Automotive Oven Temperature Profiling – the Key to Paint Shop Performance!

Abstract
The following paper discusses the use of oven temperature profiling as a technique to help maximize the quality of paint and material cure operations, undertaken in the OEM car manufacturing industry. Automotive paint cure application challenges, and recent technical developments are discussed in detail. The Oven Tracker® XL2 system, developed specifically for the automotive paint industry will be discussed, with examples of how it can be used to improve paint quality, line productivity and process efficiency.

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The Worldwide Leader in Temperature Profiling
Coating and Material Cure Application Challenges
What and Why?

As shown in Fig 1, a number of coating, sealant and adhesive systems are used in the car manufacturing process, which are described in more detail in the following section.

Ecoat (Electrocoat/Elpo)
Ecoat the first physical coating applied to the virgin metal body shell to provide corrosion protection (particularly, indifficult to access areas). The car body shell is immersed in an Ecoat tank where the charged paint is electrostatically attracted to the metal surface. Coating residue is rinsed off before being baked in an oven at 180°C/360°F for 20-30 minutes.

Achieving the correct cure schedule for all areas of the car is critical to the performance of the Ecoat, but the rate of heating is also important. Trapped moisture within thin metal panels collected from the Ecoat rinse tank or earlier phosphate pre-treatment, needs to be evaporated slowly to prevent boiling. If moisture boils, it can damage the Ecoat surface layer before it is fully cured, leaving the surface unprotected from corrosion. The temperature ramp rate of the initial Ecoat cure oven therefore needs careful control.

High Temperature Structural Adhesives
Adhesives are used to give structural strength to areas of the car that need additional strength, such as B pillars, for side impact resistance during a crash. Adhesive is used since there is no space for welding on the B pillar flanges. The adhesives are often used in regions of the car where metal density is high, so the thermal mass required to be heated is also high. These regions are often difficult to heat, so it is a challenge to ensure the correct cure (typically 30 mins @ 180°C/356°F) of the material, especially at its core. Differential heating of inner and outer surfaces of metal structural panels can create significant distortion, especially when mixed material types are employed (steel and aluminum). Such distortion can create issues where the adhesive or other sealant materials cannot expand enough with the distortion, causing failure of the adhesive bond between mating surfaces.

When choosing a new car, a key purchasing decision for many is the color. The cosmetic appearance of the paint is critical to the visual quality of the product but the appearance alone underlies the far more important role that the coating technology brings to the operation and performance of the car during its operational life.

To provide protection to the car body, a series of coatings are applied (Fig 1) to the raw substrate, which are in turn are thermally cured. The accurate control of the thermal cure process is critical to the performance of the coating both cosmetically and physically. To complete the cure reaction (cross linking of the paint), it is necessary that the part of the car on which the paint is applied achieves the paint supplier’s recommended cure schedule. The cure schedule or target bake is in most situations defined by achieving a critical peak metal temperature and holding that temperature for a time sufficient enough to allow the full cure process to be completed.

Complementing the paint systems in today’s innovative manufacturing processes, many new materials, such as sealants and adhesives are being employed in place of mechanical fixings to give lightweight physical strength and watertight characteristics to the car body. These materials themselves require thermal curing, which is also critical to the performance of the materials and therefore, to the strength and safety of the final car.

Getting the thermal cure process wrong in any part of the manufacturing process will compromise the product quality and manufacturing productivity, which is costly. When production values of typically $15k per minute and scrap costs of $1k per car body are being discussed, any problems with the cure processes need to be avoided and when encountered, fixed as quickly and efficiently as possible.
**Sealants & Mastics**

The correct thermal cure of sealants, mastic and sound deadening materials (20 mins @ 150°C/302°F) within the car body is critical to provide waterproofing, reduced road noise and prevent engine gasesentering the car interior during use. Curing of these materials is either performed in the Ecoat oven, along with the Ecoat or in a separate specific ‘Deadner oven’.

If sealer is over-baked, Hydrochloric Acid (HCL) leaches from the sealer. This acid then attacks the sealer, causing it to break down and become brittle. The HCL leached out of the sealer can further affect the quality of paint cure operations, as it causes bubbles in the paint surface. The over cure of sealer is a major issue and would lead to having to scrap the whole car body. If any cars are identified as possibly having been over-cured, they are quarantined and physical tests are performed over a few days to see if the HCL leaching problem exists.

**Primer Surfacer**

The primer surfacer is a spray-applied coating added on top of the Ecoat to provide a smooth metal surface, resulting in a more appealing reflective appearance. This coating creates a cushioned layer against impact damage (reduced paint chips) and further corrosion resistance, adhesion and weathering durability (UV protection). The typical cure specification (PMT) is 30 mins @ 180°C/356°F.

A well balanced oven is important to ensure consistent primer cure, but also essential to eliminate the risk of condensate contamination. During the cure process, volatiles released from the paint surface are normally safely exhausted from the oven. If released volatiles, experience cold spots (areas of cooler air) in the oven, it is possible that they may condense, drip back onto the painted car surface and cause surface imperfections.

**Base Coat & Clear Coat**

The base coat is the cosmetic coating layer that provides the color characteristics of the finished product. The thermal cure specification is generally 30 to 40 mins @ 125°C/260°F.

The final coating layer is the clear coat, which provides a scratch resistant top layer. The clear coat is applied to retain the classic show room car finish for a longer period of time. It protects against sunlight, weather and chemical damage (example – bird droppings). The cure specification for the clear coat is typically 30 mins @ 180°C/356°F.

In many modern paint lines, the base and clear coats are applied in a “wet on wet” fashion. Water-based base coat is applied to the cured primer surface. The car body is left in the Quiet Zone (30-40°C/86-104°F) to allow gradual solvent (H2O) evaporation and coating coverage of the substrate. The remaining solvent is removed in the flash off oven (80°C/176°F for 10 mins) and the base coat is left tack hard, but not cured. Clear coat is applied and then both the base coat and clear coat are cured concurrently in the same oven for 30 mins @ 160°C/320°F. The two surface layer are cured simultaneously to optimize adhesion between the two coating layers. The two chemistries need to react together to optimize adhesion properties.

**Paint Repair**

At any stage during the paint operation, surface imperfections can be caused by either dust contamination or physical damage, which needs to be repaired. Paint repair involves rub down, manual touch-up and IR cure of the isolated paint area. IR heating is provided via static IR lamps or by passing the complete car body through a Spoven. Heat is directed to the area needing repair, but needs to be controlled accurately to ensure that the repaired surface reaches the correct temperature for the correct duration.
Oven Temperature Control and the Need for Product Temperature Profiling

In the previous section it is apparent that for successful paint cure, irrespective of the paint chemistry being used, there is a critical need to be able to measure and control the temperature of the car body as it travels through the oven. Today paint ovens are controlled in a sophisticated fashion with static thermocouples located in each zone that gives constant feedback on the ambient temperature of the oven. Although this temperature data is helpful in giving an idea of process control from an oven perspective, it does not tell the whole picture.

As discussed previously, to cure the paint to specification (cure schedule), the critical information required is the peak metal temperature and the time that peak metal temperature is maintained. The control thermocouples in the oven cannot provide this data for the following reasons:

**Why oven control thermocouples don’t give you the complete paint cure picture**

1. Air temperature measured by the control thermocouple is not necessarily an accurate measure of the air temperature at the product surface. The data is only accurate for the exact location of the sensor.

2. The temperature at a particular location on the car body may be different for the same oven zone temperature because:
   - Metal thickness varies, so there are different thermal masses and heating rates.
   - Materials used vary (Steel or Aluminum), with resulting differences in heat transfer characteristics.
   - Air flow characteristics vary, affecting the rate of heat transfer, even if the temperature is constant.
   - Internal surfaces can heat slowly, since they are shielded from convective heating effects.

3. Control thermocouples measuring air temperatures will not detect influence of IR heating from black body radiation.

4. Control thermocouples give constant temperature read out but do not provide any data relating to the transition time of the car body through the heated zone which is critical to validate the cure schedule has been achieved. The effect Line speed changes or stoppages on cure cannot be quantified.

5. The control thermocouple may not accurately give a true representation of the effect of oven loading patterns on the car body shell temperature as the total thermal mass of cars inside the oven needing heating changes significantly.

Oven temperature profiling is the only truly accurate method by which the oven paint cure process can be monitored to determine that the paint cure schedule has been correctly achieved. The oven profiling system is designed in such a way that it is able to travel with the car body through the cure oven, measuring continuously the product temperature at selected locations on the car body. At the end of the process, the collected temperature creates a thermal profile of the product from which the cure schedule can be measured and validated.
An oven profiling system consists of four elements

- **Thermocouples** – These are attached to the product to measure product temperature or used to measure ambient air temperature at the product.
- **Data Logger** – A data logger captures and stores the temperature data from the thermocouple.
- **Thermal Barrier** – An insulated box designed to protect the data logger from the hostile conditions within the oven.
- **Software** – Software provides the end-user with tools to review, analyze and generate reports on the temperature profile.

![Fig 6](image)

Datapaq Oven Tracker XL2
Oven profiling system designed specifically for the automotive paint industry.

- 1. Thermocouples
- 2. Data logger
- 3. Thermal barrier
- 4. Profile software

Applying Oven Profiling to Automotive Production Strategies

In the automotive paint shop, use of the Datapaq system for routine oven profiling has become a way of life. Every day in most automotive plants, systems like the Oven Tracker XL2 will be used to confirm that the cure schedule is being achieved to guarantee paint performance and hence, the quality of the final car product.

The frequency of profiling for each paint line varies from plant to plant and supplier to supplier, ranging from once per shift per oven to once per month. In general, there are often key events that would naturally drive the need to run a Datapaq system where there is some risk that the oven operation may have changed. These key events are listed below:

- Model Start Up
- Complete Oven Clean
- Major Line Breakdowns (Damage to ducting)
- After Oven related facility modifications
- Changes in production schedules
- Any extended “down” periods exceeding four days
As with frequency of runs, the method by which profiling is performed can be very different from plant to plant and even from process to process. Oven profiling can either be done by a direct or indirect method.

**Direct Profiling**

The direct method involves the testing of a car body that is part of the production schedule and as such, will be painted and supplied to a customer. Being painted and part of the production run, the Datapaq system will need to be installed live on the car just prior to the cure oven and the thermocouples are located internally on the car body shell to eliminate damage to the outer painted surfaces. The inner surfaces will be covered by fixtures and fittings, so paint damage will not be critical.

**Indirect Profiling**

The Indirect method involves the testing of a unique car body that has been sacrificed for testing purposes. The car body is nonpainted and will be permanently rigged with thermocouples. This test body is installed on the paint line when testing is required and run directly through the oven.

The benefits and disadvantages of the two approaches are summarized in Table 1.

<table>
<thead>
<tr>
<th>Benefit</th>
<th>Indirect Profiling</th>
<th>Disadvantage</th>
<th>Direct Profiling</th>
</tr>
</thead>
<tbody>
<tr>
<td>No test body requiring storage</td>
<td>Thermocouples always in same location so data accuracy guaranteed run to run</td>
<td>Car Body painted so can’t be touched</td>
<td>Car Body needs to be stored in clean environment to avoid process contamination</td>
</tr>
<tr>
<td>Car available on line when required</td>
<td>No risk of damage to production body</td>
<td>Risk of damaging paint adding repair time to production</td>
<td>Car body needs to be moved to oven to perform testing</td>
</tr>
<tr>
<td>Probe placement can be customized for specific run quickly and easily</td>
<td>System installation on stationary Car – Operator Safety</td>
<td>Car Body may be moving (Safety)</td>
<td>Customized probe placement difficult as probes rigged on car body</td>
</tr>
<tr>
<td>Probe placement must be quick (&lt; 60s)</td>
<td></td>
<td>Probe placement rushed adding risk of bad placement?</td>
<td></td>
</tr>
<tr>
<td>Probe measurement accuracy needs validating against external probes</td>
<td></td>
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</tbody>
</table>

Table 1: Benefits and disadvantages of direct and indirect profiling strategies
Logger Technology – making the profile challenge efficient and easy

One of the biggest challenges of oven profiling in an automotive paint shop is the sheer scale of the operation and time it takes to transfer equipment to and from the QA office to the paint line requiring testing. To help address this issue, the Oven Tracker XL2 has been developed with key features that allow sequential testing of multiple ovens without the need to download profile data between runs. The XL2 logger can be programmed to perform multiple runs (up to 10), so that each oven can be tested and its data stored separately in the memory of the data logger. The process is simple at the end of the first run. The logger is stopped by disconnecting the MemoryPaq and Transducer, and then re-started before transferring to the second oven in the barrier by simply reconnecting the two components.

Complementing the multiple run operation mode, the user can employ a unique feature called SmartPaq. Prior to the run, the user can program the logger with critical target performance criteria (Maximum Temperature limit, Time @ Temperature target or acceptable Datapaq value range). The data collected by the data logger is analyzed against these criteria at the end of the run and the logger displays whether the criteria have been achieved or not. The SmartPaq feature makes profile qualification as easy as checking for a Green Pass LED, which means you can move on to the next oven with confidence and without any need to download data. The data can be analyzed in full later after all runs are completed. If the LED is red, you immediately know at the oven exit that you have a process problem. Knowing this fact as soon as possible is critical to reducing rework, since the root cause of the problem can be identified much earlier in the process.

Moving away from the traditional sequential oven profile approach, Datapaq has worked with key automotive manufacturers to develop a barrier technology that allows not just one or two ovens to be tested sequentially, but the complete paint operation from start to finish in one single run. The “single pass” method is used with a test car, allowing the system to be installed off line. The test car is then installed onto the paint line after the e-coat dip tank and allowed to run through the entire paint line, as if a production car. Completing the run in one operation removes labor (60% Labor cost saving) as the system does not need to be installed and removed for each oven, as it would with a conventional profiling procedure. The thermal barrier is designed to protect the system during the process (including delays) without any risk to the data logger overheating. The TB0081 single pass barrier is completely silicone free, as are all standard Datapaq barriers used in automotive paint operations, and gives protection at 150°C/302°F for 13 hours continuously. After the test run, the test car can be moved offline and the data logger retrieved by the operator at his/her convenience. This can be done safely after the test body and equipment has fully cooled.

From the single profile technique, a single profile graph with numerous oven peaks is created, but these can be separated easily and efficiently using software tools that allow each paint process to be analyzed against its own unique criteria.

▲ Fig 8
Oven Tracker XL2 two part data logger – MemoryPaq and Transducer Interface with multiple run capability and SmartPaq operation. Identify whether the profile is successful or not without downloading data by simply checking an LED status light. Green means Pass and Red means Fail.
An important component of the oven profiling system is the thermocouple. The correct choice and placement of the thermocouple sensor is critical to the accuracy of the data collected and hence, interpretation of what is happening in the oven. Placement of the probe will by definition be determined by the type of product (car, truck, etc.) being monitored and its design. In general, probe placement is selected to measure areas on the body that are at risk of over curing (thin metal sheet – roof, hood) or areas that will potentially suffer from under curing (thick structural members – B pillar, Rocker panel, Sill).

The choice of thermocouple design will obviously be controlled by the material type being monitored and the location/space available for probe placement.

The MicroMag (Fig 10.1) is a probe designed specifically by Datapaq to meet the demands of general automotive paint profiling strategies. The compact sensor can be placed in the tightest of recesses, allowing those difficult areas to be measured accurately and efficiently. The high performance, encapsulated Samarium Cobalt magnet guarantees secure fixing of the temperature probe.
sensor to the product steel surface. The metal base plate protects the magnet, allowing use in the most hostile of environments. Even in Ecoat or other wet paint processes where it is possible for the probe to become bonded to the product by the cured coating, probe removal is possible without risk of magnet damage or loss.

As with usage, the number of profile measurement points will vary from customer to customer and even plant to plant and operation to operation. For standard QA profiling of operational processes, 6 to 8 points of measurement are regularly used. During new product launch programs, oven set-up and optimization requires often far more detailed profile information. To get a detailed process profile, the 16 channel XL2 becomes very helpful, as it allows a single system the capability of monitoring up to 16 product locations in a single run.

The Dual Interface block is designed to allow two transducer interfaces to be connected to a single MemoryPaq. The configuration of the system allows the two sets of thermocouples (2 x 8) to exit the barrier from different ends, making cable management more efficient. Placing the barrier in the center deck of the car/truck, probes can then be easily routed to the front or rear of the car.

Accurate documentation of probe placement is critical to the interpretation of product temperature profiles. It is important for QA processes that the probe is placed in exactly the same location test after test. Any variation in probe placement, possibly from operator to operator, can create data that implies that the oven operation has changed, when in fact it hasn’t – it is just that the probe is measuring different information. To help with this task profiling software is offered with the ability to show not only probe placement on a schematic image of the car, but a complementary probe library allowing detailed photos to be incorporated that show specifically where the probe should be located. Such information is not only vital for detailed reporting of the profile, but also as a training aid for operators performing the profiling task.

Converting Raw Temperature data into meaningful process information

Collecting oven temperature data is only part of the story. Although important, the data needs to be reviewed and analyzed in such a way that it can be used to determine what is happening to the product being cured.

To determine whether the process matches the paint supplier’s cure schedule, a variety of analysis tools can be considered. At the simplest level, time at temperature calculations can give an approximation to whether the coating has experienced enough heat to allow the cure reaction to reach completion.
On a more sophisticated level, the Datapaq Value index of cure calculation can be employed. This calculation is based on the Arrhenius equation that describes the first order rate of reaction kinetics followed by many cure type reactions. The calculation uses the sum of all time and temperature contributions taken from the profile graph to generate a single cure index value. A value of 100 indicates that the profile matches perfectly the desired cure schedule as designated by the coating supplier. Higher than 100 indicates a theoretical over cure condition and under 100 indicates an under cure condition.

The Datapaq value accurately quantifies total cure over the whole profile, so curing below and above the target cure temperature is captured. Using the Time @ Temperature calculation oversimplifies things and sometimes does not give the correct information, especially when temperatures well above the cure temperature are experienced. At such temperatures, the cure reaction will be much quicker and higher levels of cure will be experienced that are not represented in the basic Time at temperature data.

A popular method of quantifying cure in the automotive paint operation is the use of visual BakeCharts (Bake Windows). These are graphs which show what ranges of Time at temperature are acceptable to the paint cure process. These BakeCharts (Fig 14) are supplied by the paint suppliers to allow accurate selection of oven operation characteristics to give the best paint performance. In some situations the BakeChart can be split into various regions giving specific paint characteristics, so that the user can select the required cure conditions to give the desired paint qualities while optimizing productivity (car throughput) and efficiency (selected oven set-point temperatures).

Historically, Bake Charts have been employed independently of the Datapaq operation. Time at temperature data taken from the Datapaq profile graph would be recorded on a hard copy of the BakeChart to prove process QA. This process is obviously tedious, time consuming and prone to human reporting errors. To alleviate such issues, Datapaq has developed within its Insight™ operating software, the BakeChart function. Using the BakeChart function, the user can generate a digital copy of the BakeChart within the Insight software, which is then used automatically to analyze the profile data. In this way, fully digital archived BakeChart results can be generated and linked to the profile data. Such information can be shared electronically with ease.

Below in Figure 15, there is an example of a BakeChart used for a Top Coat application. As you can see, the profile analysis data (Time @ Temperature) for each thermocouple is superimposed over the BakeChart. As data falls within the green perfect region of the BakeChart, the profile is identified as being acceptable. For this example, the data is optimized to fall within the bottom corner of the BakeChart, guaranteeing the optimal conditions – not just for paint quality, but also car production throughput and lowest energy consumption.

A challenge of any automotive paint operation is getting consistency of cure on all areas of the car and in particular, eliminating different side to side heating effects within the oven. In many plants, engineers are working to very tight operating variables requiring that side to side body metal temperatures do not differ by more than ± 5°F. To help with these important criteria, the Insight software can perform...
an automatic temperature difference analysis to highlight problem areas within the process. Figure 16 illustrates the graphical Temperature Difference function showing where in processes the temperature measured on the left and right door panels is out of tolerance. Such data is important to allow identification of the root cause and necessary corrective action.

At the end of the day, data reporting and archiving is critical to the certification of automotive processes, whether working ISO9000, QS9000 or even CQI-12. The Datapaq Insight system has been developed to allow customization of the full report generated to include the specific data and information required. If
necessary, the archived data can be used to generate SPC charts to show how key parameters (Datapaq Values, Time @ Temperature etc) are changing within time. Within the Insight software, the SPC program automatically produces SPC charts without any need for data export or use of the SW packages.

Figure 17 shows a typical profile report showing clear process information and data. The report can be automatically converted to a .pdf file, allowing it to be shared with anyone via e-mail, even without access to the Insight operating software.

Conclusion

Although oven profiling has been used for many years in the automotive coatings industry, it has come a long way from its humble beginnings. Updated technologies from Datapaq now provide a range of benefits that allows the paint shop or production manager to understand, control and optimize oven cure processes with even more accuracy and efficiency. The paint shop manager is now able to maximize the coating quality of his finished product, ensuring customer satisfaction, and the efficiency and productivity of the complete paint finishing operation.

Fig 17
Example of Datapaq Full Insight Profile Report (Pages 1-4)