of thermal control laminates. Laminates can be manufactured using a PSA, but better bond strength, lower weight, and lower costs can be achieved through the use of thermosetting adhesives.

We have specifically designed three adhesive systems for our thermal control laminates. All have been flown on missions and are space qualified. For standard temperature applications, our A528 polyester thermosetting adhesive will meet most requirements. When a conductive adhesive is required, our modified Thick Film Black carbon loaded adhesive provides conductivity. For very high temperature or cryogenic applications, our 3P adhesive system is unmatched.

"3P" Adhesive System

High Temperature Applications

3P adhesive (polyimide/polyamide/polyester base resin) has been used in applications requiring performance at extreme temperatures. Sheldahl® Brand Materials has provided a variety of film/film, film/fabric, and film/foil laminates primarily to the military and aerospace markets where low outgassing and high temperature resistance is required. Applications include continuous exposure (months) to temperatures in excess of 250° C (450° F), and intermittent exposure (seconds) to temperatures in excess of 535° C (1000° F).

Low Temperature Applications

3P laminates have also been used successfully at cryogenic temperatures. The SSCL radiation resistance evaluation included mechanical property testing at 4K.

Radiation Resistance

The mechanical properties of cured, Sheldahl® Brand 3P polyimide film tapes were tested before and after irradiation in the SSCL (Superconducting Super Collider Laboratory) radiation resistance evaluation. Lap shear test specimens coated with 3P adhesive (manufactured and cured by Multek personnel following the recommended cure cycle) have been mechanically tested before and after accelerated irradiation at 4K to stimulate the long-term service in cryogenic magnets. No significant changes in ultimate adhesive strength were recorded after exposure dosages in excess of 4×10^9 rads. The result of this testing is documented in SSCL Publication Number 635, dated July 1993.

Outgassing Characteristics

Samples of unsupported 3P (bare adhesive without film) were tested per ASTM E595 (vacuum outgassing). They easily passed the requirements of 1.0% maximum Total Mass Loss (TML) and 0.1% maximum Collected Volatile Condensable Material (CVCM), as shown in Table 5.

Table 5 Results of ASTM E-595 testing of 3P adhesive

Agency	Johnson Space Center 313-686-11-04-01	Space Systems Loral July 1993	European Space Agency
Total Mass Loss	0.74%	0.012%	0.94%
Volatile Condensable Material	0.06%	0.002%	0%
Water Vapor Reabsorption	0.36%		0.38%

Roll–to–Roll Processing - Perforation & Embossing

Our products may be Perforated to facilitate air passage during launch, to provide electrical contact between surfaces, or even Embossed to diffuse optical characteristics or for separation between MLI layers. Sheldahl® Brand Materials can run up to 62” wide through state–of–the–art equipment.

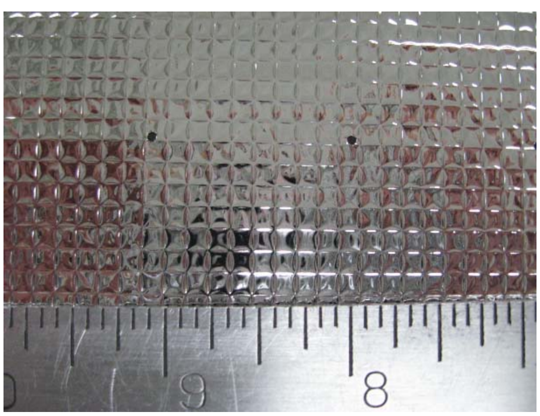
Our process is capable of running very thin gauge films, fabrics, non-wovens, foils and composite laminates either produced here, or supplied by the customer.

Many perforation options exist. Sheldahl® Brand Materials can be supplied with both visible and invisible methods.

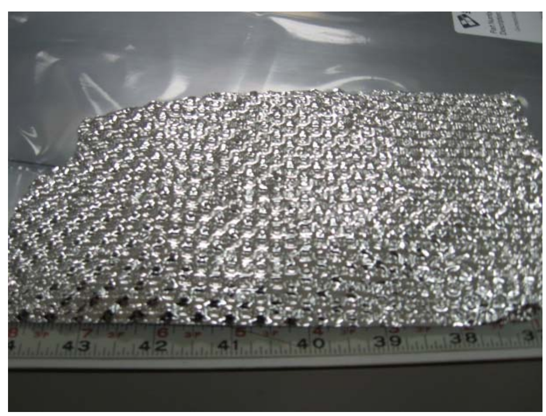
The invisible method is called Porolation, or Micro-Venting. This method results in approximately 125 regularly spaced holes per square inch (18,000 holes per Sq. Ft.) that are produced with the end of a needle. No material removal is made with this method, and generally the material must be held up against a back light to see the holes. Porolation is used for air permeability and breathability while preserving the integrity of the material.

With visible perforations, the customer has many more choices to enhance the material’s functionality. Sheldahl® Brand Materials can be offered with a variety of Pin Densities, % Open Areas, and Hole Patterns. The standards range from hole diameters of 0.045” – 0.187”; hole densities of 0.04 – 10.3 holes per square inch; and % open areas of 0.02 – 2.8%. Many opportunities exist within and outside of these standards for custom applications. Please contact a Multek representative to discuss your project in detail.

Embossing: There are two standard patterns:



Square Tile Pattern consists of 0.125” squares with 64 squares per square inch



Sheltherm™ pattern has 3,850 dimples/SQ FT with a profile height of 0.060”

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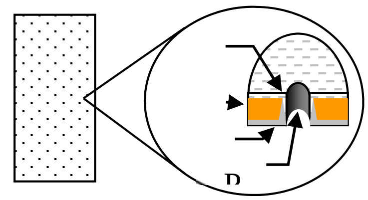
FILM PERFORATION PATTERNS



S = Square Pattern
D = Diagonal Pattern
No Letter is the Staggered Pattern with holes at 60 degree angles.

Example: 059-0500D

1. Diameter of the perforation holes **.059 inch**
2. The distance between the center of the perforation holes, .**500 inch horizontal and vertical distance between centers.**
3. **D = Diagonal pattern**

PATTERN NUMBER	PATTERN	HOLES/ SQ. IN	% OPEN	Page
045-0270	60° STAGGERED	15.583	2.48%	16
045-0405	60° STAGGERED	7.132	1.13%	17
045-0405S	SQUARE	6.045	0.96%	17
045-0810	60° STAGGERED	1.743	0.28%	18
051-1156S	SQUARE	0.760	0.16%	18
051-3000S	SQUARE	0.110	0.02%	19
059-0312S	SQUARE	10.295	2.81%	19
059-0500D	DIAGONAL	8.000	2.19%	20
059-0750D	DIAGONAL	3.550	0.97%	20
059-0843D	DIAGONAL	2.823	0.77%	20
059-0843D	EXPLANATION			21
059-1000D	DIAGONAL	2.000	0.55%	22
059-1000S	SQUARE	1.000	0.27%	22
125-4000S	SQUARE	0.073	0.09%	23
187-5500S	SQUARE	0.044	0.12%	23

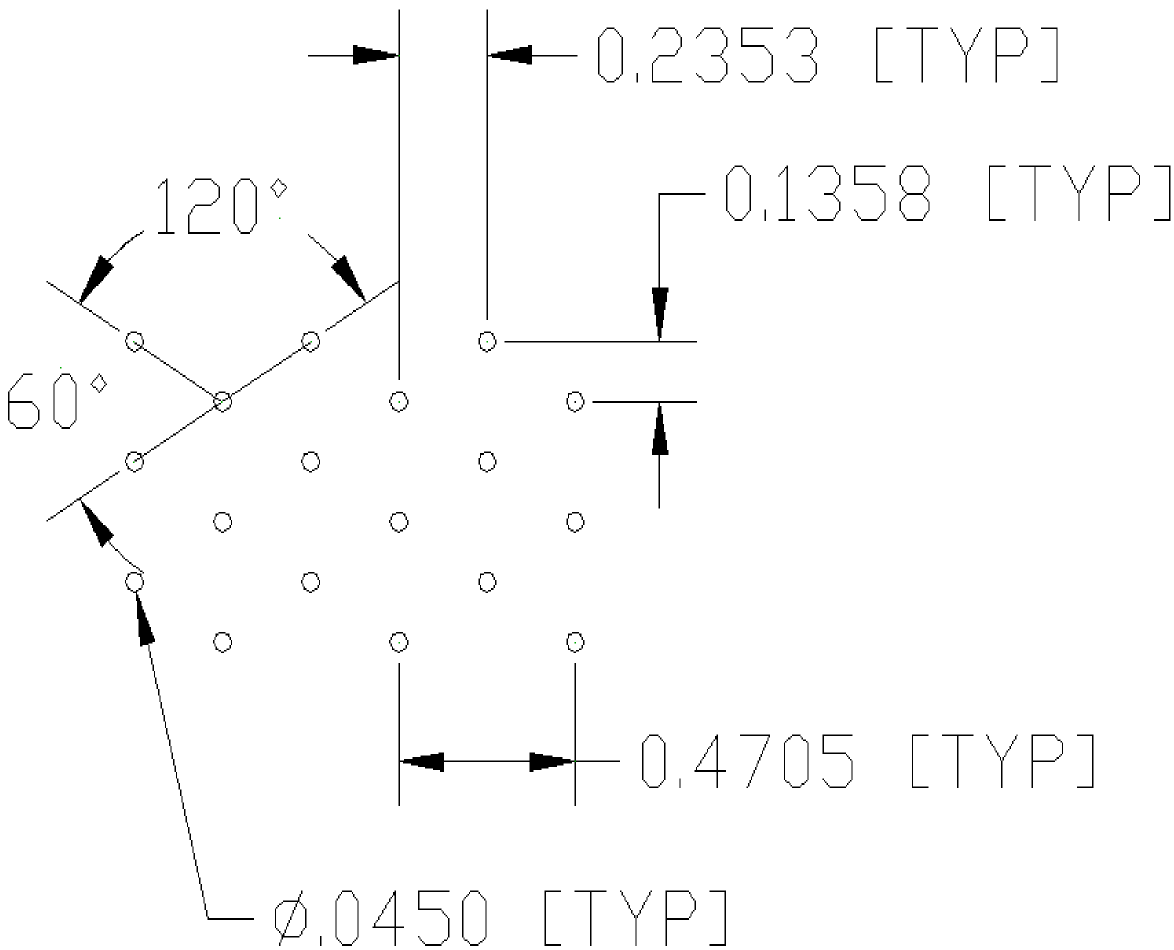
POROLATION PATTERN

Porolation	18,000 pin holes per sq. foot.	

TAPE PERFORATION PATTERN

PERFORATION Tape Pattern	0.76 diameter hole on 6.35mm centers per sq. foot.	1.1%

For custom perforation or porolation patterns contact Jim Prince at Jim.Prince@Multek.com



045-0270

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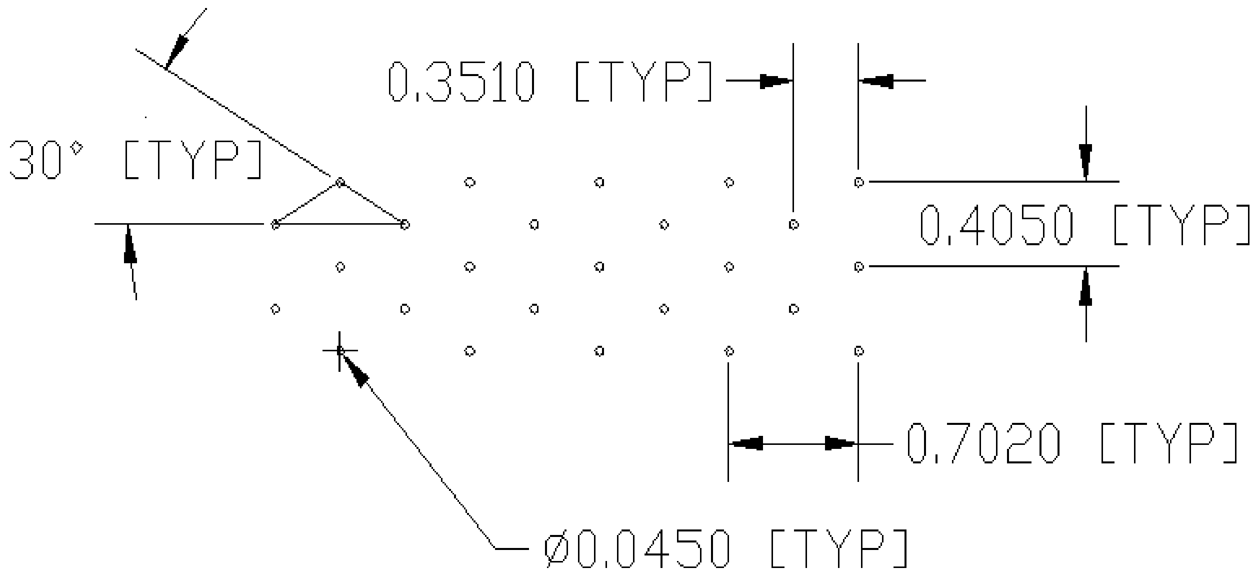
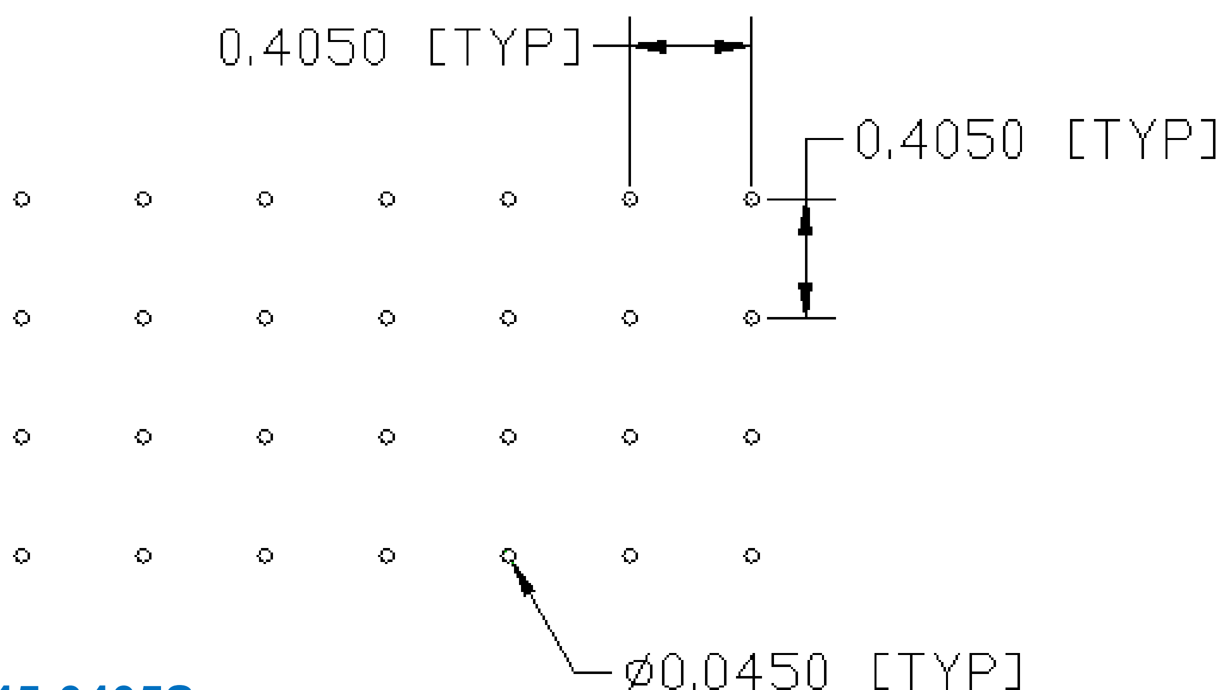


045-0405



045-0405S

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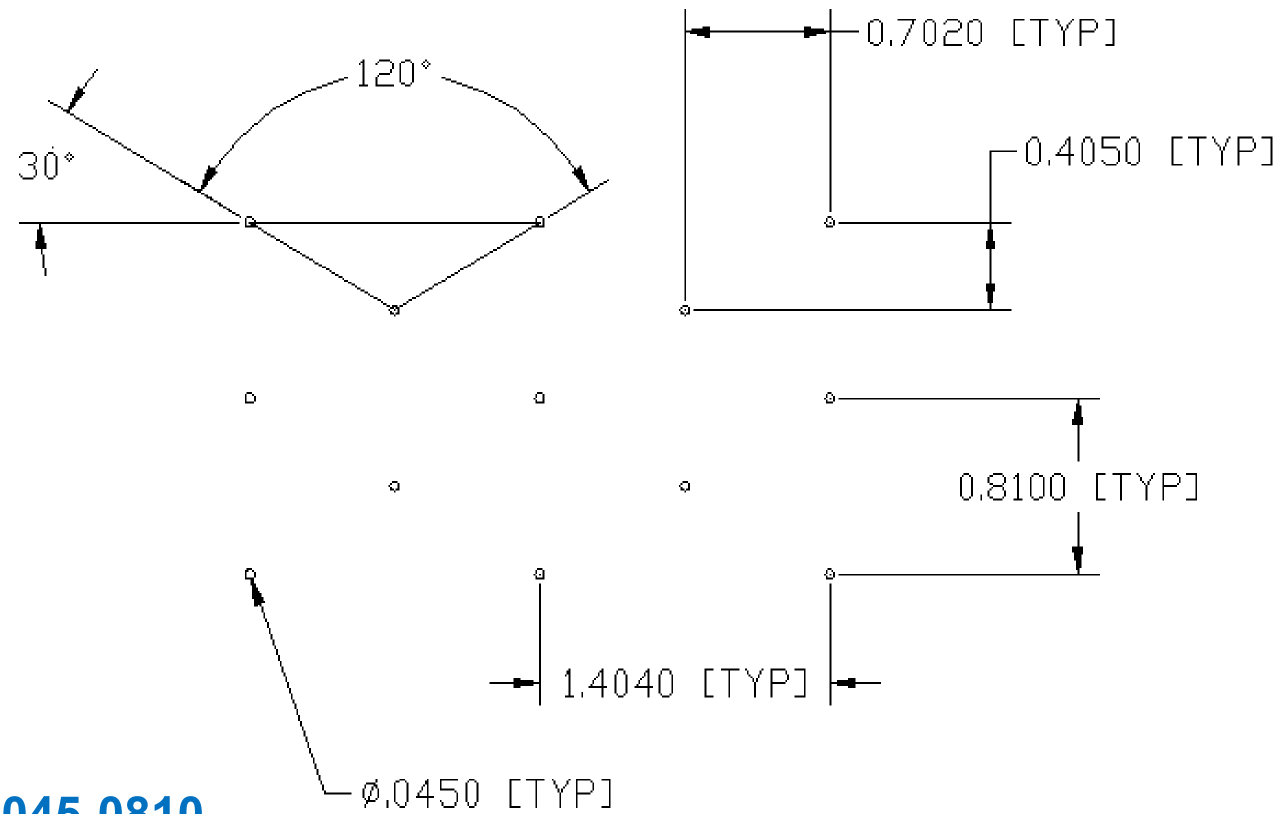
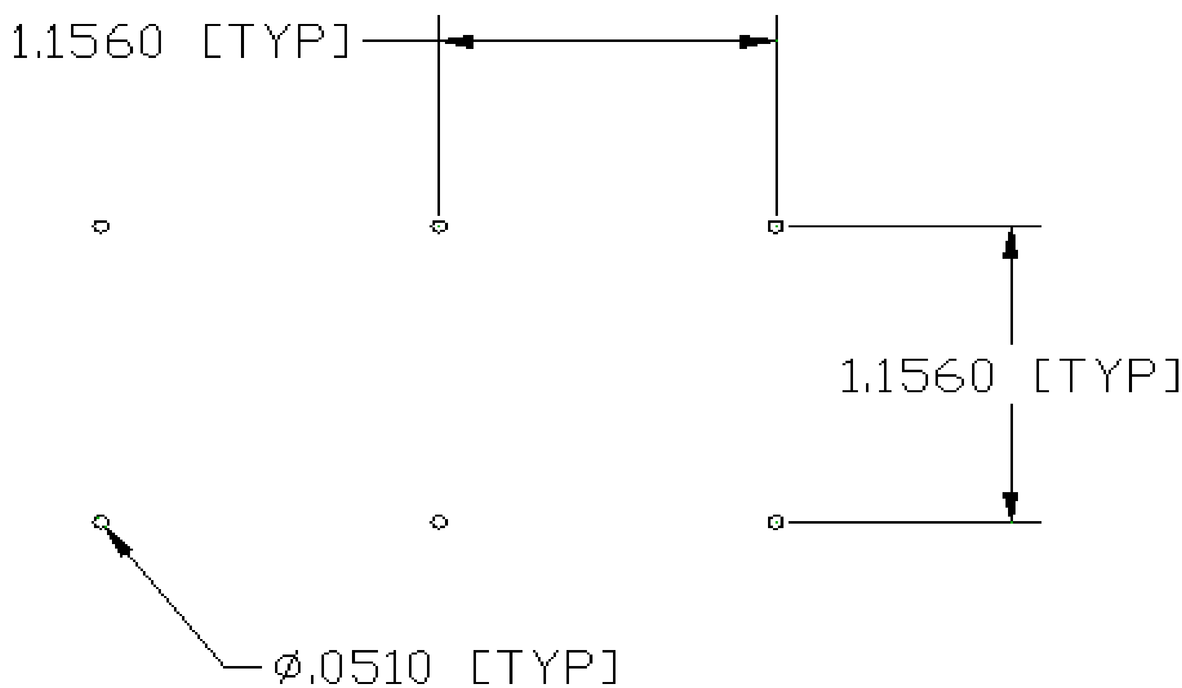


045-0810



051-1156S

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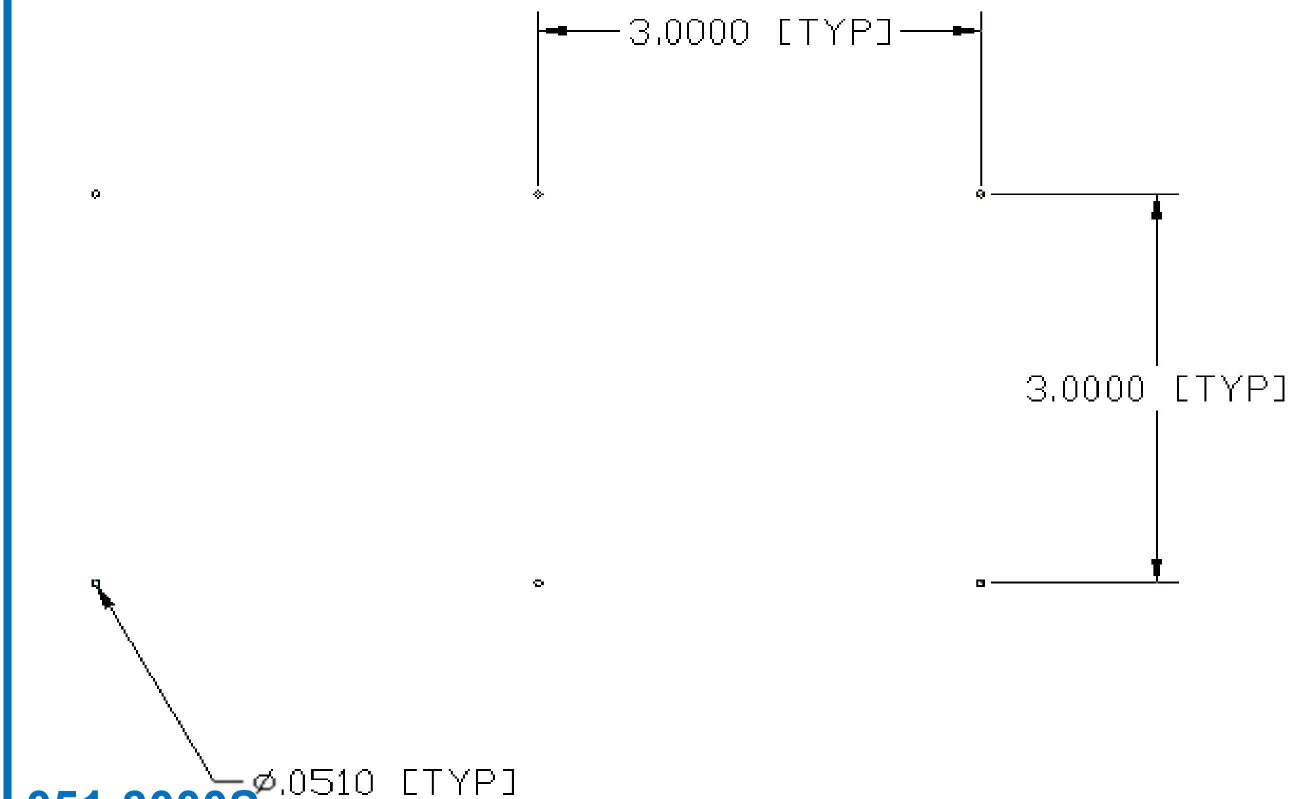
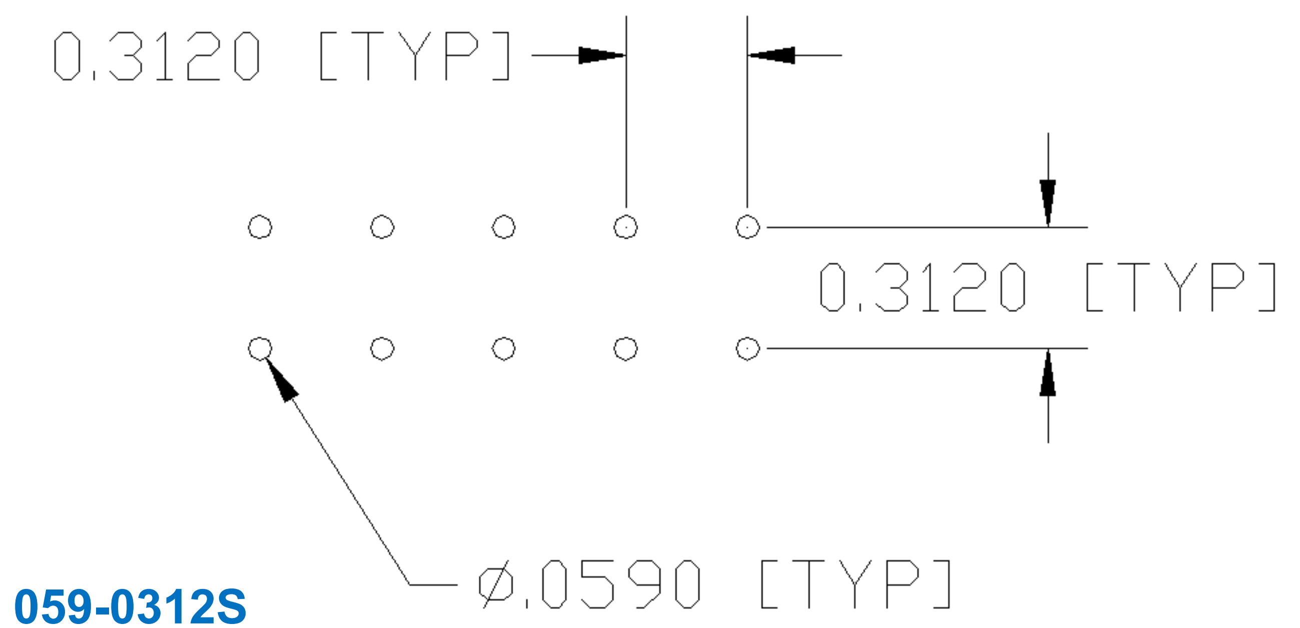


051-3000S



059-0312S

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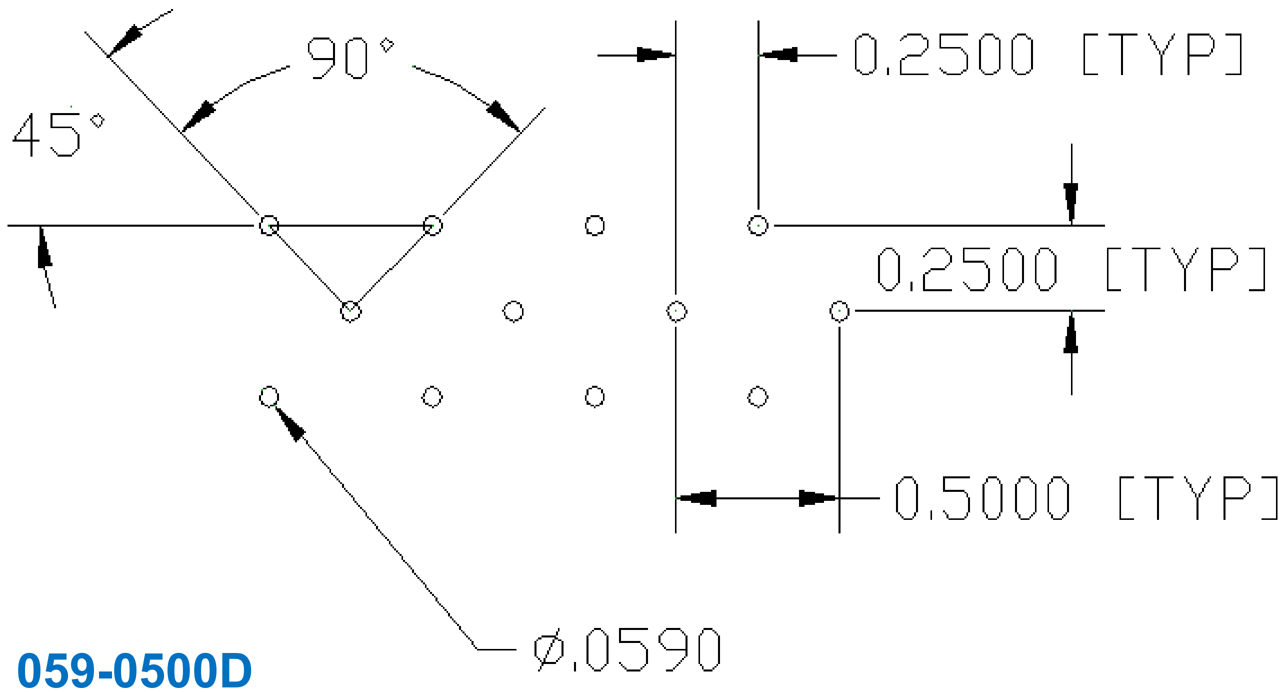
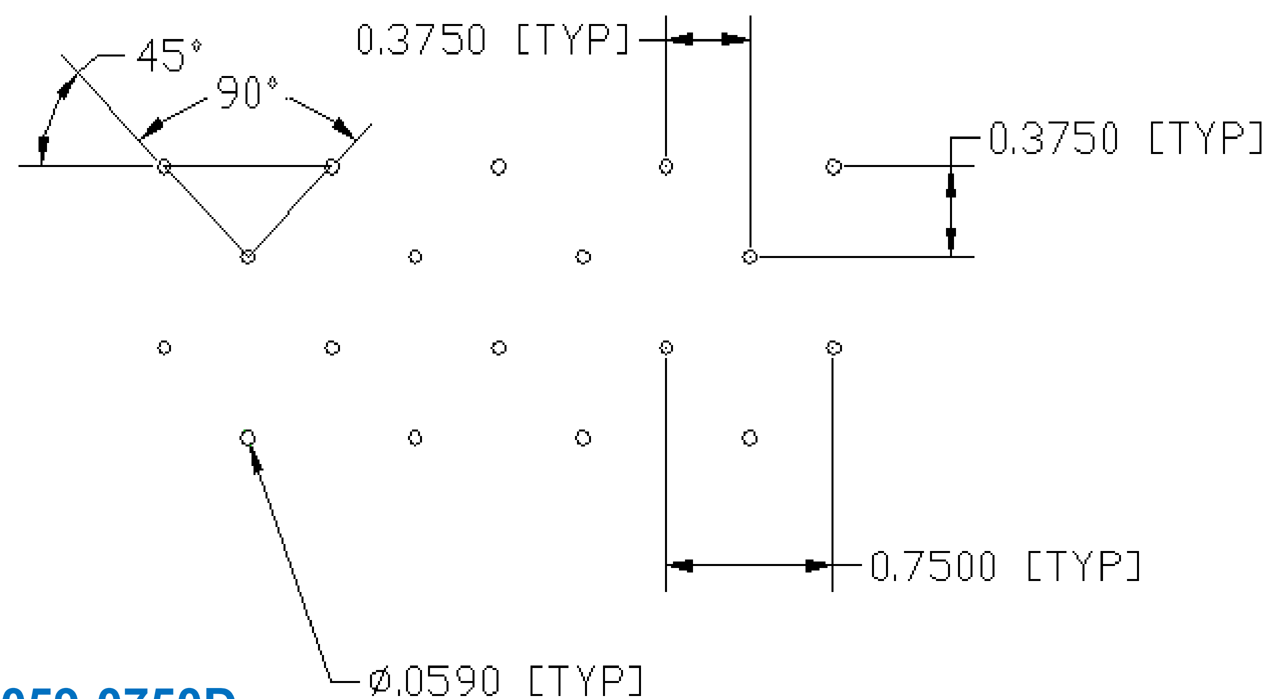


059-0500D



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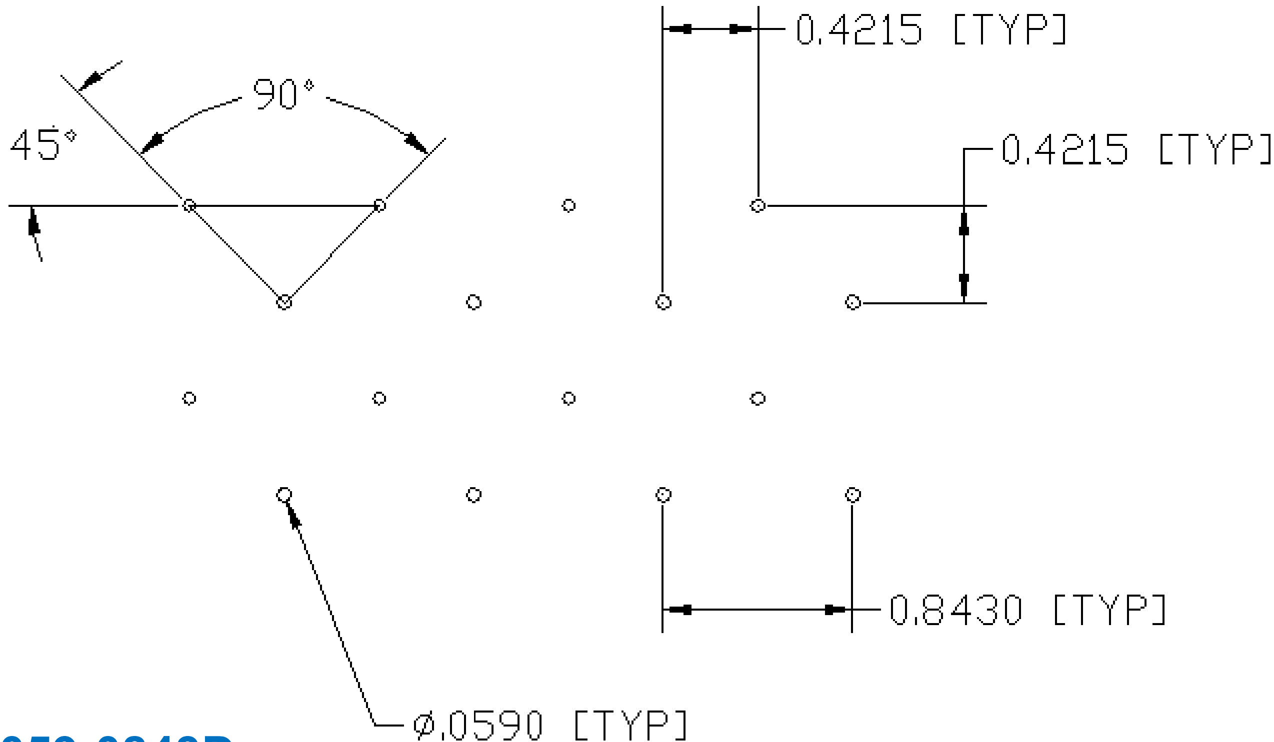
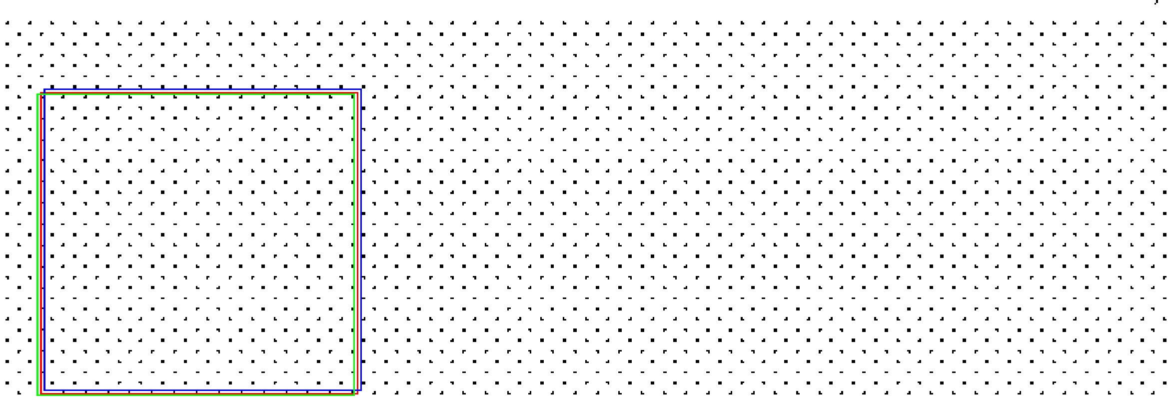


059-0843D

392 TO 421 HOLES PER SQ FT.
EFFECTIVE AVG = 406.5
HOLES/SQ. FT, THUS
2.8229 HOLES PER SQ.
INCH.
HOLE AREA = 0.002734
SQ. INCHES * 2.8299
== 0.0077363
0.774 % OPEN AREA

RED = 7.5+7+196+196=406.5 HOLES
BLU = 196+196=392 HOLES
GRN = 225+196=421 HOLES
[LISTED PER SQUARE FOOT]
EFFECTIVE AVG = 406.5 HOLES/SF



059-0843D **Explanation**

PATTERN: 059-0843D

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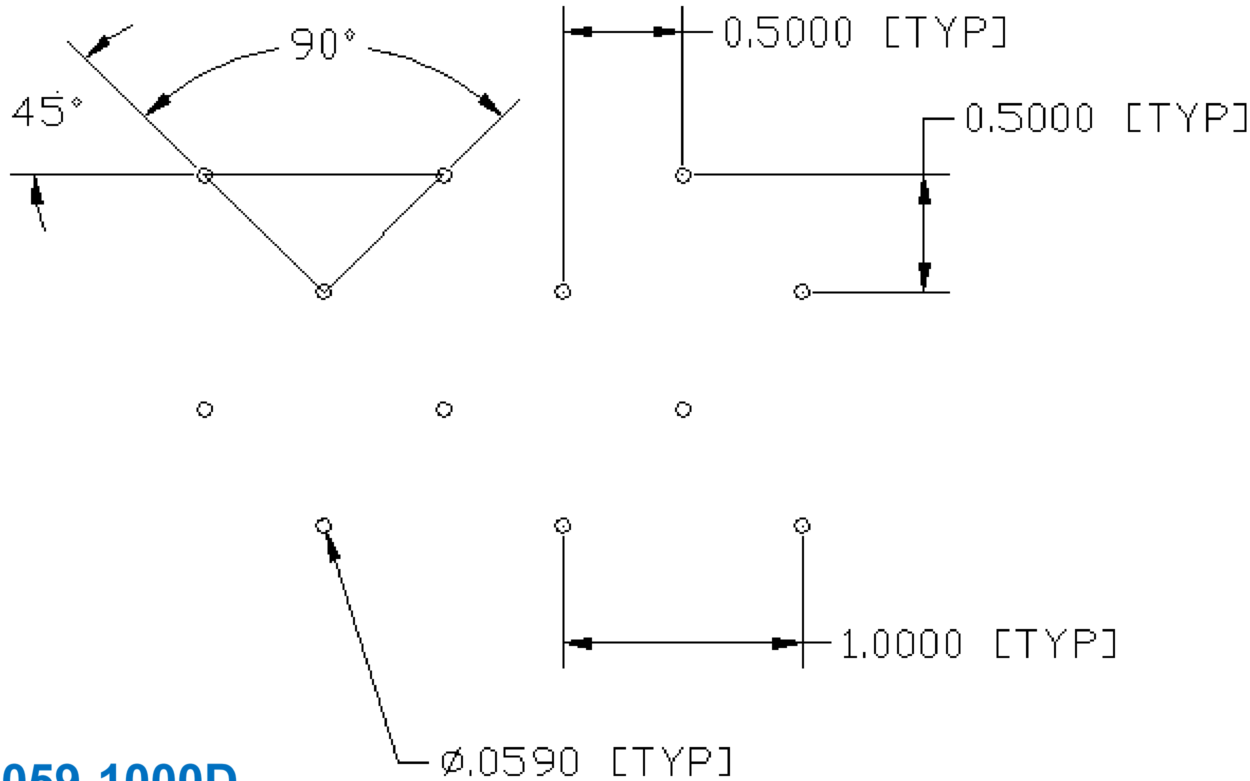
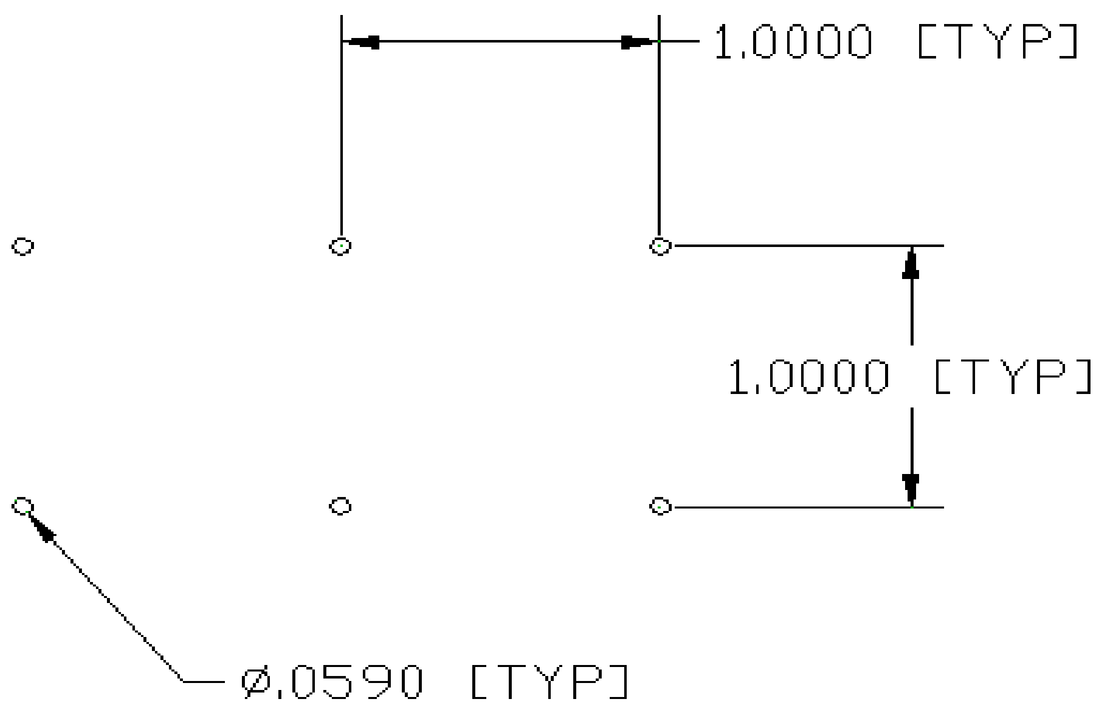


059-1000D



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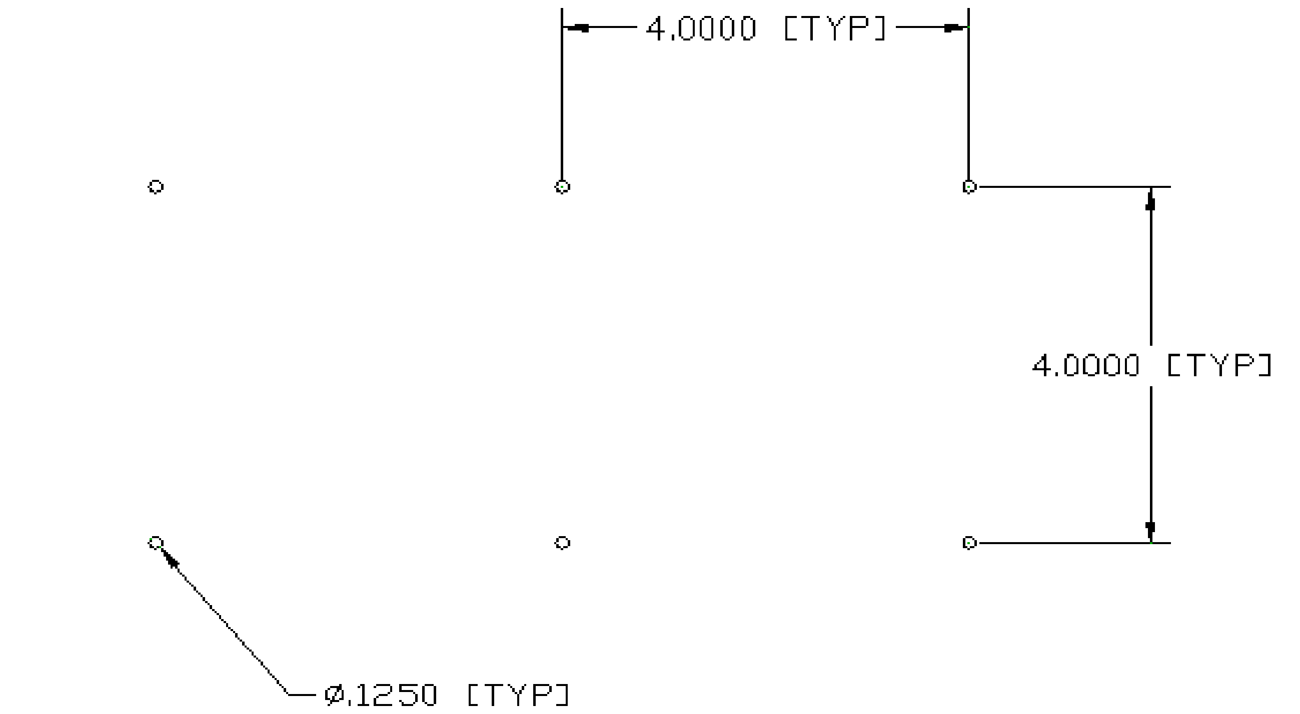
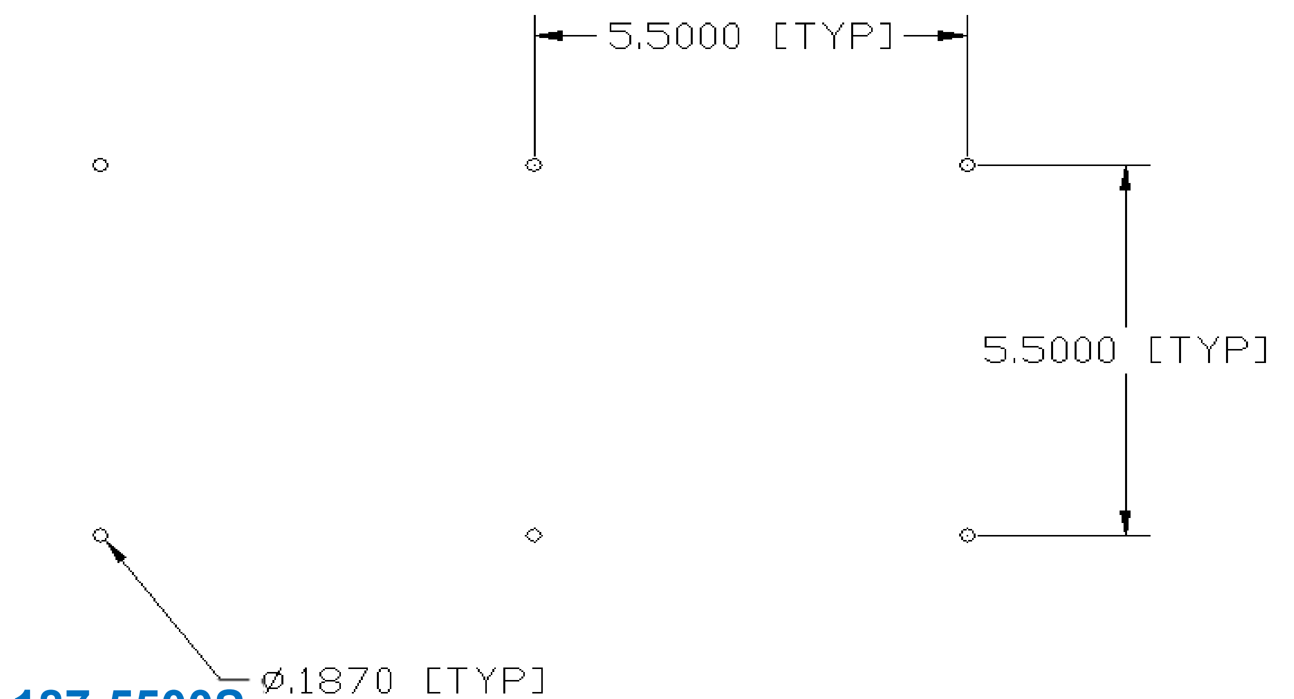


125-4000S



187-5500S

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Special Fabrications Overview

Applications for Special Fabrications range from environmental seals used to protect delicate electronic components for long term storage to inflatables for a variety of end uses to large polyimide sheets for satellite solar collectors. We service customers in the military/aerospace, commercial and electronics industries.

Sheldahl has engineered custom fabricated products for over 40 years. Custom products are created from a variety of materials and processes based on customer requirements. The raw materials used may be purchased, manufactured at Multek, or customer supplied. Fabrication methods include heat or pressure forming, punching, cutting, and sewing resulting in unique shapes, forms, and configurations.

Sheldahl® Brand flexible materials are joined using butt or overlap seams or mechanical fasteners. Overlap seams can be made using pressure sensitive or thermosetting adhesives or by fusion bonding the material to itself. Butt seams are made with Sheldahl® Brand tapes typically using thermosetting adhesives. Using our proprietary adhesive systems and many years of experience we can make these seams into air and moisture tight seals.

Please contact our Special Fabrications department for more information or a quotation.

FORMING CAPABILITES	**COMBINING CAPABILITIES**
• Slitting	• Laminating / In-Line coating
• Die Cutting	o Thermoset Adhesives
• Heat Forming	o Pressure Sensitive Adhesives
• Sheeting	• Sealing
	• Platen Pressing