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Permanent Magnet Stabilizing and Calibrating

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Executive Summary

Magnetic fields produced by permanent magnets vary with temperature in a reversible way unless key limits to performance are exceeded. Even within the acceptable-use temperature range, minor irreversible changes in magnetic output can occur. This effect can be mitigated by stabilizing the magnets.

In a second case, the variability of flux output from magnet-to-magnet may be too large to satisfy a demanding application. It is possible to pre-treat magnets so that entire lots of material perform within a tightened range of flux output. This is often called calibration.

This paper will explain what these processes are, how they are performed and the resulting product characteristics.

Intended Audience

This document is intended for manufacturers that use permanent magnets and need magnets or assemblies that are magnetically stable over the expected temperature range of use or those manufacturers requiring magnets to perform within a very tight tolerance of flux output.

Presented by Adams

This white paper is presented by Adams, a leading global manufacturer, and supplier of permanent magnets and magnetic assemblies.

What is meant by Stabilizing and Calibrating Magnets?

Reasons for performing stabilization and/or calibration are stated in the definitions.

Stabilizing: This most often applies to thermal stabilization, accomplished through exposure to elevated temperatures (or to low temperatures for ferrite magnets) for limited times as a pre-treatment to stabilize them against future change. Magnets will always suffer some irreversible loss when exposed to high (or low) temperatures and the idea is to cause the irreversible change to occur in production rather than during use in the application. In addition to thermal stabilizing, magnets can also be stabilized against the presence of demagnetizing fields by exposing the magnet, during production, to a suitable reverse magnetic field. The effects of thermal and reverse magnetic stabilization are complementary and not equivalent in effect. Therefore, the method of stabilization must match the demands of the application. In this paper we will explain both thermal stabilization and reverse magnetization calibration.

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Calibrating: Typical magnet production results in a distribution of magnetic (flux) output. These variations can occur within a single batch of magnets, between succeeding batches, and over extended periods of time. Even in a well-controlled process, there may be too much variation in flux output to satisfy a customer's demanding application requirement. Typical variability from production might be +/-5% while the application requirement might be +/-1.5% delivered from batch-to-batch, month-to-month, and year-to-year. Ensuring the tightest possible range of magnetic output can be accomplished by a selection process (e.g. "cherry picking") which is inherently wasteful, or by adding a production step wherein magnets are "treated" to reduce the range of magnetic flux variability within and between batches. Each magnet, within a batch of magnets, is treated with a reverse magnetic field strength suitable to knock it down to the desired flux output resulting in a batch of magnets having a tight tolerance range. This process can even reduce out-of-spec-high magnets to an acceptable flux output.

Let's see how these tasks are accomplished.

Stabilizing Permanent Magnets

To stabilize a magnet, we are going to remove the irreversible portion of a magnet's flux variability which results from changes in temperature. When we speak of a magnet's output, it is most often relating to the induction (Br) or to the change in induction (Br) of the magnet. Two definitions:

Reversible Magnetic (Flux) Output: that portion of the change in flux output due to characteristics of the magnet material which *do not* result in a permanent change in flux output. This is quantified by the Reversible Temperature Coefficient (RTC) of Induction and is expressed as the average rate of change in residual induction (Br) as a function of temperature. The values are reported in %/°C over a defined temperature range usually from 20 °C to the maximum recommended use temperature of the magnet.

Irreversible Magnetic (Flux) Output: that portion of the change in flux with change in temperature that results in permanent loss of flux output. Irreversible loss is often due to the temperature of the magnet exceeding its useful range of operation. However, even minor changes in temperature can result in small irreversible losses in magnetic flux output.

These changes can be shown graphically as in Figure 1. We start with a magnet that has not been exposed to high temperature. The magnet's induction (Br) starts at position "A". As the magnet is heated, the induction is reduced continuously until the upper treatment temperature is reached at point "B". When the magnet is cooled from point "B" to point "C", the induction increases but does not return all the way to "A". The irreversible loss portion is the difference between points "A" and "C". The difference between "B" and "C" is reversible. After the first exposure to T2, the magnet

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can be repeatedly cycled between "C" and "B" with negligible additional flux loss. (Here we use magnetic induction, induction, and flux or flux output as equivalent expressions).

It is possible to re-establish flux output to point "A" by remagnetizing the magnet though this is seldom commercially practical. Both the reversible and irreversible portions are recoverable when no permanent damage or structural changes to the material have occurred.

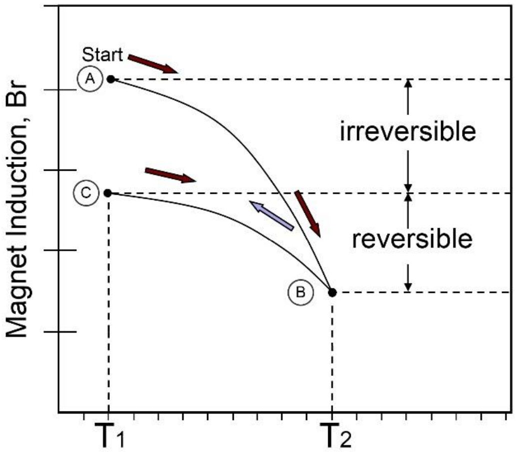

Figure 1. Graphic depiction of reversible and irreversible flux loss as a function of temperature.

Stabilizing magnets thermally is achieved by exposing magnets, or an assembly containing magnets, to a temperature at or slightly above the most extreme temperature expected in the application. The length of time for this exposure is dependent upon the magnetic material and size of the object to be stabilized.

Exposure times are usually 1 to 2 hours, but longer times of up to 8 hours offer improved stabilization. Improvement in stabilization diminishes exponentially with increases in time. As a safety margin, treatment temperatures are 5 °C to 10 °C higher than the maximum expected application temperature. Exposure temperature and time can affect other parts of the system such as coatings on the magnet or assembly and adhesives used in assembly, therefore care must be exercised to minimize negative effects.

As mentioned earlier, stabilizing a magnet thermally is not the same as doing so using a magnetic field. An explanation for this is that the thermal loss is the result of lattice vibrations in the magnetic crystals which permit portions of the magnet to spontaneously re-orient out of alignment with the bulk material. Irreversible changes caused by strong demagnetizing fields cause reversal of

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regions of lower intrinsic coercivity coupled with low permeance coefficient. A thorough discussion is beyond the scope of this paper.

Exposing magnets to elevated temperature pre-conditions them so that subsequent exposure results in negligible additional loss. How this works is explained as follows. Figure 2 shows the normal and intrinsic demagnetization curves for a typical Adams Magnetic NdFeB 4517 (H) magnet grade. The magnet in this example has a permeance coefficient (Pc) of 0.57. In this case the Pc is determined by the dimensions of the magnet in free space. Point 1, the operating point, is the intersection of the Pc line and the normal demagnetization curve. As the magnet is moved from free space to a closed magnetic circuit, the operating point shifts upward along the normal curve to Br. For this grade at room temperature the normal curve is a straight line in the 2nd quadrant. The slope of the normal curve is called the recoil slope. Movement upward along the normal curve will return the magnet to a value of residual induction equal to Br.

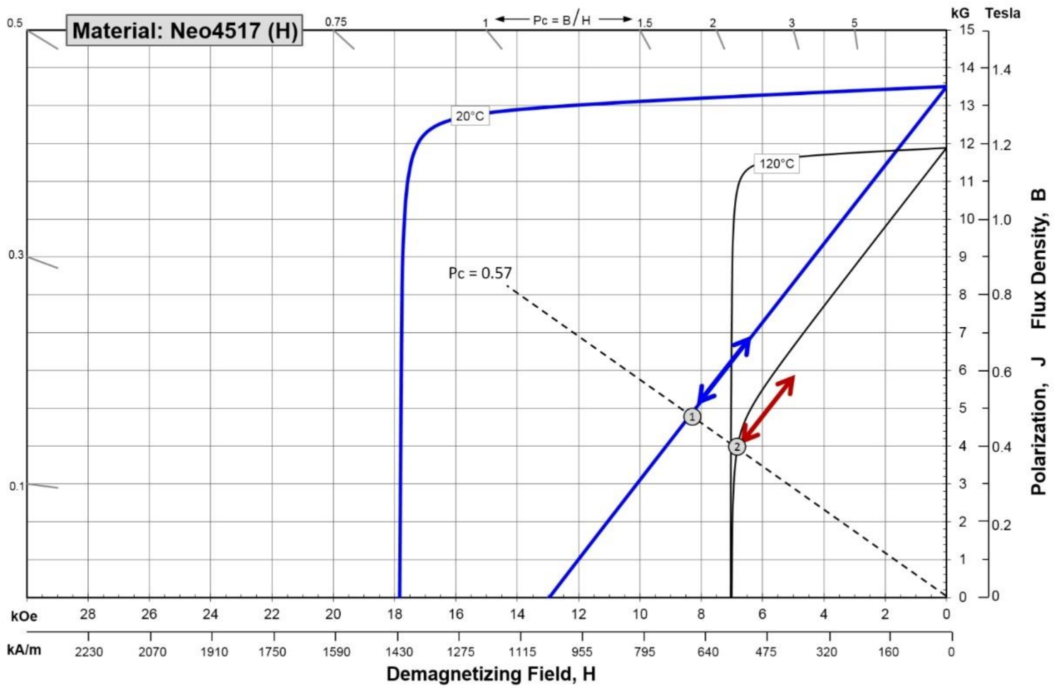

Figure 2. The 2nd quadrant demagnetization curves for a magnet, grade Neo4517 (H) at 20 °C and at 120 °C. The dashed line represents the operating slope and point 1 is the operating point. Point 2 is the operating point at 120 °C.

When the magnet is heated in open circuit to 120 °C the operating point (point 2) is below the knee of the normal curve. If the magnet is returned to closed circuit at 120 °C the recoil is along the heavy red line and intersection with the

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B axis is at a value of “B” which is lower than the starting Br. The magnet has been partially knocked down. This is shown more thoroughly in Figure 3.

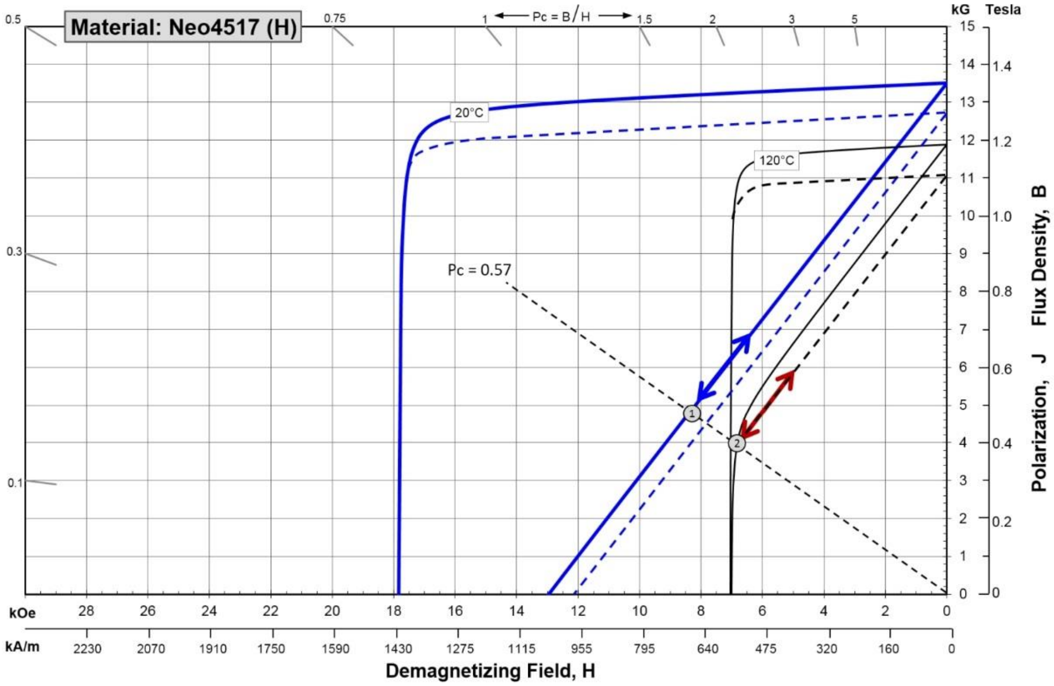

Figure 3. Thermally treated magnet.

When the magnet is cooled from 120 °C back to room temperature Br does not recover to the original value (13.5 kilogauss). In this example it is reduced to approximately 12.8 kilogauss. The new room temperature demagnetization curves are shown as blue dashed lines. Further exposure to temperatures as high as 120 °C will result in negligible additional loss of magnetization. Note that the value of Hci is not diminished. Hci is determined by those domains which are most resistant to re-orientation. Thermal knockdown (stabilizing) first affects the most easily re oriented domains.

Theoretically it is possible to thermally stabilize a magnet until there is very little flux output at room temperature. In practice, proper magnet selection should permit stabilization with less than ~3% knockdown.

The typical production method for accomplishing thermal stabilizing is to place magnetized magnets into an oven in one of two conditions.

1. Magnets are spaced apart and fixtured so that they do not move during stabilizing treatment. The permeability of Neo and SmCo magnets is very close to 1, the permeability of air, so their mutual effect is small. It is not necessary to separate magnets far apart but they will need to be fixed so they don’t jump together.

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2. On steel plates, preferably with a thin spacer of fixed dimension. This produces a higher permeance coefficient requiring thermal stabilization at a higher temperature that can be estimated and confirmed through trials. The spacer can be hard cardboard (pressboard) – hard to prevent crushing by the attractive force of the magnet. Cardboard is adequately soft to prevent chipping of the magnet during placement on the steel plate. Magnets can be placed more closely together facilitating both handling and efficient use of the oven space.

A final comment about stabilizing: be sure that the magnets are fully magnetized ("saturated") prior to treatment. Saturating the magnet provides both full magnetization (Br), maximum value of intrinsic coercivity, and fully developed demagnetization curve shape. An under-saturated magnet with irregular demagnetization curve shape will respond very differently during stabilizing.

Calibrating Magnets

In the previous section we spoke about stabilizing magnets. This is performed almost always to stabilize a magnet against future exposure to elevated temperature. In this section, we'll discuss partially knocking down magnets to adjust magnetic performance thereby reducing the range of flux output from magnet to magnet.

Production of any product results in a range of quality. A goal of manufacturing is to produce a narrow range of product characteristics, in this case magnetic flux output. No matter how much effort is applied to improving process controls, mass production of magnets results in a range of flux output that can exceed requirements of demanding applications. Within limits it is possible to adjust flux output by carefully applied demagnetizing fields. An explanation of how this is accomplished follows.

To calibrate a magnet such as shown in Figure 4, grade Neo4517 (H), we will need to partially knockdown the magnet. In the example, we will make the knockdown large enough to be readily apparent. In practice the amount of knockdown can range from less than 1 percent to about 10 percent. While possible to do so, it is not practical nor advisable to knockdown more than about 10 percent.

In Figure 4, as in the earlier thermally stabilized example, our magnet has a permeance coefficient (Pc) of 0.57 and an operating point indicated by the marker with number 1.The dashed line from the origin through the operating point represents the operating slope, also called permeance coefficient. Pc=0.57 is the ratio of B/H. Note that values of H in the 2nd quadrant are negative as is the slope of Pc. By convention, we often omit the negative sign.

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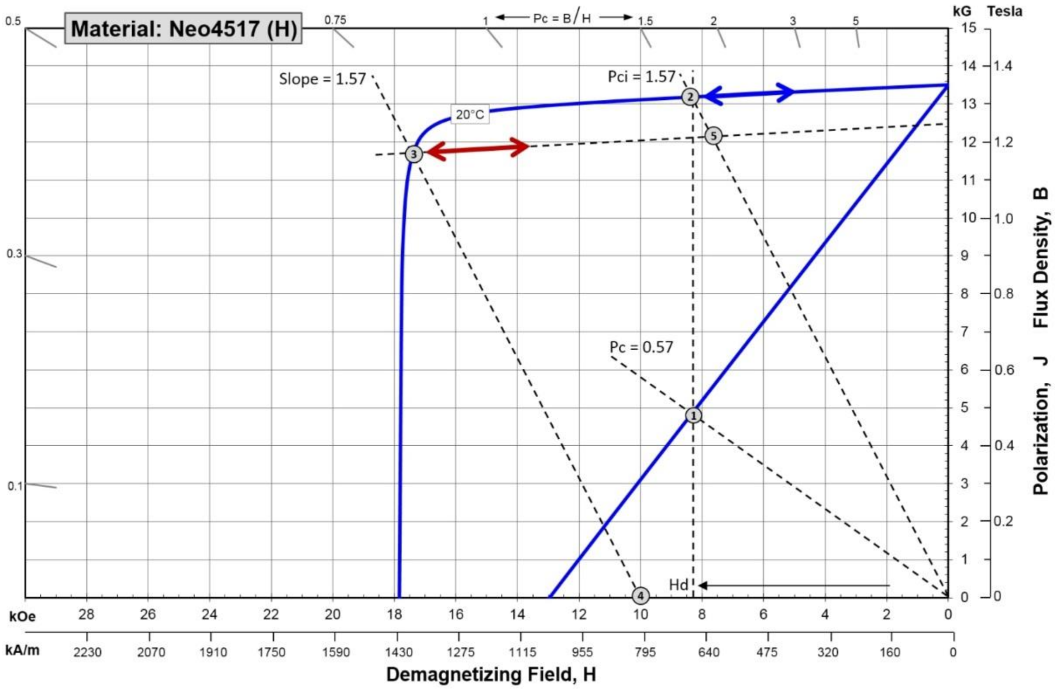

Figure 4. Calibrating magnets

If a vertical line is drawn upwards to the intrinsic curve and downward to the H axis we establish two more points. The value of H at the intersection of the vertical is often called Hd and is approximately 8200 oersted. Point 2 on the intrinsic curve is called the intrinsic operating point.

A line drawn from point 2 to the origin is called the intrinsic operating slope. In the Gaussian system (1 gauss = 1 oersted), the intrinsic permeance coefficient equals the (normal) permeance coefficient plus 1. That is, Pci = Pc+1 = 1.57. The slopes of both the permeance and intrinsic permeance coefficients are determined solely by the magnet dimensions when the magnet is in open circuit.

To magnetically calibrate the magnet, we will apply a demagnetizing stress. This is shown in Figure 4 by shifting the dashed line representing the intrinsic operating slope to the left so that instead of the intersection with the H axis being at the origin, it is at point 4, a value of 10,000 oersted. The new intrinsic operating point is at point 3 which is below the knee of the intrinsic curve. When the demagnetizing force is removed, the magnet will "recoil" following the heavy red line and continue along the dashed line to point 5, the new intrinsic operating point.

Now referring to Figure 5, the adjusted room temperature magnet performance follows the green lines. Once again, we see that the Br and flux output are

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reduced but that the intrinsic coercivity (resistance to demagnetization) remains unchanged.

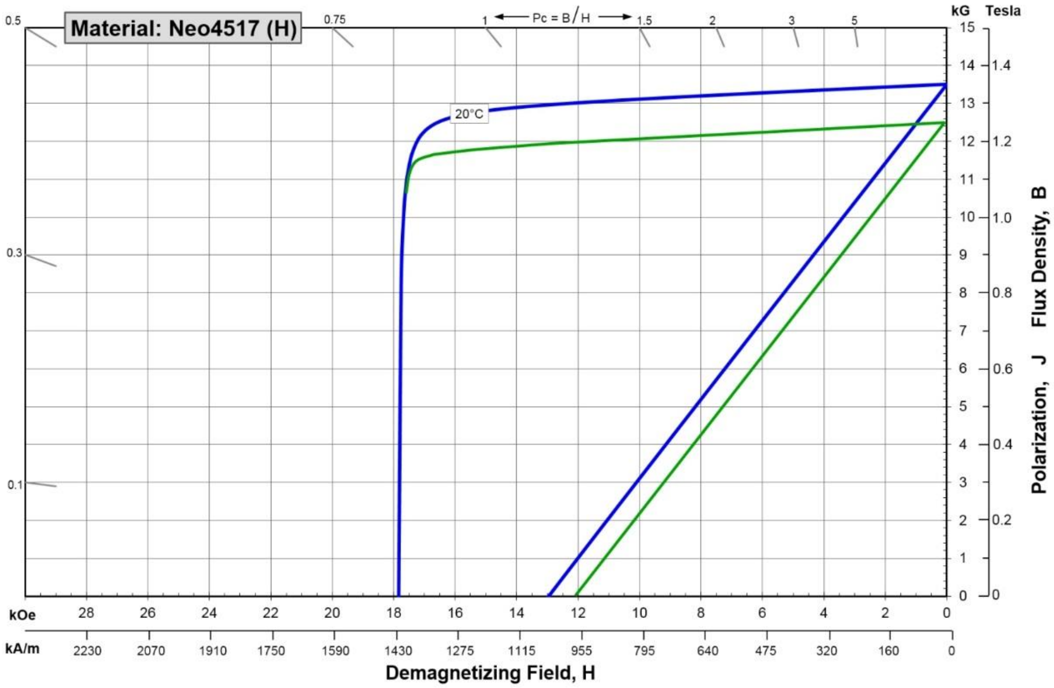

Figure 5. Calibrated magnet. The blue lines are the original demagnetization curves; green lines are demagnetization curves alter calibration.

The primary objective of calibrating magnets is to reduce the range of flux output within and between batches of magnets. Figure 6 shows the result of calibrating a set of magnets. Prior to treatment, the 2.5 sigma range of flux output was 5.2%. After treatment, the range was reduced to 1.4%. To accomplish tightening of the range of flux output requires reducing flux of the strongest magnets to become closer to the weakest magnets. However, even the weaker magnets will experience some knockdown in this procedure. The result is a downward shift of the average flux output, in this case of 3.9%.

Calibration can also serve the purpose of weakening magnets that are too strong to meet application requirements. While not desirable as it adds manufacturing cost, it may be a practical alternative to meet a tight production schedule when the optimal material is not available.

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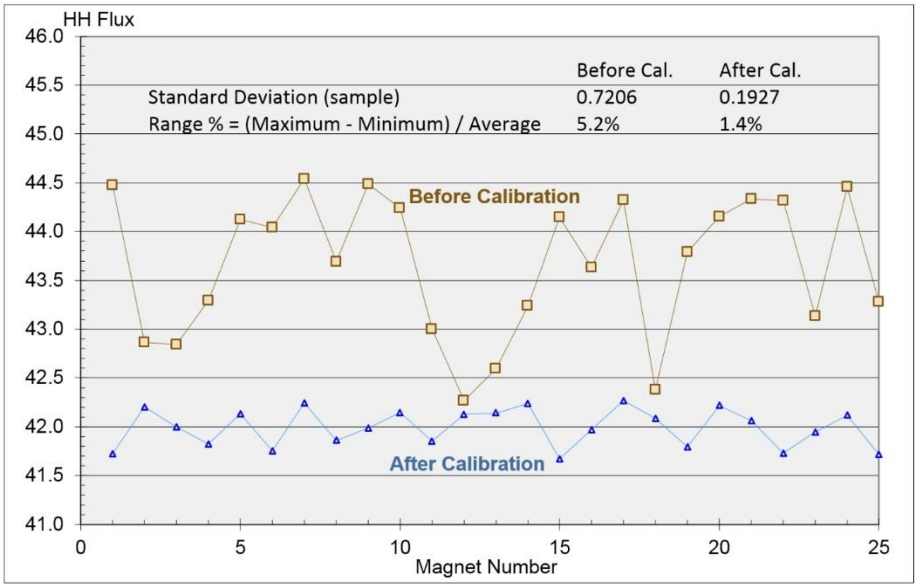

Figure 6. Set of 25 magnets measured prior to and after calibration.

Conclusion

Both thermal stabilization and magnetic calibration serve useful purposes in the manufacture and supply of magnets into demanding applications. The two procedures accomplish similar but not equivalent effects.

Adams can help you determine and implement the best stabilization and calibration path to ensure the resulting product characteristics meet your requirements. Contact us to get started.