# Screen Making for Printed Electronics- Specification and Tolerancing

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**Abstract**

Six decades of legacy experience makes the specification and production of screens and masks to produce repeatable precision results mostly an exercise in matching engineering needs with known ink and substrate performance to specify screen and stencil characteristics. New types of functional and electronic devices, flex circuits and medical sensors, industrial printing, ever finer circuit pitch, downstream additive manufacturing processes coupled with new substrates and inks that are not optimized for the rheological, mechanical and chemical characteristics for the screen printing process are becoming a customer driven norm. Many of these materials do not work within legacy screen making, curing or press set-up parameters. Many new materials and end uses require new screen specifications.

This case study presents a DOE based method to pre-test new materials to categorize ink and substrate rheology, compatibility and printed feature requirement to allow more accurate screen recipes and on-press setting expectations before the project enters the production environment where time and materials are most costly and on-press adjustment methods may be constrained by locked, documented or regulatory processes, equipment limitations and employee experience.

**Keywords:** Screen specifications, Printed electronics, Flex circuits, Medical sensors, Functional printing. Substrate testing. Ink testing

## 1. Introduction

At its core, the information in this paper can be useful for screen specifications for all screen printed electronics.

In general, screen tolerances and printed part specifications affect all screen printed electronic applications.

In specific, this is aimed primarily at Flex circuit, membrane switch, and the wider field of specialty industrial, surface mount, specialty consumer electronic and medical/sports/cosmetic printed electronic applications housed under the generic PTF (polymer thick film) moniker. Historically the rigid board applications of screen printed electronics are the segment that comes closest to having standards for print and by default, standards for the screens used to produce them.

IPC and ASTM (and other) standards help develop test methods for the quality and specification of the printed features (deposit, pitch, radii, feature shapes, life cycle, drying/curing, testing of all types etc.). The subsequent semi-standardization of the "inks" used in this industry segment (solder, silver, gold, carbon and copper pastes, ceramic frit mixtures etc.) and with regard to their rheological characteristics (very high metal solids to binder/solvent ratios and very little thixotropy or shear modification) mean that the screen recipes required to operate these inks will be remarkably similar from plant to plant without actually having to regulate that a particular mesh, stencil type, EOM, Rz quality etc. are used.

Because most of the inks used in rigid board applications are less susceptible to shear based changes and the range of pitch, feature shape and deposit are relatively controlled and narrower in scope and the substrates/boards are less varied in type than the print substrates found in the wider PTF segments of the industry, the combined level of standardized and default controls are adequate. In most cases it is not necessary to specify more than a best practices approach for print set up and screen making.

The PTF segments are not yet so fortunate. With the vast range of inks, substrates, feature shapes and unique device types added to the flexible nature of many of those inks and substrates and the huge range of deposition, ink chemistry and rheology variables, the printed electronics industry at large is effectively "the Wild West".

The fact that IPC and others are currently engaged in helping to set up standards for the printing of Flexible printed electronics circuits/and devices (one of the largest segments of the non-rigid printed electronics industry will eventually drive at least a "best practices" movement in screen production if not actual standards for screen recipes and production.

## 2. Problem/position

The core differences in rigid board printing and "flex" circuit and PTF printing are seen in the material sets:

- Wide ranging deposit thicknesses required for different device types
- High degree of flexibility required of substrates and inks
- An increasing use of printed "solutions"/suspensions/liquids and coatings or non-standard inks, some of which are conductive and some that are functional in other ways
- The vast majority of flex/PTF inks, conductive or otherwise are thixotropic to some degree
- Due to the wide range of printable "liquids/pastes" used, the screen mesh technology and its requirements are also wider (polymer meshes of numerous types as well as wire mesh)

These core differences create a wide range of what is both required and acceptable in screen formulae and specification to produce a given trace pitch and definition in the flex arena.

## 3. Variables

The added variables of ambient condition, ink variation from lot-to-lot, substrate and stencil hydrology/rheology combined with the ink thixotropy can mean that the same exact flex circuit device may be printed in different plants in different locales and even with the same equipment and it can and will have wide ranging differences in screen and stencil specification, press set-up parameters, running and curing speeds and still maintain the same process capability. However, taking and transplanting individual screen and set-up formula for this same product from one production location to another can produce results that range from failure to better than that at the original location. The local variables affect the set-up and screen recipe as much or more than the ink and substrate.

## 4. Standards or Best Practices

While flex/PTF circuit printed part standards (and most probably actual printing standards) will become a reality, screen making standards for this print arena will likely not be a reality anytime soon. The key to maintaining the new printing and printed part standards in the face of high variability of ink and substrate characteristics will be found with better and more frequent measurement and analysis for substrates and inks for pre-printing, in-situ and post-printing characteristics. Printed part measurements are also critical and include ink deposition (wet and dry), texture, detached metals/dusting, porosity, viscosity, shear ratio, curing, lifespan and electrical. The substrate measurements may include, dyne level, surface profile, chemical bonding, and temperature stability with cycling and lot-to-lot comparison. There will also be measurements that are device specific.

## 5. Measurement and Data Gathering

This level of data gathering should be found at the printer/producer level and not just accepted in its general form from supplier documentation. It will need to be added to actual screen DOE data on production or near equivalent production equipment to properly assess how a given ink and substrate combination with a specific range of feature sizes and deposition will perform in the exact required environment with a specific mesh/EOM combination. How this combination is actually set up on press will also indicate actual production run settings.

It is this process of R&D printing and measurement that is used to indicate screen production formulae and some guarantee that the screen formula is robust and repeatable. A truncated DOE format will also show whether a given screen/ink/substrate/printed feature set is sensitive to normal lot-to-lot variation of inks and substrates or ambient conditions.

It can also indicate what range of screen recipe adjustments are allowed within the written process or when the variation can be offset simply by a controlled range of on-press adjustment without risk of downstream printed devices becoming a non-conformance, or when the amount of on-press settings adjustment becoming a non-conformance in the printed part variation.

The key point is one of the largest problems with this level of data gathering and pre-production/pre-design R&D is that a very large proportion (typically about 70%+ of the industry) do not make their own screens in-house. They are outsourced.

This causes two primary problems:

Outsourced screens will typically have a wider range of allowed tolerance in their specification. This is mostly a necessity for the screen production houses because:

**i.** The final tension achieved in the tensioning chaise will rarely be exact to what is delivered once adhesive is applied, the frame deflects as load is taken up and the mesh relaxes.

**ii.** Exact coating thickness accurate to within 1-2 microns, with an exact design tension being either the "floor" or middle of that range and with exact surface profile (Rz) can only be repeatably achieved by coating "up" to exact numbers or with exact application with film emulsion to screens whose tension and thread count is uniform. This is possible at most screen houses but can be prohibitively expensive as its time consuming.

As long as the printed part does not have ink deposit variance, image distortion, EOM, Rz or other sensitivities to a wider range of tension this is not a problem. However, in the arenas of specialty and medical printed electronics, this wide tolerance range may not work with written process tolerance.

Below are examples of what is meant by common/wide screen recipe tolerances versus tighter/narrow tolerance screens:

1. **Common/wide tolerance**

230/48 Yellow Polyester @ 30ncm +/- 2ncm (ideal design tension is 30ncm for this printed part)
7-10µm +/- 1.5µm EOM (ideal design EOM is 8µm for this printed part)

2. **Tighter/Narrower tolerance**

230/48 yellow Polyester @ 30ncm +2/-0ncm (ideal design tension is 30ncm for this printed part)
7-9µm +2/-0µm EOM (ideal design EOM is 8µm for this printed part)

The tighter tolerance ensures that the operative tension and EOM do not fall below the ideal #'s required by findings during the R&D process.

A more lenient "tight" tolerance to help the outsourced screen maker meet the target is below:

230/48 yellow Polyester @ 32ncm +/-2ncm (ideal design tension is 30ncm for this printed part)
8-9µm +1/-0 (ideal design EOM is 8µm for this printed part)

Typically, most flex and PTF screen formulas can handle a slight increase in tension without changing off contact, distortion or squeegee and floodbar settings. However, many cannot work with tension and EOM numbers that drop BELOW the design ideal sensitivities found for the ink, substrate and printed feature discovered during R&D. Some of the specialty PTF inks can vary printed deposit radically and in some cases cease to transfer from the screen.

## 6. Logistical Issues

The problems encountered with outsourcing screens are not just the tolerance variations described above but the time lag and the added variables into the R&D process. When ink/substrate R&D is in progress, depending on the ink sensitivity, a few microns of EOM or a few Newtons/cm of tension may make a huge amount of difference. Test data obtained under these variable circumstances may drive a screen formula and set-up decision that produces screen recipes that do not translate to production printing. This can be a costly time loss or even a customer/job loss.

## 7. R&D Screen Tolerances are More Critical for Accuracy than Production screen tolerances

The object for any R&D test screen set is to get all of the screens in the set to be very narrow in tolerance/specification and as functionally identical as possible so that the variables of the ink, substrate and printed parts are readily discernable. For most R&D this is usually simplified to getting tight tolerance mesh tension first within a single mesh count so that the EOM can then be varied for the range of testing to qualify or disqualify that mesh count. The key is having a tight spread of tension variation with virtually identical finished thread count, mesh thickness and mesh opening size. This also makes coating of progressive EOM's on this screen set easier and more accurate.

Note: This is not to say that all outsourced screens for production must have tighter tolerances. Once the range of sensitivity of the printed circuit design within its ink and substrate set is found during pre-production R&D, the screen recipes may indeed be stable with fairly generous +/- tolerances for both tension and EOM. You have to find what works first and know why it works. However, you cannot discover what works for screen formulas and tolerances and their sensitivity range without first testing with a narrower controlled range.

Stencil parameters can be harder to control than mesh parameters. There are more of them and their successful application and control will also be affected/leveraged by the mesh parameters. These parameters include edge definition, resolution, porosity, particle size in the stencil surface and wall, EOM, print side Rz and squeegee side Rz in many specialty PTF applications. Added to this are chemical compatibility, abrasion and lifespan considerations.

The difficulty with outsourcing stencil production, with mesh parameters put aside for the moment, will primarily be affected by logistics. The cost for time lag to get screens whose mesh count, tension or EOM are adjusted for the next testing phase will be very high.

To then get screens that have otherwise perfect mesh parameters, returned to your screen house to be recoated with what may only be 1-2µm difference of EOM to continue testing can put a week or more between R&D cycles.

The added gamble is that the screen mesh may lose tension during the round trip, be damaged in transit or may even arrive with the new EOM or Rz not exactly as advertised (it has happened to all of us). All of the while, substrate and ink lots are ageing and any specialty treatments (corona, flame treating etc.) are dissipating and ambient or production window conditions may not be ideal when the reworked screens return.

Note: A large portion of this risk is also that a printer’s in-house screen instruments (tension meter, thickness gauge and Rz gauge) must be either synched to match the screen making house instruments or have an exact traceable offset that can calibrated. Without this synchronization, incoming screens cannot be qualified as to whether they match the written specification or tolerance range. Far too many printers who outsource their screens do not even have these instruments. This makes R&D expensive and dangerous to written processes.

The point being that more R&D has been impaired or derailed and customers and jobs lost simply by not having the right materials on hand, screens on hand, ambient conditions ideal and a production window that allows work to begin. It can seem to be similar to a “moon shot”.

## 8. Improving methods for determining screen formulas and production tolerances

Better understanding of the screen recipe tolerances required to print a particular circuit design will be gained through expanded testing of substrates, inks and screens using a modified DOE method. Printed part observation/data gathering is a key component of this testing.

**1. Print Observation:** One primary component of screen recipe specification is actually printing and observing/analyzing the printed traces or device. Too often, many printed parts are measured but not enough is actually “observed”.

Typically, (again it can be device dependent) R&D is a rushed process. The most common screen print “observables” tend to be state of cure, adhesion, pitch, edge definition, deposit thickness and electrical response/continuity. This is a healthy handful but when the printed part, deposition, substrate or ink moves toward “different than standard”, this handful leaves a lot of important measureables on the table including.

- Texture of conductive inks
- Detached metals/dusting
- Gradually incomplete screen clearing over production run length (ink build up requiring washout)
- In wetting observations (substrates, emulsion/feature walls and mesh threads)
- Staged retesting of resistance to observe solvent migration and moisture absorption effects
- The use of volume resistivity testing in lieu of or alongside of surface resistivity
- Squeegee wear (time weighted microscope observations)
- Time and date logging of ambient conditions during printing (RH and temperature)

Each one of these observable/measureable characteristics is a data point with a story to tell.

It is far too common that new devices/designs that advance from R&D printing to sampling or even first article live printing face unforeseen failures…. producing tell-tale problem features that were there but ignored or simply not observed during the R&D phase.

When you can see, document and measure the effects of a screen recipe variable change on the listed print quality parameters it is far easier to gauge real progress and make tolerance/recipe change decisions that are robust and accurate.

**2. Mesh, substrate and ink characterization**

Other key parts to this process are the ability to measure and record the "as received" condition of the raw materials. This is useful on several levels to determine if the materials even meet the C-of-C from the manufacturer (specification met), if the materials are changing during production and under what conditions over what span of time (process stability and lifespan) and to characterize the lot-to-lot variation of the materials. Lot variation does not mean they are not usable materials. The range of variation available and allowed for raw materials before they affect the print process and the finished part is a large part of what print R&D is all about discovering.

## 9. Raw Material and Process Measureables

**Tools for Raw Material and Process Measurements:**

In the following list some of the same required measurement functions appear under all categories of raw materials. Careful selection of tools will allow gauges to fulfill multiple functions.

**Substrates:**

- **Thickness:** electronic is preferable to mechanical as mechanical gauge increments are typically .0001"/2.5µm at best with +/- tolerance.
- **Dyne level test solutions:** preferably coupled with training and traceability to ASTM Std. D-2578.
- **Texture/surface profile:** The basic gamut of Ra, Rz, Rv, Rp and Rt in a hands-off gauge with a 5mm minimum sample length.
- **Optical inspection:** a microscope with 10X-200X+ with as wide of a field of view as possible for observing porosity, surface flow and texture. The ability to take medium resolution photographs is also ideal.
- **Cross cut adhesion test kit:** with multiple blade spacing sets, training and in-house standardization to at least one of the several methods and test material sets described under ASTM Std. D-3359,
- **Durometer gauge:** Shore C or D for rigid plastics
- **RH meter:**

**Inks:**

- **Basic viscometry:** When your range of ink viscosity allows, simple and cheap gravity/time based viscosity tools can suffice (Zahn, DIN, ISO cups etc) for a baseline characterization.
- **Viscometer:** More advanced viscometry is preferable. A rotational viscometer with shear stress mandrels and cups or a "rheometer" using a heated cup and cone is preferable. The range of inks/printable functional liquids you encounter will dictate the level of sophistication required.
- **Thermocouple/Thermoprobe:** Simple and expendable probes are available to plug directly into a Multimeter. These are required for ink baseline and production monitoring.
- **Heated desiccation scale:** This type of scale can be found quite inexpensively and can double as a small accurate scale for dosing ink with additives as well as finding the solids ratio of inks. The solids ratio is useful for finding when inks are depleted or when there is a lot-to-lot variation that is significant.
- **Mixing scale accurate to 1/10th gram:** for additive dosage, solvent evaporation tracking and ink lot sub-division
- **Draw down bar:** A handy and inexpensive tool for making a quick ink film characterization. Available in multiple styles and film path thicknesses.
- **Thickness gauge (dry):** Required for checking printed ink films.
- **Wet thickness gauges:** A key tool for verifying how an ink actually prints with a given stencil and also required when testing curing time and temperature windows.

- **Hegman gauge:** Required for checking metal particle size of conductive inks for incoming pre-inspection and also for checking ink depletion rate.
- **Optical inspection:** Loupe and microscope inspection of surface texture and porosity of draw down samples and printed parts is critical. Inexpensive and accurate USB microscopes with high resolution photo, video, filtering and measuring ability are available and the best option.
- **RH meter:** There is a wide range of options from tracking and data-logging sensors, wall gauges (usually the least accurate) and simple sling type Psychrometer (most accurate) that should be used to log relative humidity conditions during testing and production
- **Stopwatch:** Many tests, measurements and preparation/mixing operations are time sensitive. Useful stop watches can be purchased for low cost. You should not get into the habit of using, phones, smart phones or personal devices for this.

**Chemicals/ink additives:**

- **Scale:** accurate to 1/10th of a gram with a 1-5 kilo capacity
- **Mixing motor and rotor:** a Variable, low speed mixing motor and stand with a low shear dispersion blade and shaft.
- **Thermocouple/temp probe:** Simple and expendable probes are available to plug directly into a Multimeter. These are required for ink baseline and production monitoring
- **Stopwatch:** Many tests, measurements and preparation/mixing operations are time sensitive. Useful stop watches can be purchased for low cost. You should not get into the habit of using, phones, smart phones or personal devices for this.
- **RH meter:** There is a wide range of options from tracking and data-logging sensors, wall gauges (usually the least accurate) and simple sling type Psychrometer (most accurate) that should be used to log relative humidity conditions during testing and production

**Squeegees:** Note that squeegees must be changed when they exhibit wear. They are a raw material. Conductive inks are abrasive in general. While resurfacing/grinding/cutting a squeegee versus replacement is a specific production option and decision for each plant, knowing when to change or resurface by observation and measuring is key.

- **Angle gauge:** Squeegee angles are critical. Proper measurement and documentation are key for repeatable recipes.
- **Optical inspection:** Observance of edge abrasion and cut/grind quality is critical to squeegee performance troubleshooting and diagnosis. Typically 25X to 100X is required.
- **Durometer gauge:** Shore A is needed for the squeegee. There is considerable variation even among the best squeegees. The durometer of urethane increases at a rate of 3-5% per year and can change rapidly with solvent exposure. Knowing actual durometers of squeegees that deliver the best performance in a print formula can be critical with sensitive inks and difficult printed features.

**Electrical/Performance:**

- **True RMS Multimeter:** Quick checks of surface resistivity are a production line and R&D requirement.
- **Multimeter probes:** Probe type can be critical. Blunted/ball tip probes are required for checking surface resistivity of thin film conductive inks on flexible substrates without scratching. Alternately, flat, spring loaded contacts or alligator clips may be useful for certain device and sample types. A weight system to hold probes to circuit samples in a hands off manner for taking accurate measurements is required.
- **Four point probe:** A high requirement tool. These tools can usually perform both surface resistivity and volume conductivity. This is the primary tool used by ink manufacturers for testing their printed ink films. It is the most accurate tool used for testing resistance related to curing and removal of solvents. Simple surface resistance testing can cause deceptive readings when solvents are trapped in the ink and later rewet the ink film.

To this point, the discussion of measureables and tools have revolved around everything in the printing/R&D process except screen making. This is important, because to make accurate screen formula/recipes, R&D printing is required. This is even more important in the Flex circuit/PTF arena because of the sheer range of ink and substrate rheology and the rapidly increasing variation of circuit/device types. Starting screen formulas based on historic or legacy data from other screen print sectors or past experience with “similar” designs will frequently not work. For the process of R&D printing to be accurate and repeatable, the condition and stability of the raw materials, ambient conditions and press settings must be verified.

The measureable results of the R&D printing are the data that drive the decisions of what worked and what needs to be changed and by what increment for the screen that produced the printed image.

**Screen Making/Emulsion Tools:**

- **Thickness gauge:** Digital thickness gauge using combined magnetic induction and eddy current.

A good result would be basic electronic emulsion thickness gauge with 0.5µm increments and repeatability to +/- 0.5µm using a ruby ball type probe.

The best result would be increments in 1/10thµm and repeatability to 0.5µm with +/- 0.3µm accuracy. Ruby ball type probe is preferred with wide ball radius and ferrous/non-ferrous targets and switchability.
The more accurate gauge can also be readily used for measuring printed ink film and substrate thickness.

- **Rz/surface profile:** Either a bench gauge or hand shop gauge with minimum requirements have the Rz parameter and at best the parameters of Ra, Rz, Rt, Rp and Rv would also be useful for printed ink profile characterization
- **Tension meter:** Any mechanical tension meter accurate to 1ncm with an NIST traceable standard. Highly electronic digital Tensiometers would be nice but have little usefulness or increased accuracy unless you can guarantee probe placement on specific threads.
- **Scale:** accurate to $1/10^{th}$ gram with 1 kilogram or better capacity. This is useful for mixing emulsions with DI water (thinning for face coating) and adhesives.
- **RH meter:** Relative humidity is critical to screen making. The screen room should have its own RH meter.
- **Optical inspection:** 10x to 200x+ is required for screen making for stencil to positive alignment, thread counting, and open area measurement and troubleshooting of all screen room processes.
- **Backlit table/work area:** Critical for all phases of screen making and inspection
- **Exposure unit Radiometer:** a must have for mapping weak spots and lamp issues
- **Exposure Calculator:** A must have with weekly use
- **Stop watch:** Useful for timing face coating intervals, dry times and emulsion mixing.

10. **The Most Common Problem**

Acquisition of better testing equipment and adoption of a more controlled screen print R&D methodology to make more functionally robust screen recipes is a simple and affordable adaptation. It will reduce time to first article and eventual production and likewise save money by making the data result of the printed device R&D faster and more accurate. By doing so it will also increase the viability of many device designs that frequently do not make it past the proof of concept stage because the projected R&D is estimated to be too costly and cumbersome with current methods.

With an ever increasing variety of materials, device types and level of difficulty in the Flex/PTF/Medical/Specialty printed electronics industry, the upcoming standards for Flex circuit printing will have effects on a far wider range of printed electronics than is easily envisioned.

**11. The Scope of the Problem**

A high proportion of membrane switch, PTF and flex circuit printers, produce circuits for contract customers without actually adhering to any print or finished part process controls or standards outside of what is used in their own facility.

In this common contract print model the printed component only needs to conform to the written specification of the customer, supported by statistical pulls, record "retains" and a "COC" for packing and shipping. How that specification is attained is frequently not regulated by the customer/end-user or the regulations that govern the end-user's primary industry.

Many of these contract goods shops have few measuring/QC instruments outside of what is immediately required for final testing of printed parts. Those that also outsource screen making typically have few if any measuring instruments for verifying on-press screen adherence to specifications or incoming screen condition and qualification as an in-spec process tool.

Currently, many end-use customers are in effect, buying a printed result and not a process segment that adheres to their own internal industry standards. Many end user industries like medical device, aerospace and automotive will quickly adopt and absorb the upcoming Flex circuit standards into their existing written process standard system. As a combined standard system, many of these printers will no longer be able to work as only a results based outsourced part supplier with a discrete but separate process control system. They will be forced to come into the fold of the industry segments they serve.

The coming need for flex and PTF customers to adhere to the new flex standards combined with industry segment standards will drive the need for more rigid documentation of pre-production R&D, production sampling and documentation of process recipes and con-conformances for both materials and product.

We already see this with substrates and inks. The screen recipe itself frequently plays an even larger part in the process.

## 12. Improvements to R&D Processes to Improve Screen Specification Accuracy

- Categorization of screen printed electronics types by printed feature tolerance and type to indicate screen tolerances required to produce them

  This is as much about basic design of the circuit as it is about choosing materials for it and printing it regardless of circuit function. Proper categorization by feature size, print layer tolerance, required edge definition, texture, deposition etc. will greatly narrow the range of what type of screen will ultimately be required.

- Categorization of substrate materials and ink types to identify characteristics that indicate required screen types and tolerances required to work with these materials

  This is not quite the same as legacy or experienced based knowledge. Legacy knowledge is typically based on what was used to produce previous circuit types. This level of categorization should be based on what the materials allow or are capable of accepting for print with and without modification in with a +/- spread of failure to success based only on what is possible with a given ink on that substrate regardless of any particular design. This is about ultimate material capability looking forward to what screen recipes may be used to capitalize on those capabilities.

- Samples libraries of materials, screen production and production ability logs, imaging processing logs cross referenced to type printed electronics screen production

The sample library is part of the database and is a "toolbox" of knowledge. It should be regular practice to also test and include substrates and inks that are not even in use but have potential for future use. Material knowledge, compatibility and handling are key design tools and critical aids to fast screen recipe formulation for unique printed devices.

- Database (visual and written data) of screen recipe printed results with information on the ink set, ambient conditions, circuit type and substrate

  This data should include electrical, texture, porosity, adhesion, ink usage, visual appearance, numbers printed, screen life etc. It should include printed R&D results from screen recipes that were incorrect or failures as well. Much of what is learned by failure is useful.

## Case Studies

Case Study based examples and screen R&D process flows are included in Appendix A of the paper.

## Conclusions

Raw material pre-testing for new screen specifications will require creating processes for how the testing is conducted in order to mirror actual production floor print capability. The basic metrology tools for screen and ink measurement must be acquired. This method is best served with in-house screen making ability. In facilities where screen making is outsourced, this pre-testing/recipe specification process is even more critical to insure that the outgoing screen recipe specification is correct and that incoming screens actually meet that specification.

## APPENDIX A

## Case Studies

Below are two case studies presented for demonstration of the need for a change of R&D process flow methodology. Both are PTF type, screen printed circuits/sensors. Both are medical products. One is a thick film, screen printed, specialty defibrillator pad (sensor #1) and the other is a fine pitch conductive silver R&D production sample for a wearable device medical cloth transfer sensor (sensor #2).

While both of these sensors are very different, one using traditional printed traces with very fine pitch and a very high coefficient of circuit stretch and the other using no printed traces and using large printed conductive areas (pads/plates) with very precise ink deposition thickness, the primary challenge was the largely same even though the material and design constraints were different.

- Both sensors were theoretical new designs. They are either totally new device types or very alien adaptations of existing device types.
- With both sensors, the initial proof of concept from the engineering design stage had proven that the electrochemistry and mechanics behind each sensor were sound and the device architecture could complete the task the design engineer and client intended if it could be produced. However it had not proven that the part could be mass produced due to material constraints.

**Challenges with sensor #1:** Finding the exact screen/stencil/press setting recipe on automated production equipment. The caveat being that initial R&D as well as the proof of concept and initial test group printing had been produced with largely unspecified legacy screens on all hand operated equipment. None of it had been printed on even a semi-automated press. Adding to this the problem that the Ag/AgCl ink used was unique in formulation and had never been printed in such a high deposition thickness which changes the operating rheology.

This device required a specific ink with few if any additives or modification using an exact ink deposit thickness with an ink formulation that had difficult rheology and large particle sizes.

This device used legacy screen recipes and process estimates in its initial design, R&D and sampling phases. It shaped initial design considerations that made later stages of adapting the device to REAL production, costly and time consuming.

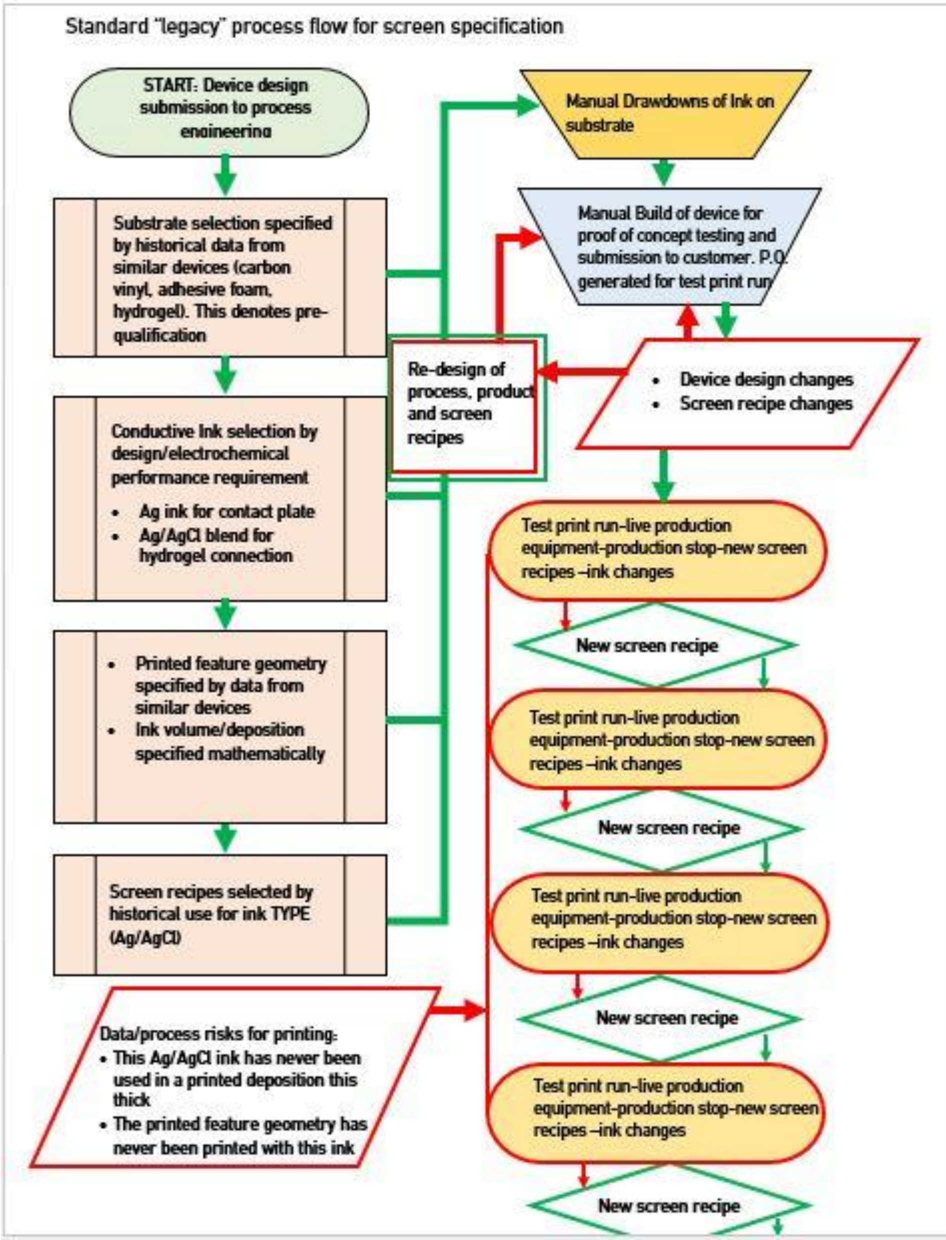



**Figure 1:** Flow Chart

The flow chart above shows a normal screen recipe and press setting start point used not only with this product but in most production facilities when beginning a new product process design. It typically specifies materials required instead of discovering materials and methods that are correct, robust and realistic for existing production methodology (the flow chart flows off the page on purpose as the level of print test permutations spanned months).

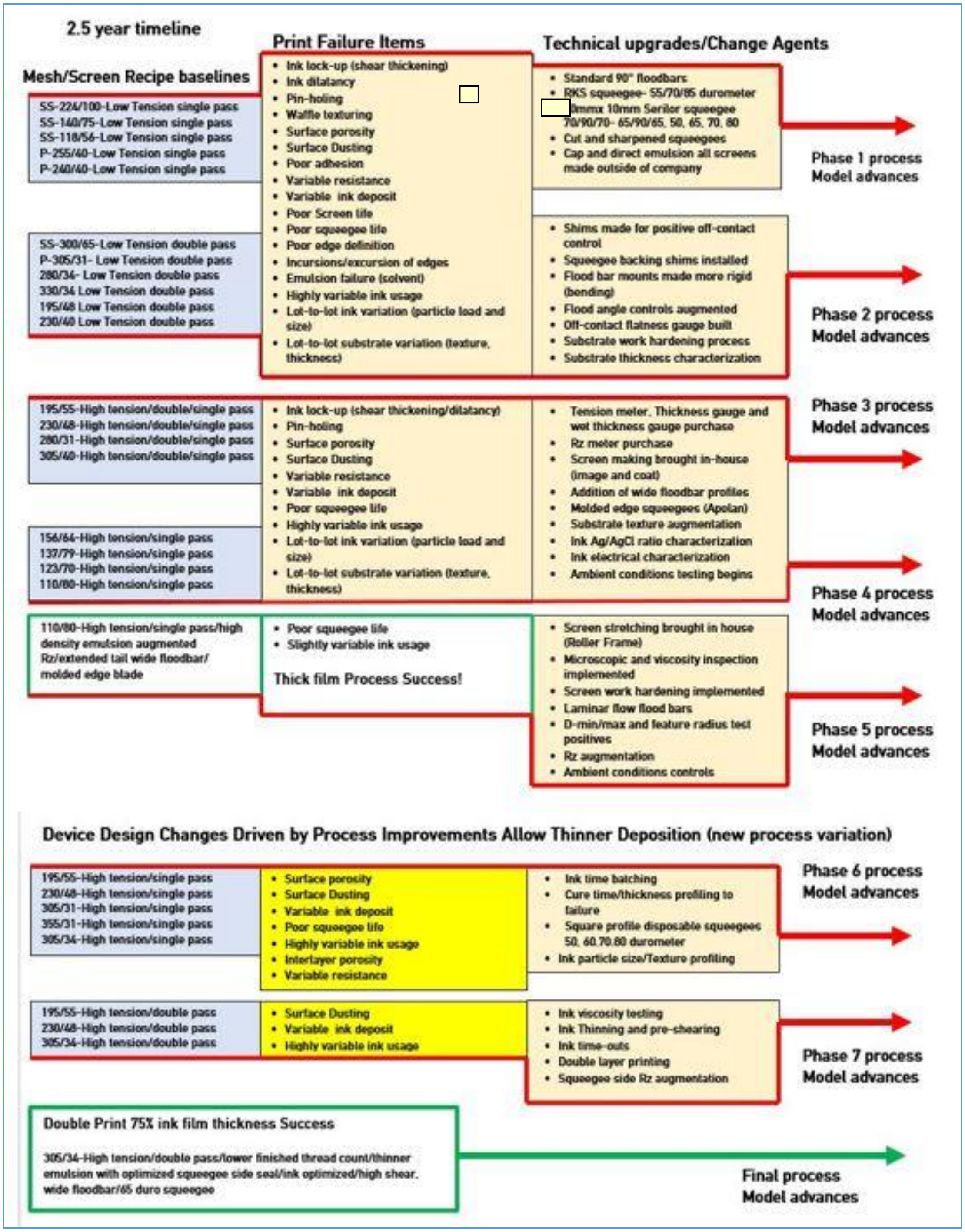



**Figure 2:** Abbreviated listing of screen recipes

Figure 2 is an abbreviated listing of the screen recipes, print failure points and redesign/reformulation change agents of the first case study device. However, this only indicates the range of screen mesh tested and does not fully detail the number of stencil, ink adjustments and press setting permutations across the indicated 2.5-year timeline.

The following list is the detail of process/recipe/method/design improvements from the seven process stages of the R&D for product #1. These take-away details went into the improved R&D model for product #2.

**Process Improvement Distillation from Phases 1 and 2**

- Establish that the press has a full range of on press adjustments (floodbar/squeegee angle and speed, off-contact, hard down stop)
  Include all axis angles, pressure, speed and stop controls. If these are not present invest in modification
- Do not limit yourself on press tools. Multiple floodbar edge angles, materials and edge widths must be available. Make sure your equipment can fit or be adapted to any flood or squeegee system on the market
- Avoid squeegee types or accessory systems that change through operator added variables (grinding/cutting changes length and porosity versus molded edge). Limit the variables in play. Have holders that can use both cut/ground edge and molded blades of any profiles.
- Test all emulsion types with the proposed range of feature sizes and deposition of any ink that is to be used before designing its use into the process. Make this process a +/- failure DOE. This is a part of the "archived tool kit". You will need a feature test film for this.
- Pre-characterize all substrates with complete physics in mind (heat, chemical compatibility
  Moisture, time elapse, texture/profile, flexibility, repeated processing, and substrate absorbency/porosity, weathering/aging, electrical/dielectric) …do not just test for the immediate intended use or combination of this material. Qualify material for its ability before designing with it. Create a standardized material intake testing regimen. Create a catalog of substrate physical attributes.
- Create a tighter tolerance for outsourced sub-assemblies like screens. This should be a +X/-0 tolerance. Limit the range to the positive side. This is for stencil, Rz, final thread count and flatness.
- Pre-test squeegees, floodbars for abrasion resistance or wear effect with a range of inks and squeegee side screen Rz before designing their use into the process. This creates a recognition pattern for when failure happens. This is for the "archived tool kit".

**Process Improvement Distillation from Phase 1 and 2 Plus:**

**Take away from Phases 3 and 4**

- Acquire process and raw material QC tools before starting the device design or printing process. Wet and dry thickness gauge, tension meter, Rz meter, calibration tools. These are capital equipment and can be tax deducted. Train for their use. Use them by regimented process. These are material characterization tools as well.
- If outsourced sub-assemblies like screens cannot be brought in within a tolerance that works with the raw materials and process bring their manufacture in-house at minimum for the phase that cannot be held in tolerance (in this case coating and exposure).
- Once substrate characterization and measurement is established, establish R&D to measure how much that substrate may be changed or augmented to fit a process consistently (texture, dyne level, work hardening/annealing, color etc.)
- Once the print equipment is modified to take any print accessory in the industry (squeegee profile, floodbar design, frame style, pin registration etc.) make studied purchases of different designs to have a DOE type range of edge profiles/angles, to have on hand to test both printing and test during ink characterization.
- Start off a standard program to characterize all planned inks for printability regarding particle/solids content loading and size and also with regard to changes in electrical behavior
- Start off tracking the ambient shop conditions (temperature, RH, Dew point). This data can be correlated to unexplained variations of work printed and materials used under any given conditions. There will be correlations.

**Process Improvement Distillation from Phases 3 and 4 Plus:**

**Take away from phase 5**

- Full manufacturing of screen brought in-house. Tension, stability, EOM, Rz, thread count to tolerance
- Microscopic and viscosity testing equipment acquired. Analysis of print problems seen from a micro level instead of just a macro level. More Data.
- Feature shape specific print test films brought in with a resolution that far surpasses the designed features of the printed device
- Non-standard Rz augmentation techniques are used (print side face coating and thinned emulsion coatings)
- Ambient conditions controls installed (humidity, airflow and temperature)
- Standardized in-situ interval sampling of product through entire run overlaid with statistical/asymmetrical "grab" sampling of product

**Process Improvement Distillation from Phase 5 Plus:**

**Take away from phases 6 and 7:**

- Initiate ink curing time with electrical checks until resistance crash or binder failure
- Custom made square profile, stainless steel squeegee holder with full length blade backing. Eliminates all flexing variables and makes squeegee 100% expendable so lifespan is never put before print effect.
- Ink texture correlation studies to track excessive ink usage to be put in place once microscopic studies, tape testing revealed texture and "surface dusting" were linked to ink changes and printability and ink consumption
- Ink viscosity studies with time weighted batching implemented
- Ink thinning and pre-shearing on time intervals before printing
- Ink time-outs. Ink removed from ink well and replaced at set intervals to maintain stable particle load and viscosity. Removed ink is then mixed with fresh ink in precise but small volumes to bleed into the print run as it progresses.
- Squeegee side Rz augmentation made standard and tested for squeegee edge stability and decreased squeegee pressure and harder squeegee durometer with resulting lower texturing.
- Improvements to this point allow very low dusting and surface texture. This allows better electricals between double printed layers. We are able to move to a double printed layer for a simpler screen formula and better process stability.

**Final Successful Production and Screen Recipe Result:**

Once the inks and substrates are stable, characterized and modified when necessary, ambient conditions under control and screen making methodology stable and in-house, press controls installed and mapped, chemical admixtures and curing known and mapped, viscosity and physics known and controlled enough we were able to use:

- High tension (28-32ncm) 305/34 Mesh
- 8-9µ EOM
- 3.0µ print side Rz, made with thinned direct emulsions
- 15-17µ Squeegee side Rz made with thinned direct emulsions.
- 65 durometer square profile molded edge blade,
- 60°stainless or anodized aluminum .090" thick floodbar with medium to fast flood and squeegee speed with normal Off-contacts and 0 Peel.
- Ink thinning held to 4% or less by weight with timed pre-shearing, exactly 5 minutes before printing begins. Ink is pulled from the screen every 30 minutes. Fresh ink is added every X impressions during print run between 0 and 30 minutes. Screen is kept 30% overfull at all times.
- Substrate is preheated/annealed to promote shrinkage, then rewound and cooled. Substrate acclimates for 24 hours on press room. Substrate must be used within a defined amount of time as it continues to move and change.

**The challenge with sensor #2:** While the trace widths and trace image shapes are not unique, there were multiple substrates in the design set. These substrates (very low temperature hot-melt TPU's and TPE's) had never been successfully used with printed circuit traces this fine even in R&D sample work. These substrates had only been previously successful with embedded wires and not printed traces. It also required a specific ink with a specific deposit thickness and narrow resistance range to be successful.

This required a wide range of testing to find the mesh/screen/stencil/settings recipe that would work on each substrate. The further testing of each substrate once robust printability was achieved was a second phase of testing.

This proof of concept, R&D for specification of screen recipe and on-press settings used a methodology that encompassed lessons learned from case study sensor #1 (and other projects) utilizing more complete parameter measurement of the constituent materials during the initial design experiments, the proof of concept phase, and the initial R&D sample batch phases and included the use of production or near equivalent equipment that could reproduce settings, scale and ambient conditions of the final destination production equipment for more accurate results faster and cheaper.

To incorporate the process lessons that were learned in device #1, the entire R&D print process was divided into sub-groups of R&D, each with a required proof of concept step. Each division had an initial purpose to discover the range of performance available to it with reference to the product that is going to be printed before it is released to be included as a viable material into the product or process design.

In short, the design engineering team can specify a range of materials or material parameters. However, these materials are not yet qualified to be integrated into the device design until performance, stability and handling ranges are tested. While pre-qualifying the suitability of a raw material a lot of data is also gathered toward how to print with this material and with what screen formulation. This usually limits/narrows the list of materials available and greatly shortens R&D time.

During these compartmented test phases the substrates are tested with the range of possible inks in a high/low, positive/negative fashion. During this phase a range of printed feature geometry, curing cycles, handling, cutting and a host of other parameters are tested. Once the materials are released for design specification the range of potential testing required for proof of concept models and initial sample batches is focused and more robust.

The other benefits of pre-testing in a compartmented fashion is that material pre-qualification can be done with any new materials even before device design is in play. This creates an engineering “library” of substrates and inks with known handling and screen parameters for a wide range of feature sizes, shapes and electrochemical requirements.

**Improved, Compartmentalized Process Flow:**

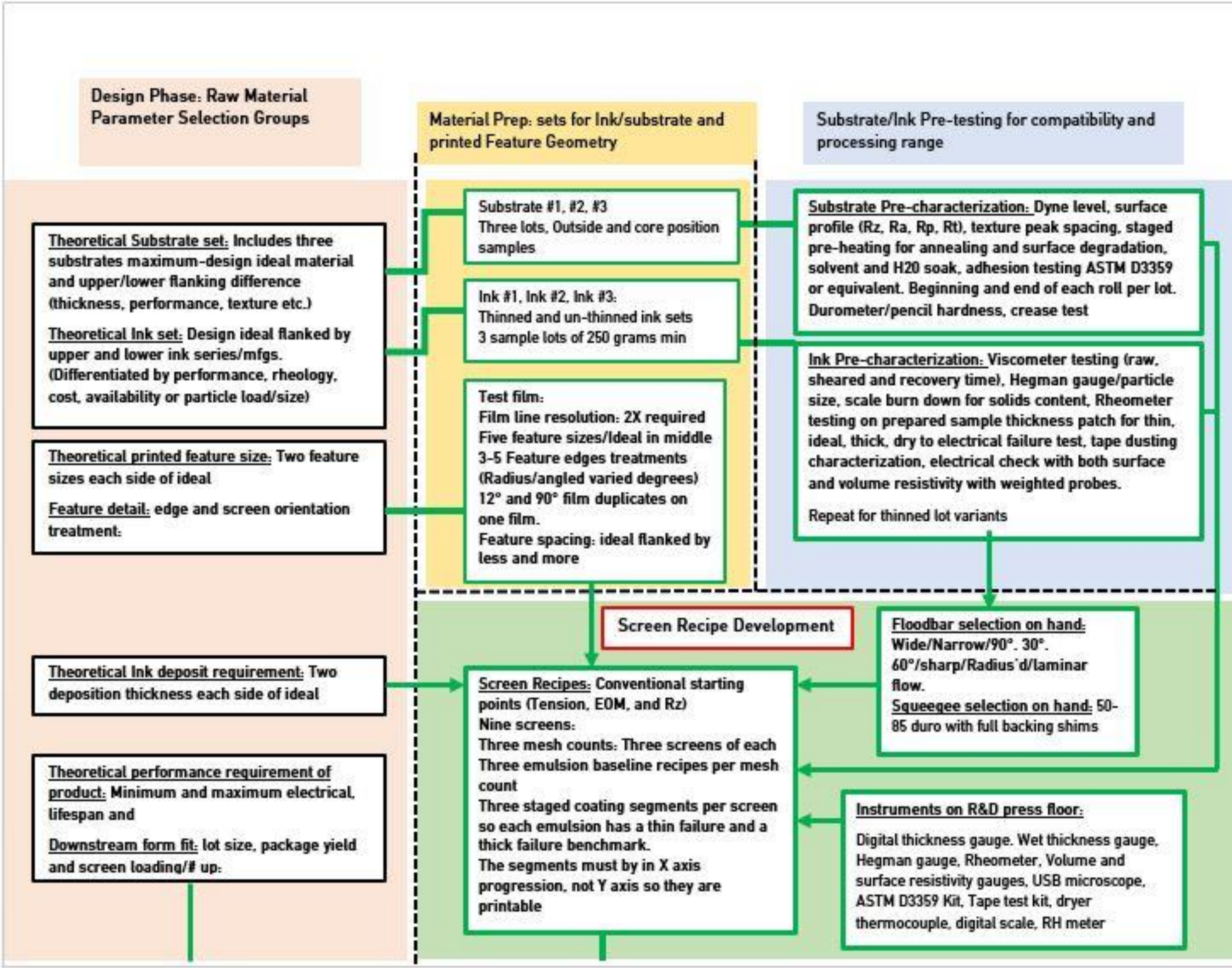



**Figure 3:** Process Stages Part A

If the above stages are properly performed, substrate and inks that have useful data for production requirements and performance can be made available to engineering design in advance. One does not have to wait until a design is pending to perform these tests and preparations.

With proper material test data and more accurate starting screen recipes, it is less common that we need to stop the process and return to the engineering design phase for redesign to fit production methods. The process can usually remain in the final testing, pre-production and first article phases listed below in Figure 4.

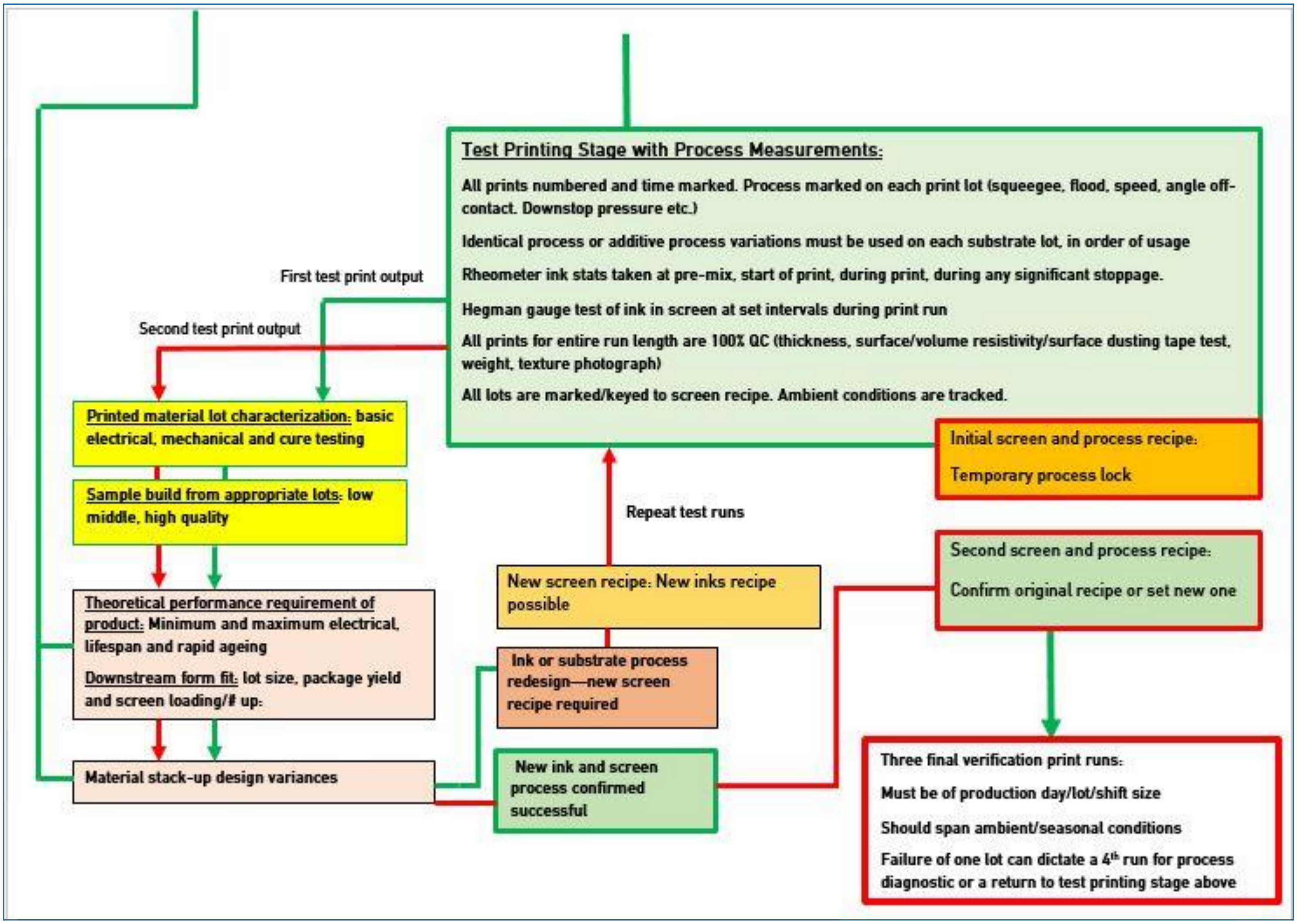



**Figure 4:** Process Phases Part B

# Screen Making for Printed Electronics

## A DOE Based Method for Developing Specifications and Tolerances

Ray Greenwood

HPCI Hazardous Print Consulting Inc.

# General Printed Electronics vs PCB/MPCB/CEM 1-3/Ceramic

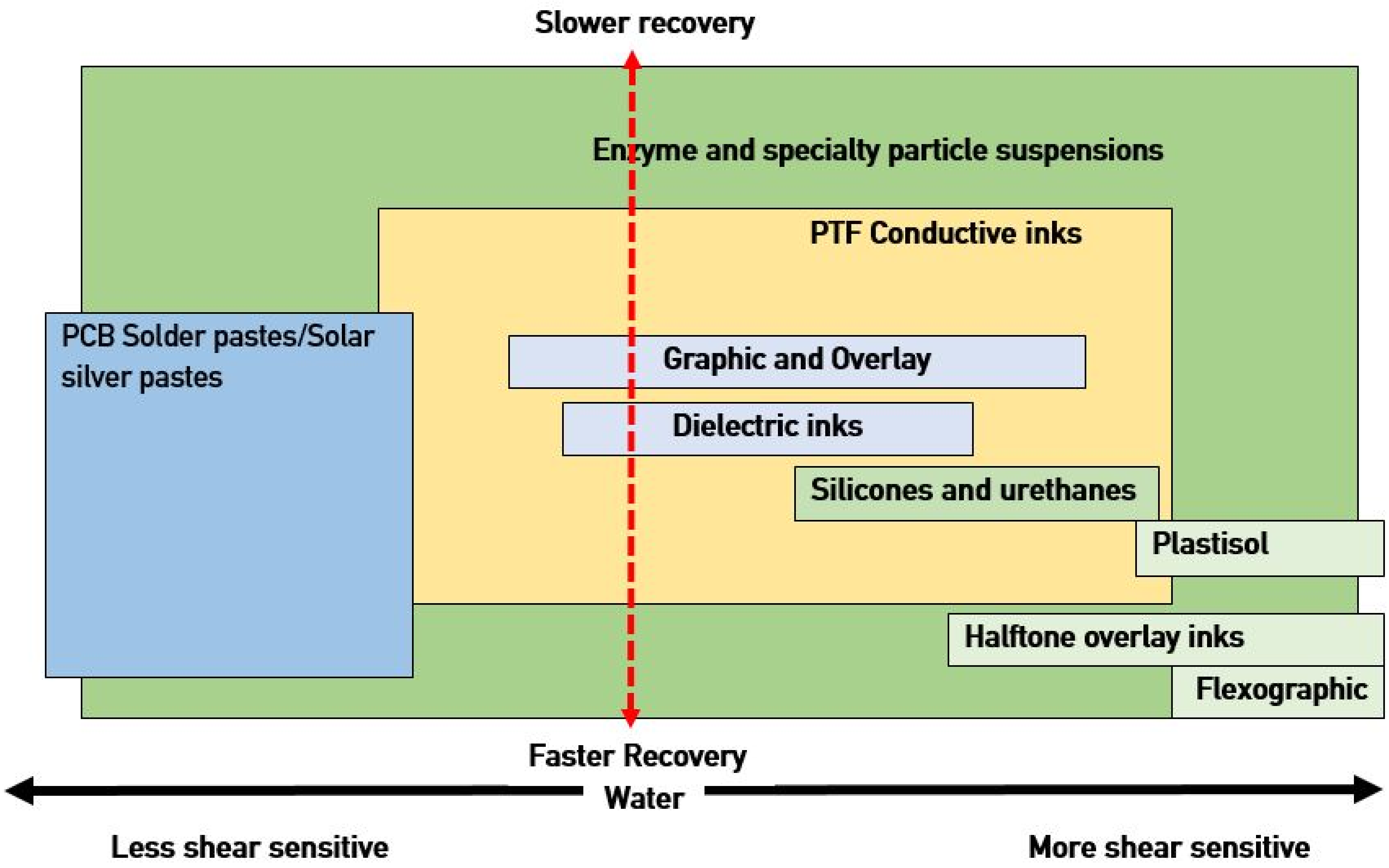
- **Non-Rigid Board PE Types:** Flex circuit, rigid/flex sensors (industrial, medical EC), membrane switch, wearables, deposition devices, functional liquid tech, surface mount
- **Substrate Materials:** metal, plastic, composite films, cloth, elastomers, in-mold insertion products, EC transfers and printed thermal circuits. Substrate hydrology is just as critical as ink rheology.
- **Ink Solids Loading:** Typically 80% or less of conductive particles, wide ranging viscosity, no limits on what can be considered an "ink"
- **Ink Thixotropy:** Most PTF inks are VERY non-Newtonian (shear based) ranging from shear thinning to shear thickening vs high metal solids inks like solder pastes and solar silvers that shear thin much less and are closer to being Newtonian
- **Wide ranging interactions with other print technology platforms**

# Viscosity and Thixotropy

- Thixotropy has no exact correlation to viscosity
- Thixotropy can be altered by particle type, shape texture and loading
- Both functional and non-functional ingredients can alter thixotropy
- Thixotropic and shear thinning/thickening are not equivalent but they are linked

# Viscosity and Thixotropy Ranges of Ink Types in PE

- Plastisol inks: 500,000 to 2,000,000
- Silicone/Urethane inks: 50,000 to 200,000
- PCB Solder paste/solar silvers 30,000 to 100,000
- Halftone inks: 15,000 to 50,000
- PTF conductive inks: 3000 to 30,000
- Dielectric inks: 3000 to 20,000
- Graphic/Overlay inks: 2000-10,000
- Flexographic-100 to 2000
- Water-75cPs
- Enzyme and specialty suspensions- 50 and up


Slower recovery
Enzyme and specialty particle suspensions
PTF Conductive inks
PCB Solder pastes/Solar silver pastes
Graphic and Overlay
Dielectric inks
Silicones and urethanes
Plastisol
Halftone overlay inks
Flexographic
Faster Recovery
Water
Less shear sensitive
More shear sensitive

# Common Printed Feature Sizes and Deposit Thicknesses

- **Rigid Board/Ceramic/Solar:** currently 25µm to 2000µm trace width with 3µm to 200µ finished deposition
- **Membrane Switch and Flex:** Currently 100µm to 3500µm trace width with 5µ to 350µ finished deposition
- **Printed Medical, Wearable and Specialty Sensors:** 5µm to unlimited for traces and pads with 2µm to unlimited finished deposition

# The High Variability of Printed Electronics

- Wide ranging deposit thicknesses required for different device types
- High degree of flexibility required of substrates and inks
- An increasing use of printed “solutions”/suspensions/liquids and coatings. In effect, non-standard inks. Some of these are conductive, some dielectric and some are functional in other ways
- The vast majority of flex/PTF inks, conductive or otherwise are highly thixotropic to some degree
- Due to the wide range of printable “liquids/pastes” used, the screen mesh technology and its requirements are also wider (polymer meshes of numerous types as well as wire mesh)

# Screen Tolerances- The Risks of Outsourcing Screen Making

- The final tension achieved in the tensioning chaise will rarely be exact to what is delivered
- Exact coating thickness accurate to +/- 1µm tolerance and with exact surface profile (Rz) can only be repeatably achieved by coating “up” to exact numbers or by the application of back coated film emulsion of exact thickness.
- Final tension and thread count affect both of the above
- Tolerances on outsourced screens are typically more generous as more exact tolerances require more production time and cost.
- The outsourced tolerance is usually a cost compromise and may not actually allow best uniformity of the printing process for some printed features, inks or substrates

# High vs. Low Tolerance-Examples for the R&D Process

- **Common outsourced screen specification tolerance:**

230/48 Yellow Polyester @ 30ncm +/- 2-3ncm (ideal design tension is 30ncm for this printed part)—**is a 4-6ncm spread**

7-10µm +/- 2µm EOM (ideal design EOM is 8µm for this printed part)—**this is a 4µm spread**

- **Tighter/Narrower screen specification tolerance:**

230/48 yellow Polyester @ 30ncm +2/-0ncm (ideal design tension is 30ncm for this printed part)—**This a 2ncm spread on the positive side of design tolerance only**

7-9µm +2/-0µm EOM (ideal design EOM is 8µm for this printed part)--**This a 2ncm spread on the positive side of design tolerance only**

# Screen Tolerances for the Pre- Production Print Process

**Once the sensitivities of the ink, substrate and printed feature are mapped:**

**A more Lenient tolerance to aid the outsource screen maker:**

230/48 yellow Polyester @ 32ncm +2-3ncm/-0ncm (ideal design tension is 30ncm for this printed part)

8-9µm +1/-0 (ideal design EOM is 8µm for this printed part)

- All tolerance spreads are on the positive side allowing for screen tension loss in shipment
- All minimum tension and EOM tolerances must be verified in R&D as above the “floor” of print viability

# Why are R&D Screen Tolerances More Critical?

- Exact screen parameters must be known so the cause of print effect is known during R&D
- Exact thread count and tension come FIRST as it affects EOM and press settings
- Stencil parameters must be exact and are affected by tension
- Screens that meet the specification exactly help to maintain control of the R&D momentum, test data and costs by limiting unknown variables that cause unforeseen results or cause R&D down time to order screens with new specs verify faults.

# Logistical R&D time loss related to outsourced screen variation:

**The Effects of outsourced screen shipping time delays:**

- Screen to Screen tolerance variation within a set
- Non-viable recipes due to stacked tolerance variation
- Screen parameter changes are delayed during the R&D process
- Repeatability of in process replacement screens

# Added Variables that Leverage or Magnify Process Changes

- **Ambient conditions:** Temperature, RH, static electricity, dust
- **Ink variation from lot-to-lot:** Viscosity, solids content, solvent to binder ratio (sometimes modified to adjust viscosity and particle loading), particle size, particle texture. All of this affects shear rate and drying and can affect texture, dusting and interlayer connectivity
- **Substrate and stencil hydrology/rheology combined with ink thixotropy:** substrate dyne level, texture, flatness, surface profile temperature and humidity level, outgassing, shrinkage. Many of the same parameters can affect the stencil surface as well.

Thk-Defibrilator_30.5µ Test Lots: 1 to 8 Center lot sample

Specifications:

Deposition: 30.5µm - 3.0µm over/0µm under Min: 30.5µm Max: 35.5µ

Surface silver dusting: <5µm

Pinhole: <25µm less than 2 per sq/mm

Texture: compare to QC sample grid

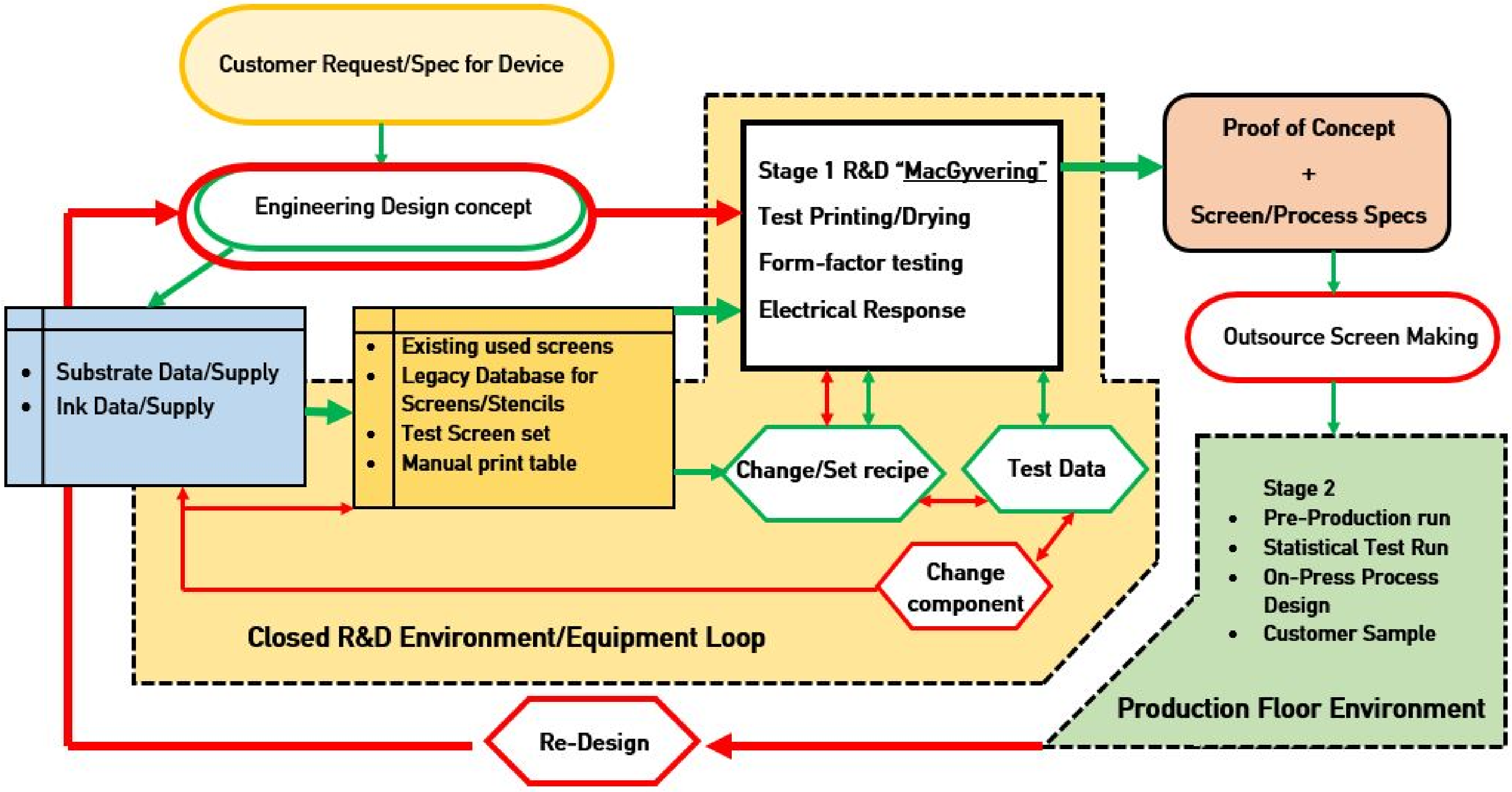
Screen spec: 1500 PET 230/48Y-32-33ncm-- 8-9µm EOM--PS-Rz: <4µm--Ss-Rz: <20µm

Setting: 65 duro ME blade-15°-100mm/s

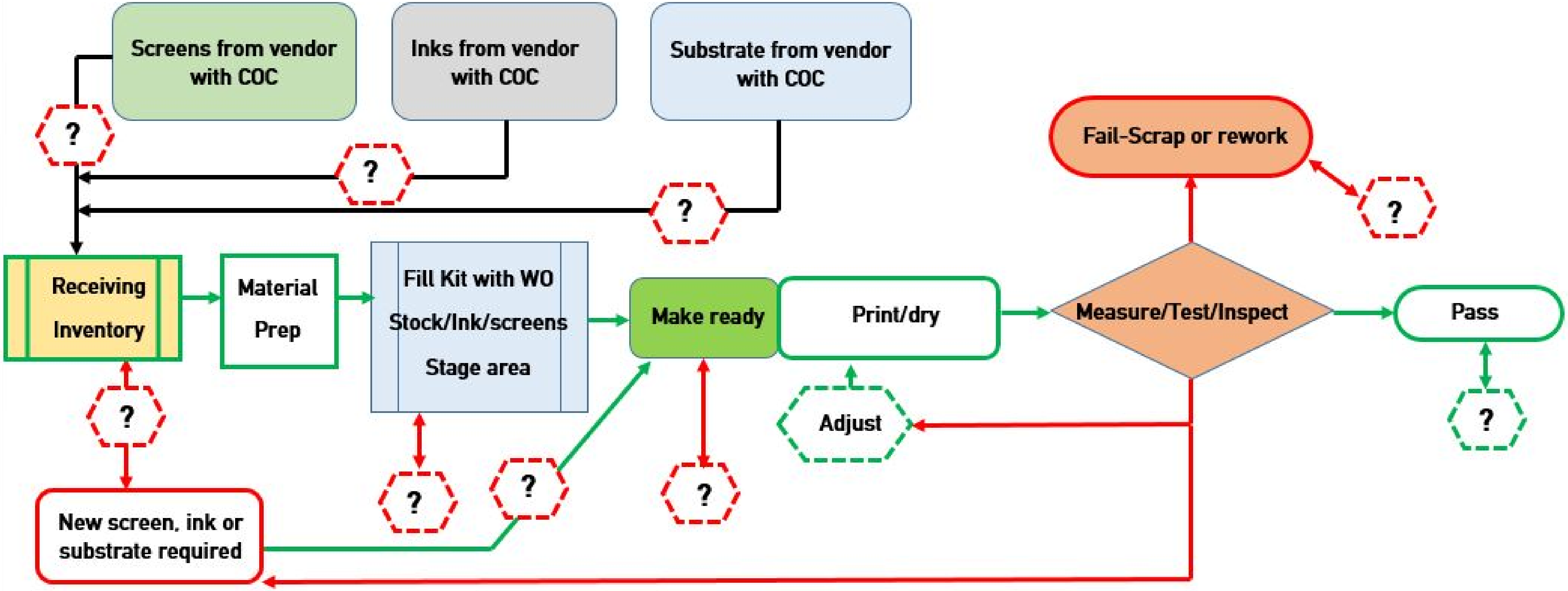
Flood: 10° Extended trail/.005" height setting- 100mm/s

| Print lot | Ink lot | Reducer | Sub lot | Rm temp | Ink temp | %RH | Dyne | deposit | Δ µm to spec | Feet | dust µm |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | KI/60X-1 | 2%DBE | Rm1825-8 | 83°F | 81°F | 55% | 42-43 | 32µm | pos 1.5 | 2300' | 3-5µm |
| 2 | KI/60X-1 | 2%DBE | Rm1825-8 | 85°F | 83°F | 43% | 40-41 | 34µm | pos 3.5 | 2000' | 2-3µm |
| 3.1 split lot | KI/60X-2 | 3%DBE | Rm1825-8 | 78°F | 80°F | 65% | 36-38 | 29µm | neg 1.5 | 1250' | 6-7µm |
| 3.2 | KI/60X-2 | 3.5%DB | Rm1825-8 | 76°F | 79°F | 70% | 38-39 | 27µm | neg 3.5 | 1250' | 5-6µm |
| 4 | KI/60X-3/4 | 2%DBE | Rm1825-8 | 87°F | 82°F | 48% | 42-44 | 31µm | pos 0.5 | 2100' | 3-5µm |
| 5 | KI/60X-4/5 | 2%DBE | Rm1825-8 | 83°F | 83°F | 50% | 44-42 | 31-32µm | pos .5-2.5 | 2100' | 3-5µm |
| 6.1 split lot | KI/60X-5 | 4%DBE | Rm1825-8 | 69°F | 77°F | 32% | 36-38 | 25-27µm | neg 3.5-5.5 | 1400' | 7µm |
| 6.2 | KI/60X-5/6 | 3.5%DB | Rm1825-8 | 70°F | 73°F | 35% | 36-38 | 28µm | neg 2.5 | 1400' | 4-5µm |
| 7 | KI/60X-6/7 | 2%DBE | Rm1825-8 | 81° | 79°F | 53% | 40-41 | 31µm | pos 0.5 | 2000' | 3-5µm |
| 8 | KI/60X-7 | 2%DBE | Rm1825-8 | 83°F | 81°F | 55% | 42-43 | 33µm | pos 2.5 | 1800' | 3-4µm |

# Common Legacy R&D Test Print Loop



# Pre-Production Print and Data Gathering Flow Chart




Common Print Process Flow

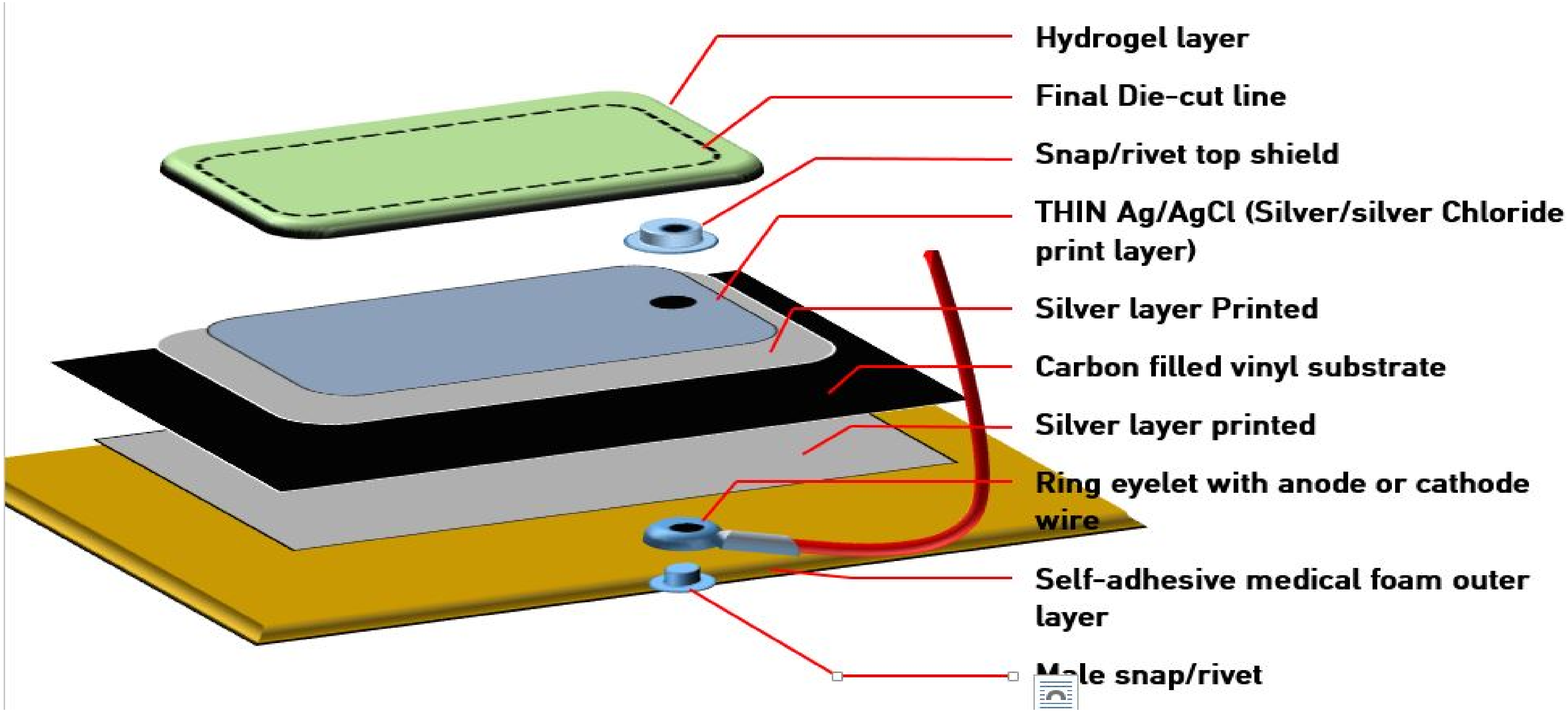
# Legacy R&D Method vs. Pre-Test DOE method: A Case Study

**The product:**

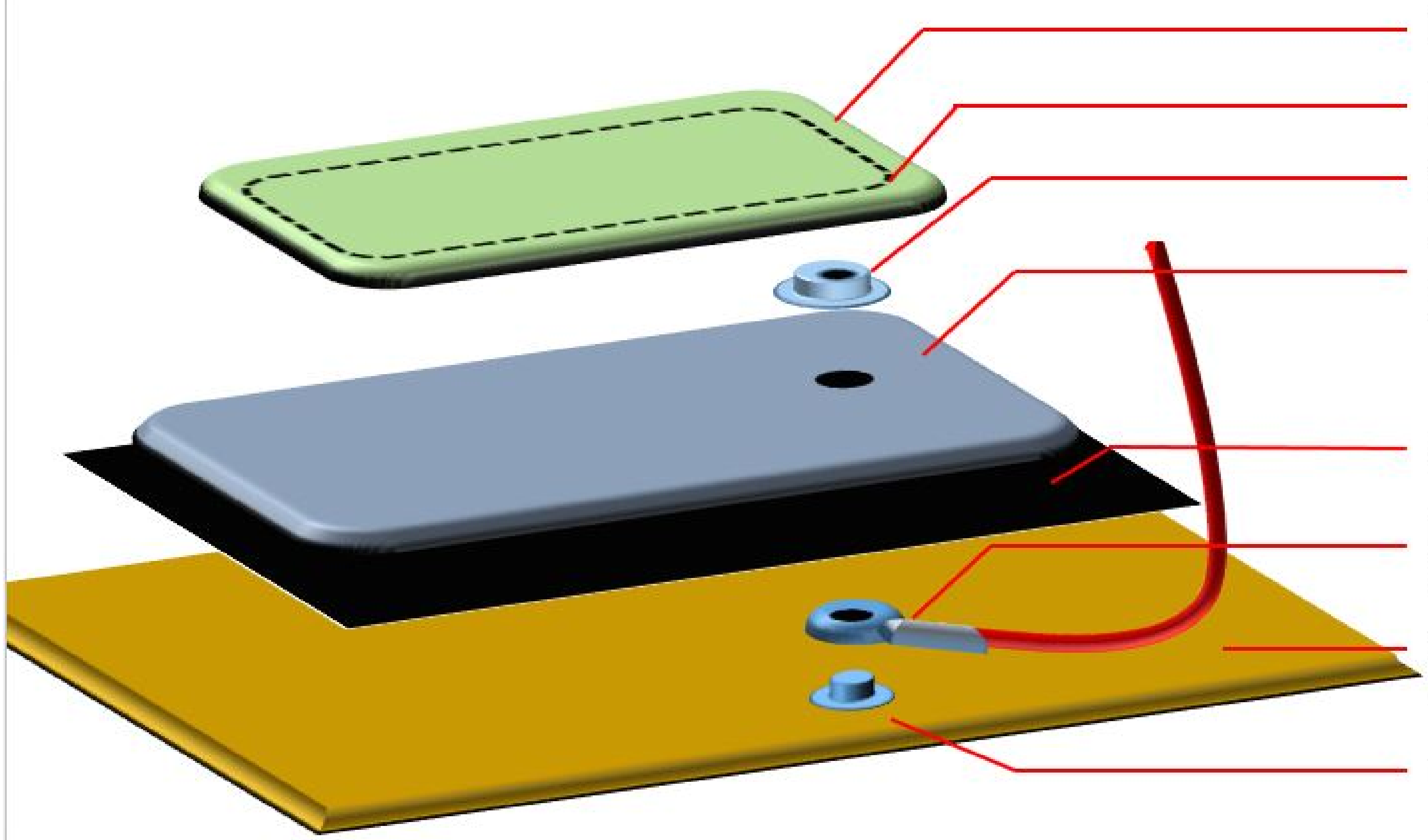
- Screen printed defibrillator pad on 3.5 mil Carbon filled vinyl with liner
- Conductive layer: 30.5µm Ag/AgCl dry/40µm wet deposition layer (high solids proprietary blend)
- Minimum surface dusting and porosity
- Must be accomplished by a single print pass
- Minimum surface texture to create "0" air voids between hydrogel and Ag/AgCl
- Roll-to-roll printing to produce source material for rotary converting
- 2.5 year span of R&D printing process

**New Product Benefit:** Three less print layers and less costly conductive ink

# Device Construction Stack-Up (Normal-Thin-Film Device)

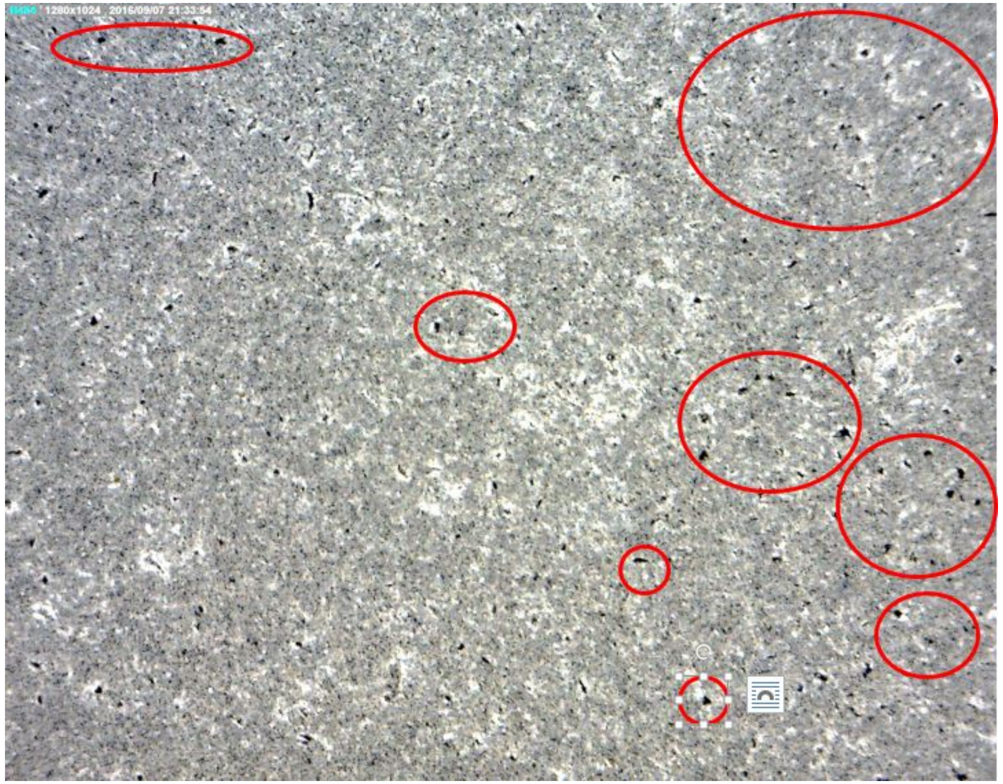


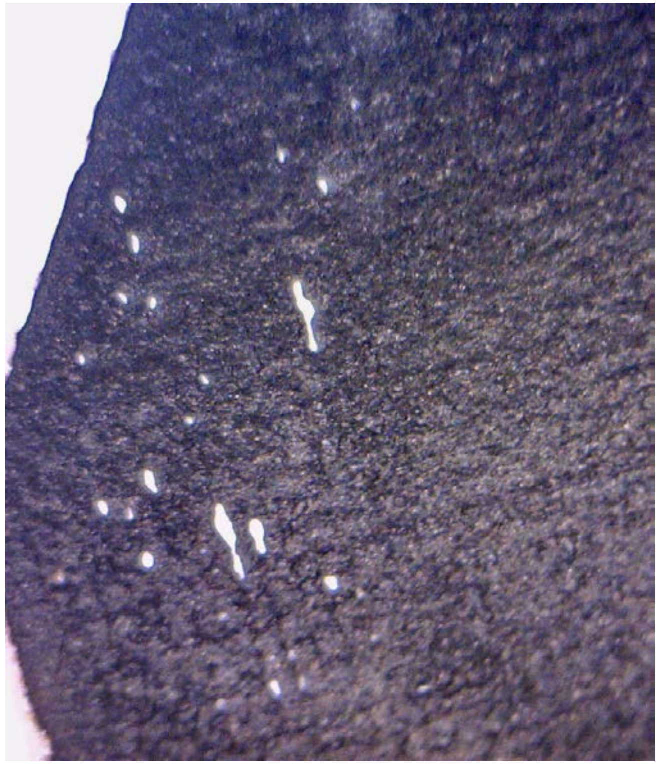
# Device Construction Stack-Up (Case Study Thick Film Device)



# R&D Primary Print Failure Points:

- Inability to print continuously. The ink transfer degrades (pin-holing and ink stripping from substrate) in as few 5-7 impressions.

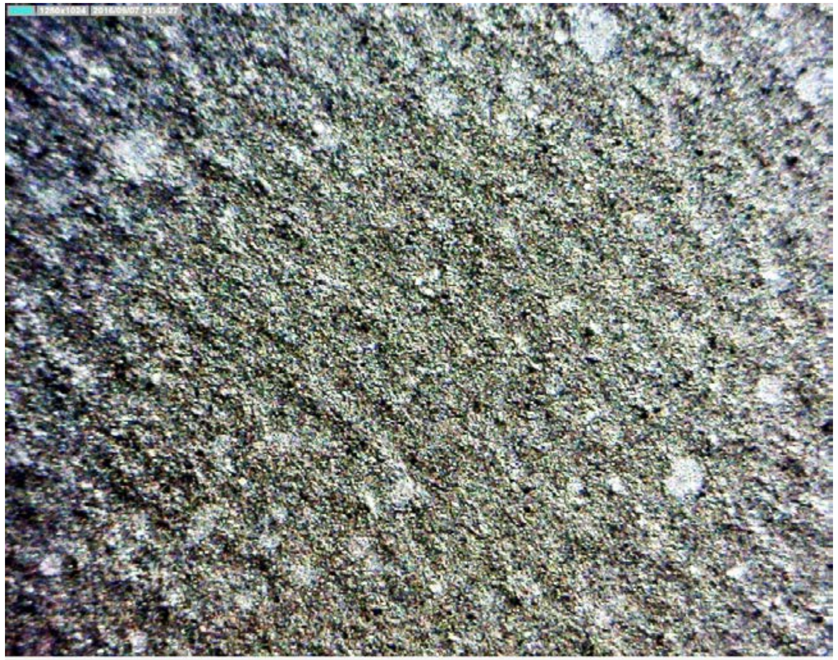




# R&D Secondary Print failure points:

**When continuous printing is actually achieved:**

- Ink deposit is poor (too thin….usually by 30-50%)
- Surface texturing is extremely high/rough

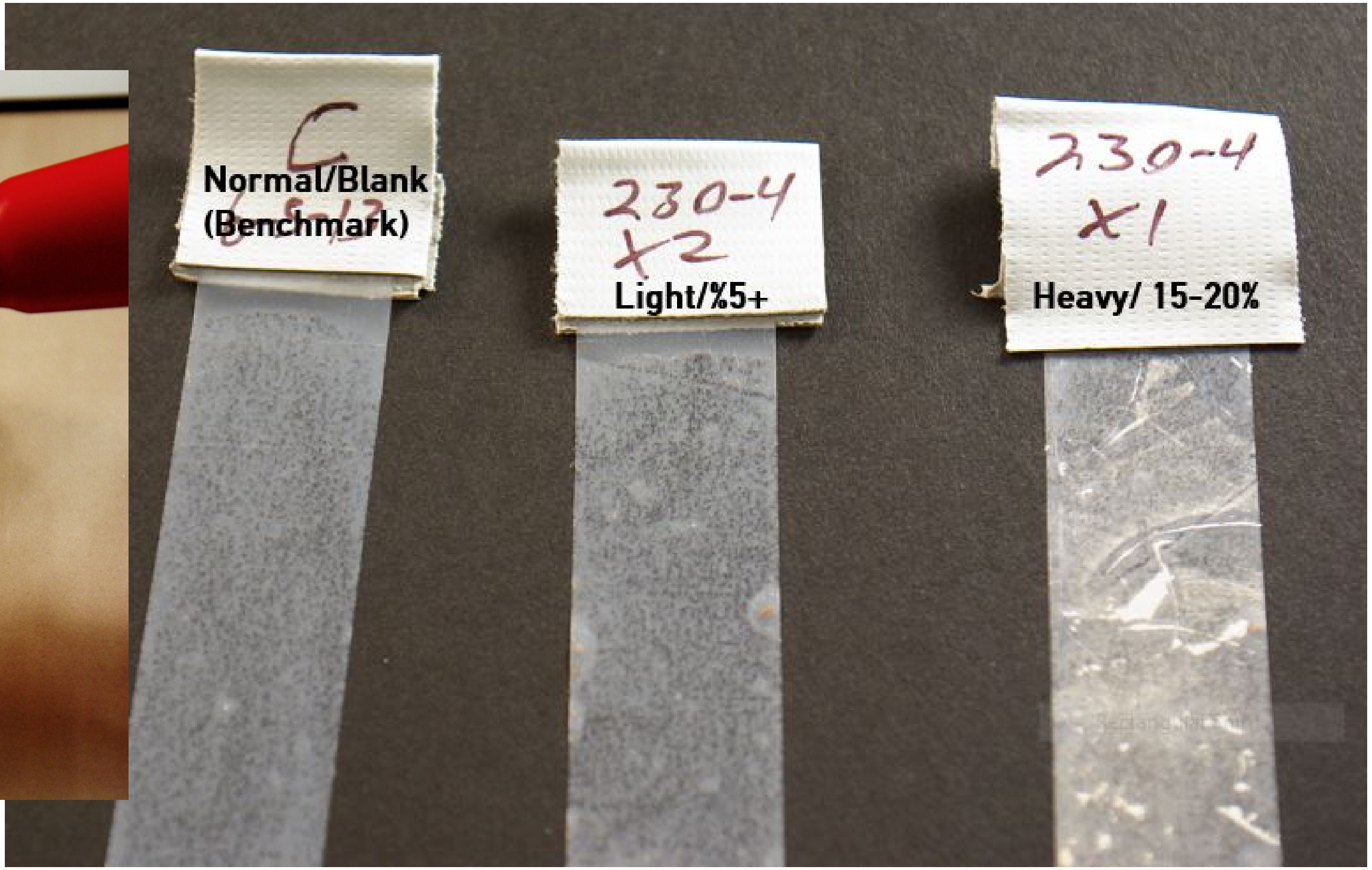


**Normal Texture 4µ-7µ**

**Poor Texture 15µ-20µ**

# R&D Secondary Print Failure Points:

- Excessive silver dusting/dross



# R&D Secondary Print Failure Points:

**Excessive curing time/slow print speeds caused by any of these:**

- moisture absorption
- solvent flashpoint issues
- porosity

**High resistance:**

- surface resistance and Volume resistivity/Conductance
- Poor electrical performance (pacing and defibrillation frequency)

# Conventional Wisdom Screen Recipe Starting Points Based on Hand R&D Drawdowns and Testing:

- **Screen recipe # 1:** 230/36 SS mesh@ 18-25ncm/ 23-25µ EOM

  70 duro cast/molded edge squeegee @ 18° from vertical/90° floodbar with .010" screen gap

- **Screen Recipe # 2:** 195/55 polyester @ 28ncm/ 25µ EOM

  70 and 85 duro cast/molded edge squeegee @ 18°-20° from vertical/90° floodbar with .010" screen gap

# A Two Year Snapshot of the Old/Legacy Method:

| SS Mesh | EOM | Tension | P-Side Rz | S-side Rz | Stencil | Variations |
|---|---|---|---|---|---|---|
| 325-30 | 10µ-25µ | 18-32ncm | 4-10µ | ND | D | 11 |
| 300-32 | 8µ-22µ | 18-25ncm | 3µF-10µD | ND | D and F | 8 |
| 325-36 | 12µ-21µ | 19-30ncm | 6µ-14µ | ND | D | 7 |
| 280-32 | 18µ-28µ | 19-26ncm | 4µ-8µ | ND | D | 13 |
| 270-36 | 20µ-30µ | 20-25ncm | 5µ-9µ | N D | D | 5 |
| 230-36 | 20µ-25µ | 18-25ncm | 3µF-8µD | ND | D and F | 4 |
| | NOTE 1: There was no on-site Rz or surface profile tool | | | | | 48 |
| | NOTE 2: Tension was not specified by the printer | | | | | |

| Poly Mesh | EOM | Tension | P-Side Rz | S-side Rz | Stencil | Variations |
|---|---|---|---|---|---|---|
| 305/34 | 8µ-18µ | 19-25ncm | 6-12µ | ND | D | 6 |
| 305/30 | 8µ-15µ | 18-25ncm | 5µ-10µ | ND | D | 9 |
| 330/30 | 11µ-17µ | 20-26ncm | 4-11µ | ND | D | 2 |
| 280/34 | 15µ-22µ | 23-28ncm | 5µ-11µ | ND | D | 10 |
| 280-32 | 10µ-18µ | 20-26ncm | 4µ-9µ | ND | D | 3 |
| 280/30 | 18µ-25µ | 20-25ncm | 3µ-8µ | ND | D | 3 |
| 255/40 | 15µ-23µ | 19-23ncm | 8-14µ | ND | D | 5 |
| 230/48 | 20µ-25µ | 18-25ncm | 3µ-13µ | ND | D | 13 |
| 230/40 | 18-27µ | 24-28ncm | 6µ-10µ | ND | D | 4 |
| 195/55 | 12-30µ | 26-30ncm | 8-12µ | ND | D | 9 |
| | | | | | | 64 |

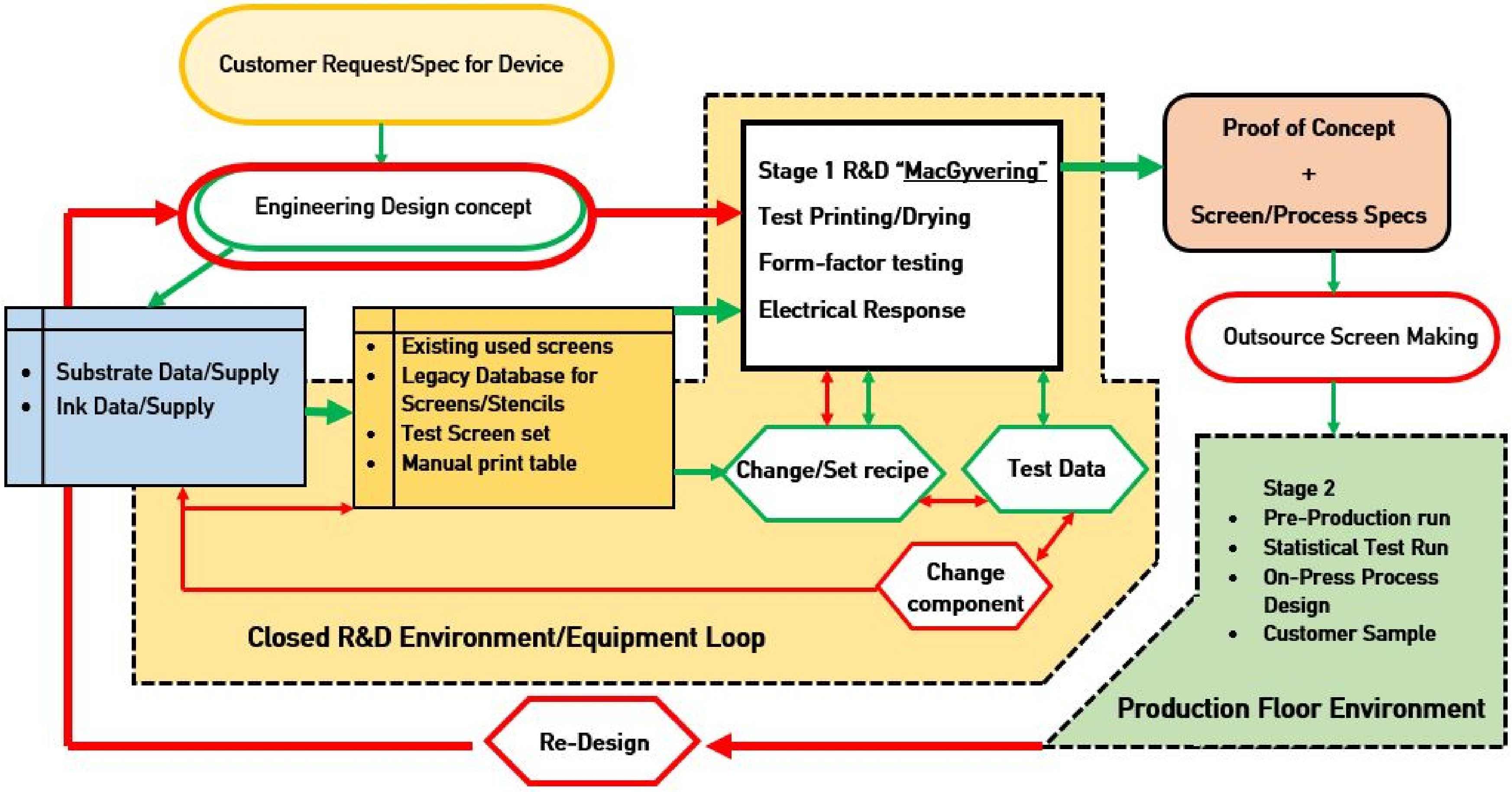
NOTE 1: There was no on-site Rz or surface profile tool

NOTE 2: Tension was not specified by the printer

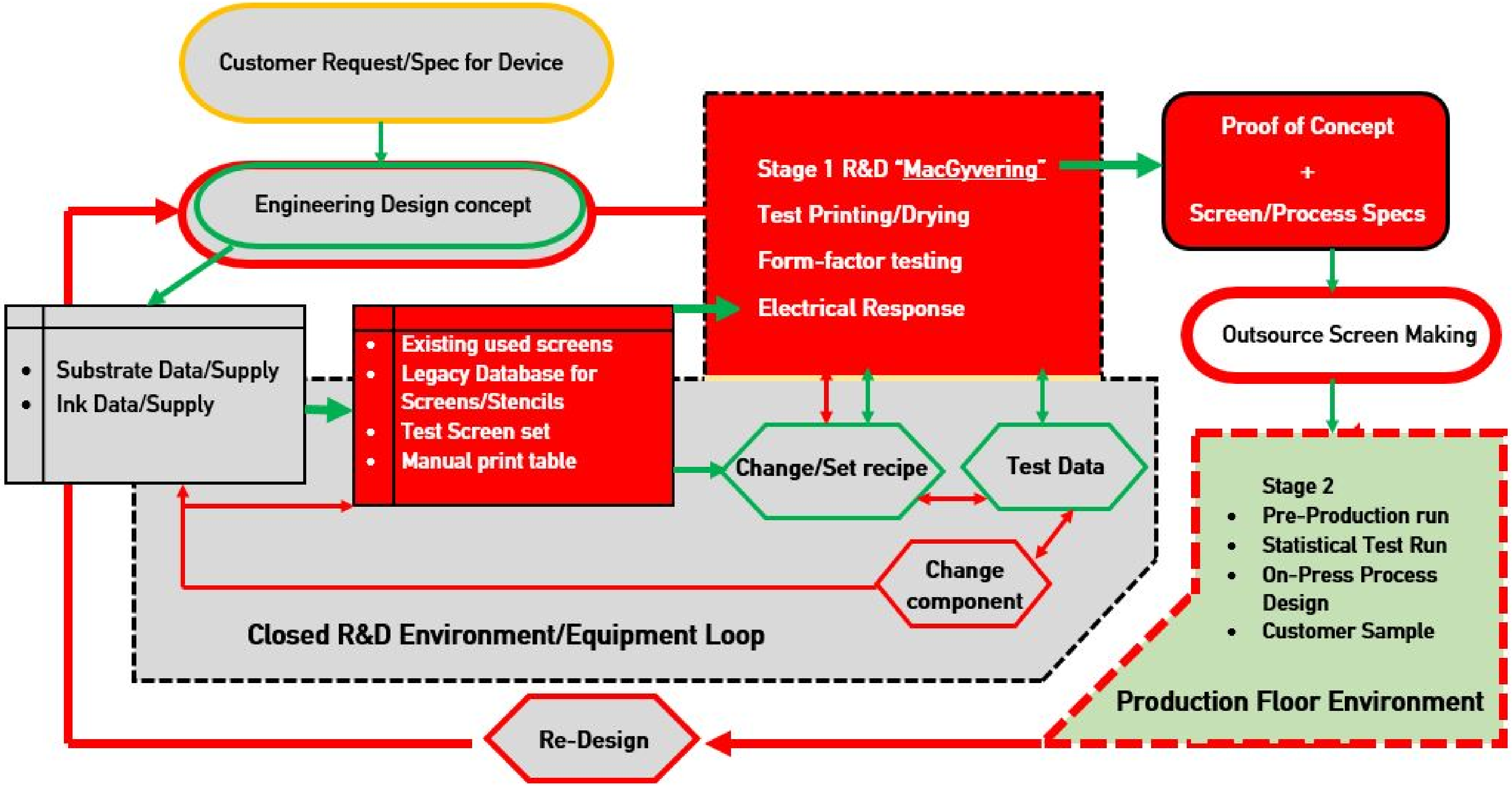
# Time and material costs:

- 112 screen variations
- 63 multi-screen print runs
- A minimum of 500’ of substrate per print run (an average of 1200’ per print run)
- Average usable sample(s) length 200’-300’ @ three parts per foot.
- Ag/AgCl Ink usage per print run is 1.5 Kilos minimum (2.0 kilos nominal), 300-400 grams of Ag/AgCl loss per run to recycle (at $900-$1200 per kilo)
- Each substrate roll required one annealing pass at print speed of 15 fpm
- The machine requires two operators
- Set up and rewind time is 1.5 hours
- In short, every sample run with annealing, adjusting and screen changes is 8 hours average.

# The problem points with the legacy R&D method

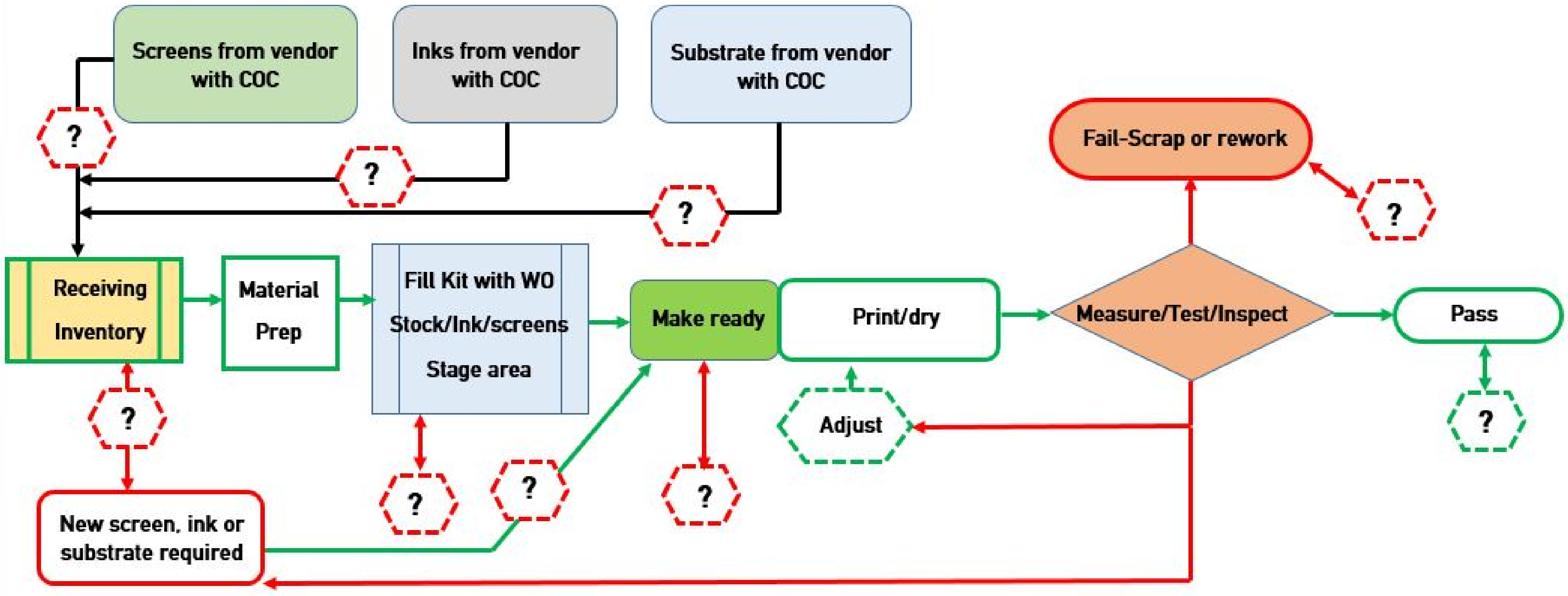


# The Initial R&D Phase Root Cause Failure Points



# Pre-Production Qualifying and Sample Print Runs

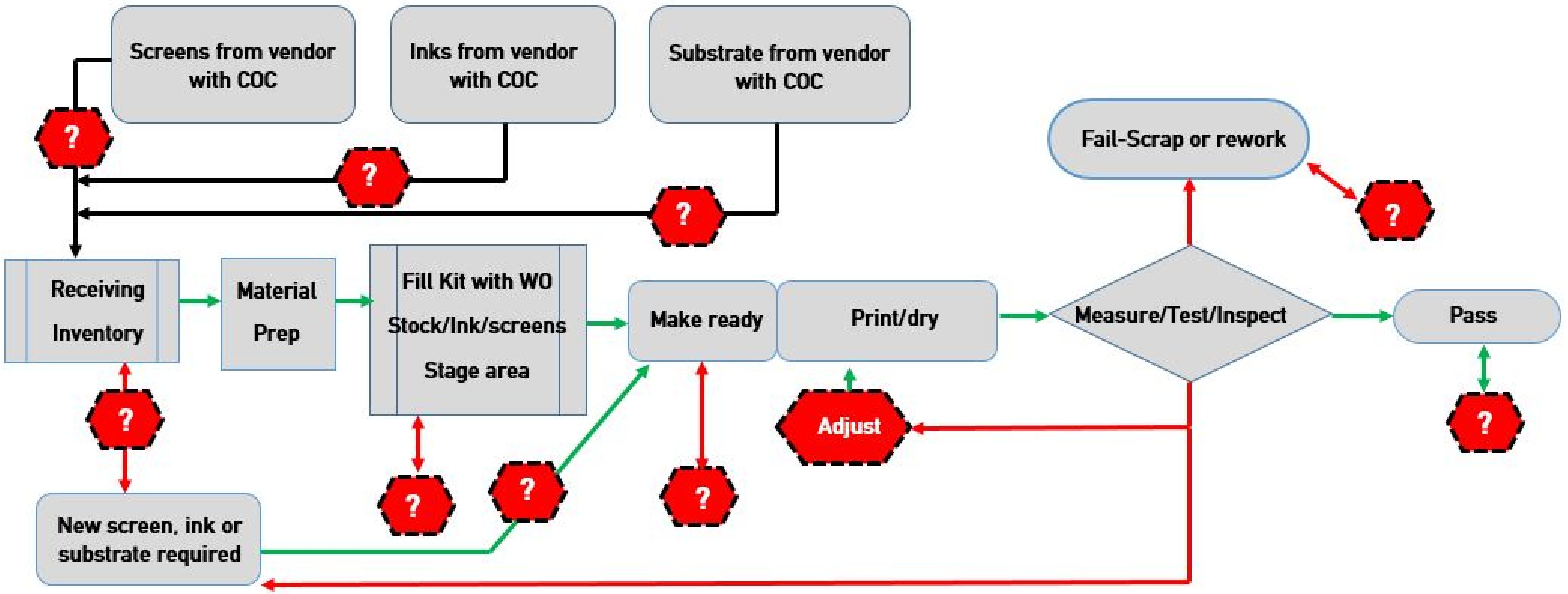
- Large Costly print runs planned with flawed/incomplete data from R&D and proof of concept printing




Common Print Process Flow

## Data Gathering Opportunities:

- Many were missed or assumed to have been logged in the proof of concept stage
- These same measurements must be performed at all stages to verify data for recipes



# Legacy Process Detail Flow Phases 1 and 2

**2.5 year timeline**

### Mesh/Screen Recipe baselines

SS-224/100-Low Tension single pass
SS-140/75-Low Tension single pass
SS-118/56-Low Tension single pass
P-255/40-Low Tension single pass
P-240/40-Low Tension single pass

SS-300/65-Low Tension double pass
P-305/31- Low Tension double pass
280/34- Low Tension double pass
330/34 Low Tension double pass
195/48 Low Tension double pass
230/40 Low Tension double pass

### Print Failure Items

- Ink lock-up (shear thickening)
- Ink dilatancy
- Pin-holing
- Waffle texturing
- Surface porosity
- Surface Dusting
- Poor adhesion
- Variable resistance
- Variable ink deposit
- Poor Screen life
- Poor squeegee life
- Poor edge definition
- Incursions/excursion of edges
- Emulsion failure (solvent)
- Highly variable ink usage
- Lot-to-lot ink variation (particle load and size)
- Lot-to-lot substrate variation (texture, thickness)

### Technical upgrades/Change Agents

- Standard 90° floodbars
- squeegee– 55/70/85 durometer
- 50mmx 10mm Serilor squeegee 70/90/70- 65/90/65, 50, 65, 70, 80
- Cut and sharpened squeegees
- Cap and direct emulsion all screens made outside of company

**Phase 1 process Model advances**

- Shims made for positive off-contact control
- Squeegee backing shims installed
- Flood bar mounts made more rigid (bending)
- Flood angle controls augmented
- Off-contact flatness gauge built
- Substrate work hardening process
- Substrate thickness characterization

**Phase 2 process Model advances**

# Legacy Process Detail Flow Phases 3, 4 and 5

195/55-High tension/double/single pass
230/48-High tension/double/single pass
280/31-High tension/double/single pass
305/40-High tension/double/single pass

156/64-High tension/single pass
137/79-High tension/single pass
123/70-High tension/single pass
110/80-High tension/single pass

- Ink lock-up (shear thickening/dilatancy)
- Pin-holing
- Surface porosity
- Surface Dusting
- Variable resistance
- Variable ink deposit
- Poor squeegee life
- Highly variable ink usage
- Lot-to-lot ink variation (particle load and size)
- Lot-to-lot substrate variation (texture, thickness)

- Tension meter, Thickness gauge and wet thickness gauge purchase
- Rz meter purchase
- Screen making brought in-house (image and coat)
- Addition of wide floodbar profiles
- Molded edge squeegees
- Substrate texture augmentation
- Ink Ag/AgCl ratio characterization
- Ink electrical characterization
- Ambient conditions testing begins

Phase 3 process Model advances

Phase 4 process Model advances

110/80-High tension/single pass/high density emulsion augmented Rz/extended tail wide floodbar/ molded edge blade

- Poor squeegee life
- Slightly variable ink usage

Thick film Process Success!

- Screen stretching brought in house (Roller Frame)
- Microscopic and viscosity inspection implemented
- Screen work hardening implemented
- Laminar flow flood bars
- D-min/max and feature radius test positives
- Rz augmentation
- Ambient conditions controls

Phase 5 process Model advances

# Legacy Process Detail Flow Phases 6 and 7

## Device Design Changes Driven by Process Improvements Allow Thinner Deposition (new process variation)

195/55-High tension/single pass
230/48-High tension/single pass
305/31-High tension/single pass
355/31-High tension/single pass
305/34-High tension/single pass

- Surface porosity
- Surface Dusting
- Variable ink deposit
- Poor squeegee life
- Highly variable ink usage
- Interlayer porosity
- Variable resistance

- Ink time batching
- Cure time/thickness profiling to failure
- Square profile disposable squeegees 50, 60.70.80 durometer
- Ink particle size/Texture profiling

Phase 6 process Model advances

195/55-High tension/double pass
230/48-High tension/double pass
305/34-High tension/double pass

- Surface Dusting
- Variable ink deposit
- Highly variable ink usage

- Ink viscosity testing
- Ink Thinning and pre-shearing
- Ink time-outs
- Double layer printing
- Squeegee side Rz augmentation

Phase 7 process Model advances

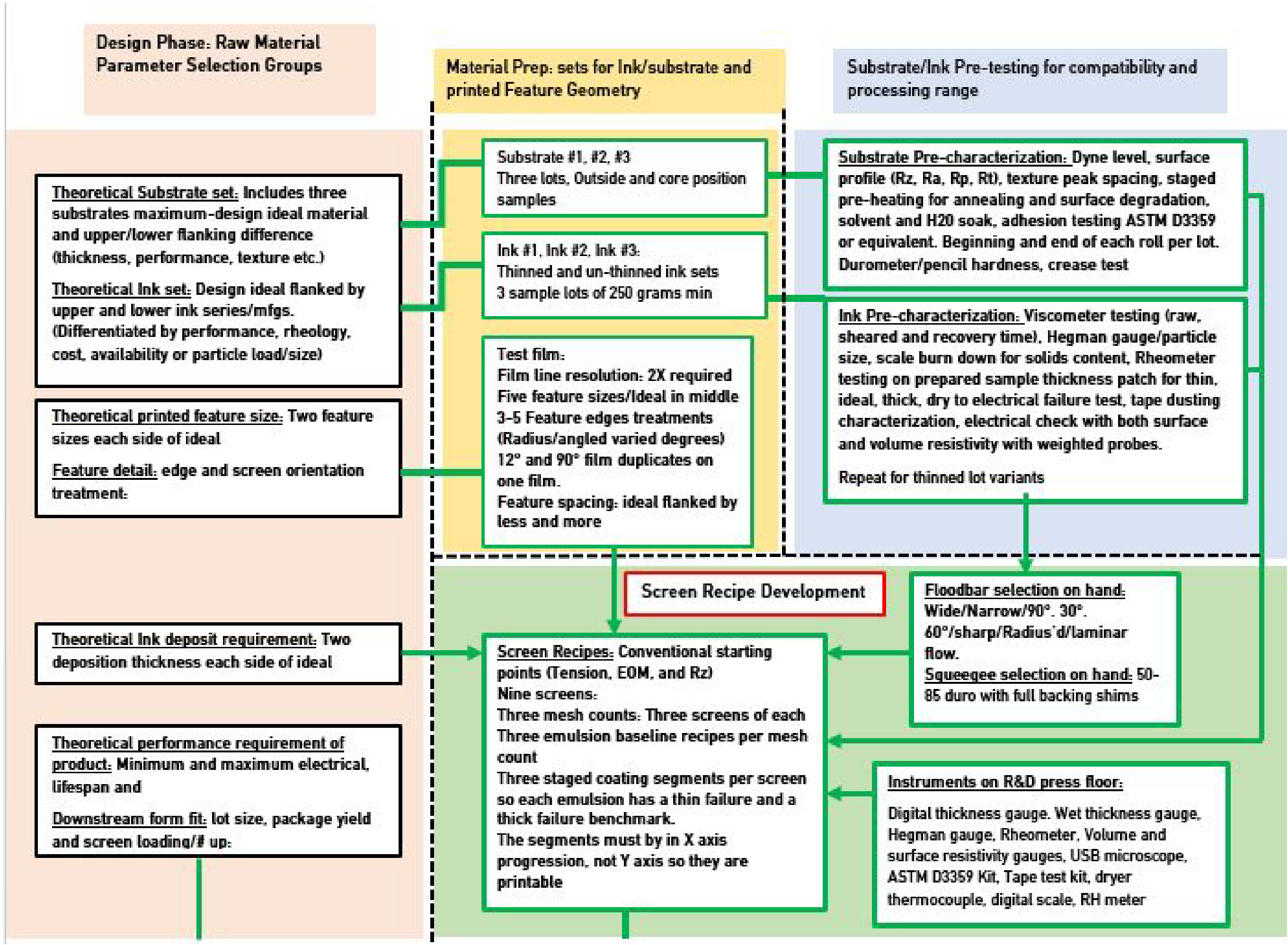
# Legacy Process Final Production Process Recipe

**Double Print 75% ink film thickness Success**

305/34-High tension/double pass/lower finished thread count/thinner emulsion with optimized squeegee side seal/ink optimized/high shear, wide floodbar/65 duro squeegee

Final process
Model advances

# Improved Compartmentalized/Semi-DOE R&D Method



# Design Phase Raw Material Pre-Test Selection Groups

**Design Phase Pre-Test critical item groups:**

Theoretical Substrate set: Includes three substrates maximum-design ideal material and upper/lower flanking difference (thickness, performance, texture etc.)

Theoretical Ink set: Design ideal flanked by upper and lower ink series/mfgs. (Differentiated by performance, rheology, cost, availability or particle load/size)

Theoretical printed feature size: Two feature sizes each side of ideal

Feature detail: edge and screen orientation treatment:

**Pre-test material acquisitions:**

Substrate #1, #2, #3
Three lots, Outside and core position samples

Ink #1, Ink #2, Ink #3:
Thinned and un-thinned ink sets
3 sample lots of 250 grams min

Test film:
Film line resolution: 2X required
Five feature sizes/Ideal in middle
3-5 Feature edges treatments (Radius/angled varied degrees)
12° and 90° film duplicates on one film.
Feature spacing: ideal flanked by less and more

**Material Pre-test and equipment pre-sets:**

Substrate Pre-characterization: Dyne level, surface profile (Rz, Ra, Rp, Rt), texture peak spacing, staged pre-heating for annealing and surface degradation, solvent and H20 soak, adhesion testing ASTM D3359 or equivalent. Beginning and end of each roll per lot. Durometer/pencil hardness, crease test

Ink Pre-characterization: Viscometer testing (raw, sheared and recovery time), Hegman gauge/particle size, scale burn down for solids content, Rheometer testing on prepared sample thickness patch for thin, ideal, thick, dry to electrical failure test, tape dusting characterization, electrical check with both surface and volume resistivity with weighted probes.

Repeat for thinned lot variants

# Raw Material and design Parameters Drive Screen Recipes

less and more

**Theoretical Ink deposit requirement:** Two deposition thickness each side of ideal

**Theoretical performance requirement of product:** Minimum and maximum electrical, lifespan and

**Downstream form fit:** lot size, package yield and screen loading/# up:

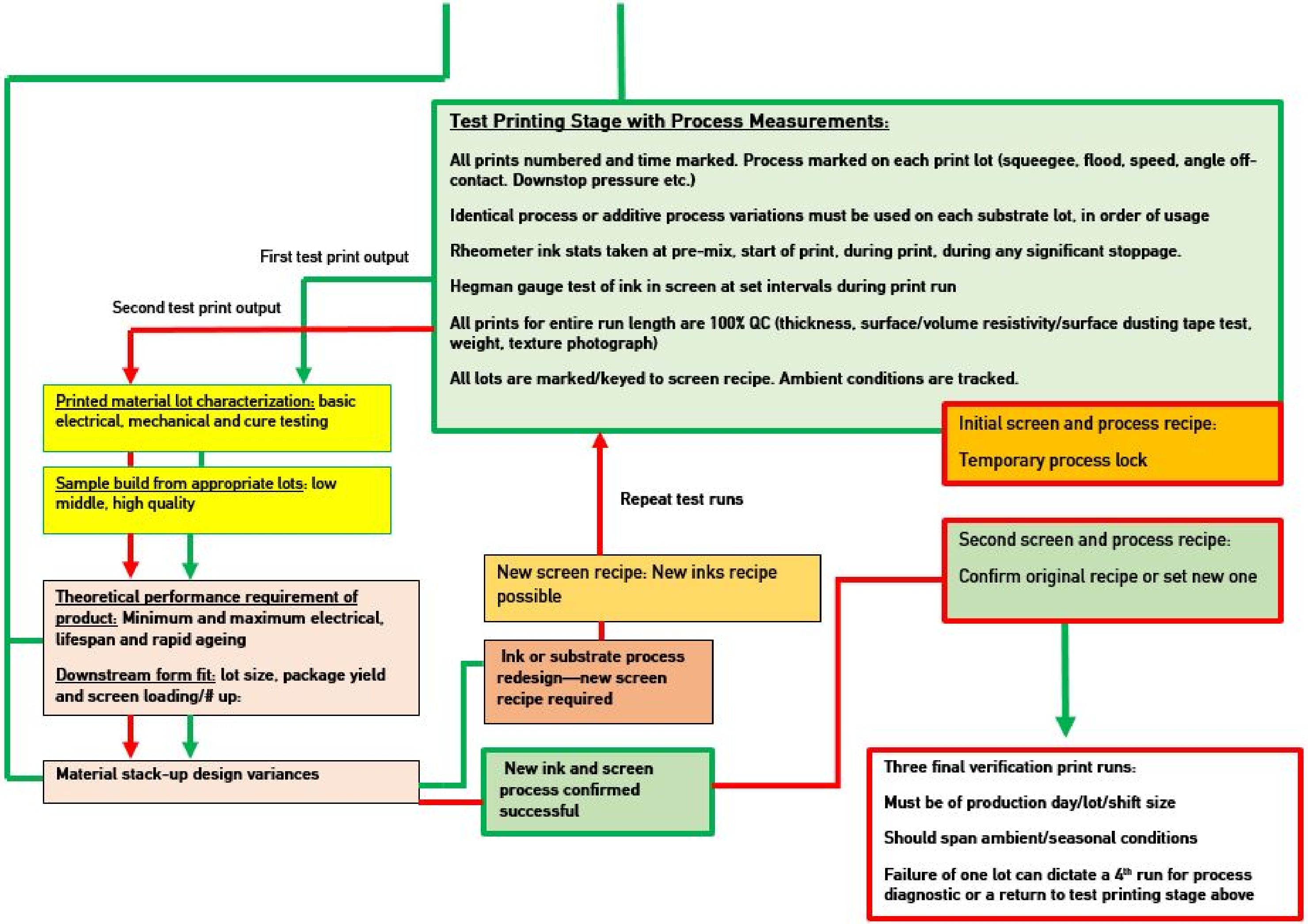
**Screen Recipes:** Conventional starting points (Tension, EOM, Rz)
Nine screens:
Three mesh counts: Three screens of each
Three emulsion baseline recipes per mesh count
Three staged coating segments per screen so each emulsion has a thin failure and a thick failure benchmark.
The segments must by in X axis progression, not Y axis so they are printable

**Floodbar selection on hand:** Wide/Narrow/90°. 30°. 60°/sharp/Radius'd/laminar flow.
**Squeegee selection on hand:** 50-85 duro with full backing shims

**Instruments on R&D press floor:**

Digital thickness gauge. Wet thickness gauge, Hegman gauge, Rheometer, Volume and surface resistivity gauges, USB microscope, ASTM D3359 Kit, Tape test kit, dryer thermocouple, digital scale, RH meter

# Production Testing, Printing and Sampling Runs



# Initial Print Run and Measurements

**Test Printing Stage with Process Measurements:**

All prints numbered and time marked. Process marked on each print lot (squeegee, flood, speed, angle off-contact. Downstop pressure etc.)

Identical process or additive process variations must be used on each substrate lot, in order of usage

Rheometer ink stats taken at pre-mix, start of print, during print, during any significant stoppage.

Hegman gauge test of ink in screen at set intervals during print run

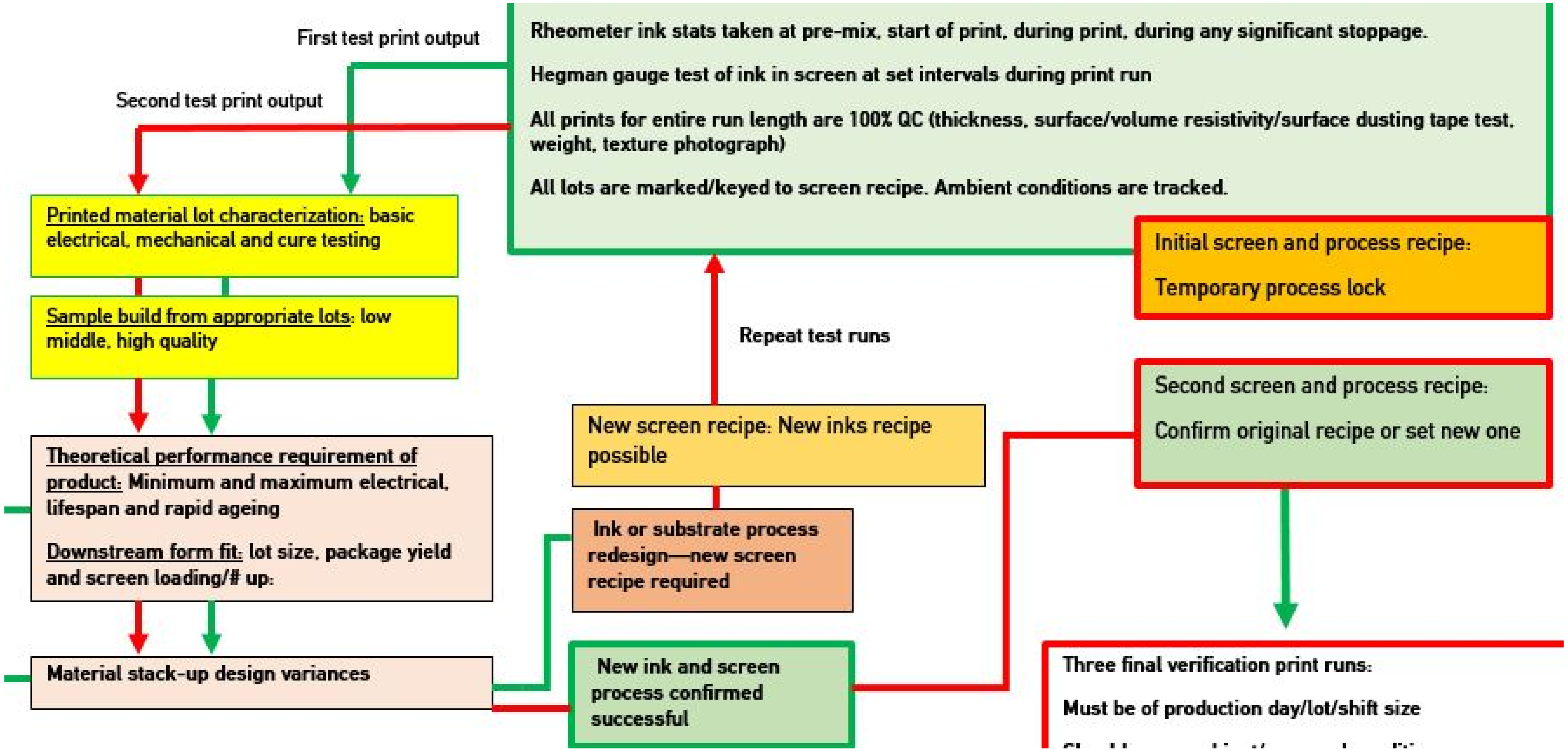
All prints for entire run length are 100% QC (thickness, surface/volume resistivity/surface dusting tape test, weight, texture photograph)

All lots are marked/keyed to screen recipe. Ambient conditions are tracked.

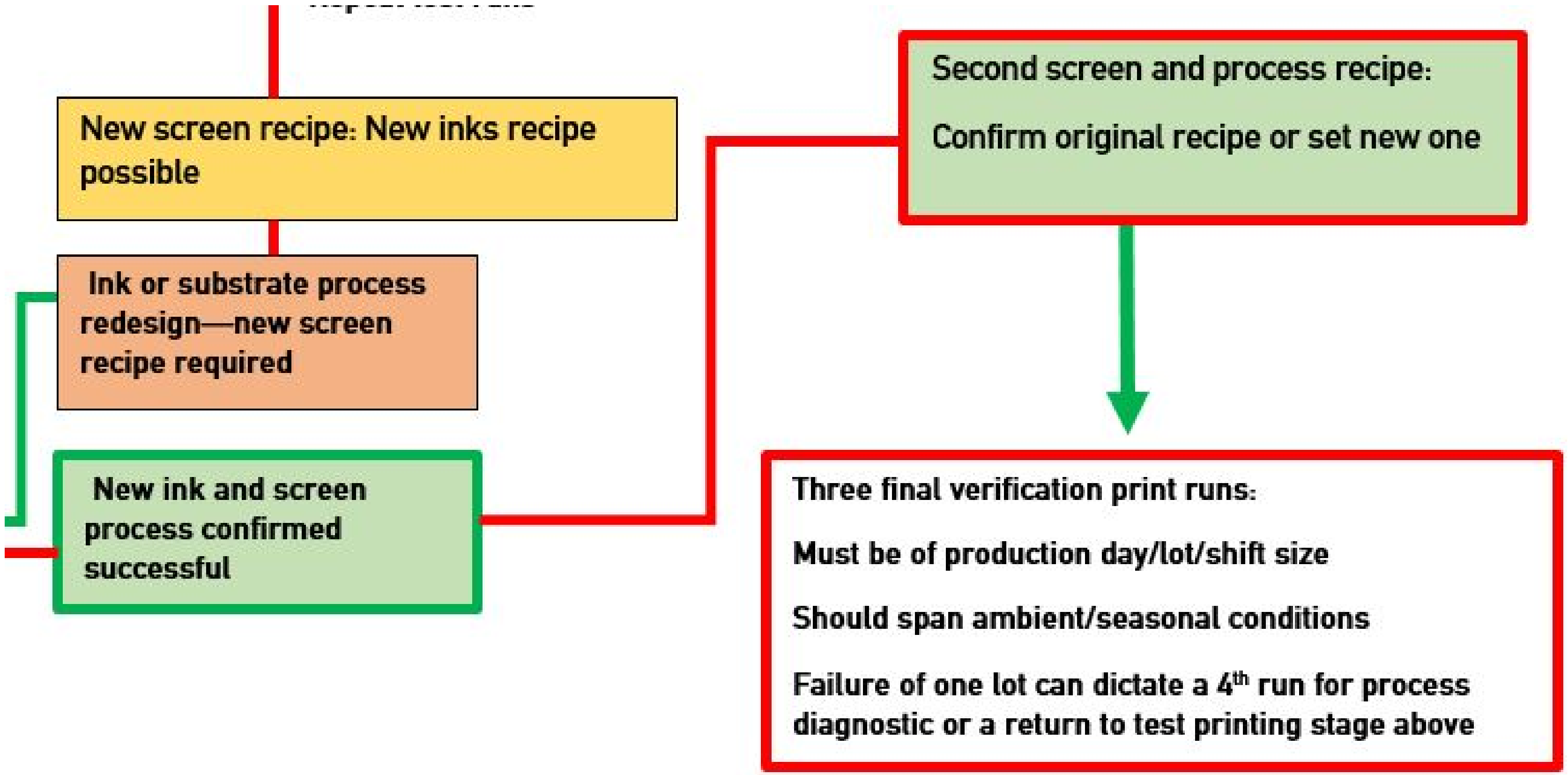
Initial screen and process recipe:

Temporary process lock

# Testing/New Screen and Process Recipe/New Print Run



# Final Sample Runs and Statistical Qualification Runs



# Thank you!

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**Academy of Screen and**

**Digital Printing Technologies**

# Appendix

- What does this amended method do?
- Benefits of a better R&D method
- Basic starting points
- Equipment issues
- Material and ambient conditions

# What does this method prevent?

- Product designs, screen and process recipes that may produce a proof of concept but cannot sustain production
- Product designs, screen and process recipes that may produce a "first article" in limited batch production by have variable characteristics related to unknown material deficiencies
- The need to return to the design phase to correct material or process deficiencies that can be solved in the R&D/Development phase

# What Other benefits Does it Produce?

- **An in-house library of data:** on the performance capabilities of substrates and inks with reference to image feature shapes, deposition thickness, electrical response and downstream processing hazards for your designers and engineers to draw from when both standard and non-standard devices are submitted for production.
- **The tools and methodology required:** to more quickly test, validate and adapt screen and process recipes to new inks and substrates that do not fit any existing reference.
- **A combined empirical and data driven method:** for greatly shortening the R&D process from proof of concept to first article to continuous production while simultaneously lowering its cost and providing hard documentation and measureable samples of success and failure points.

# What Basic Steps are Required?

**At the Proof of Concept stage:**

- **Testing for Lot-to-lot consistency of substrate and inks:** What is our range of sensitivity to viscosity, solids content, tack level etc. FOR THIS DEVICE DESIGN…not just visually or materially similar designs
- **Testing for the ranges of ink additives:** (thinners, thickeners, defoaming agents etc.) to conductive and dielectric inks allowed before the ink fails in THIS APPLICATION ON THIS SUBSTRATE AT THIS INK DEPOSIT THICKNESS
- **Tracking or controlling ambient conditions:** and the effect on inks and substrates WITH THIS DEVICE DESIGN (heat, humidity, dust etc.)
- **Establishing ink usage rules:** (screen charge change-out rates) for each ink along with the ability to blend in recycle with fresh ink to keep costs stable.

**In short: Equipment asymmetry gaps and failure mode testing and analysis**

# Avoid Using Different Equipment for R&D and Production

- **Establish guidelines:** for the minimum and maximum ranges of on-press adjustments for the main process line and duplicate those in your first article/R&D print machine
- **Standardize:** baseline physical screen specs for your main process line (screen size, image-to-free mesh ratio, min and max off-contact, off-contact increments etc.)…and duplicate those in your first article/R&D machine cell.
- **Control and monitor:** ambient conditions and drying/curing capability of your main production line and duplicate those conditions for your first article/R&D environment

# Pre-Test Materials and Control Ambient Conditions

- **Material intake:** Inks will need to be tested for: what their at-rest/out of the can consistency is (viscosity, tack-level, solvent to solids ratio etc.)…
- **Performance testing:** and then tested for what their differences are when sheared/mixed, thinned or thickened by design or contaminated by usage/ambient conditions/solids depletion or oxidized by age (shelf life).
- **Benchmarks:** A “new lot” baseline test set should be established to discover the natural range of variation whenever a new lot is opened. The temperature and cure rate with regard to conductivity and resistance vs over-cure and loss of conductivity should be profiled. With regard to UV dielectrics, joule ratings (both for ink requirement and lamp output), plus temperatures and post-cure times should be established.

- **Ambient Condition Effects:** All of these substrate and ink variables must be tested and documented along with the ambient conditions under which they were produced. Many times….just a change in the weather is a failure point for an otherwise well researched material set.
- **Handling and Prep:** The ability to clean a substrate (oils, ink residue and dust) must be tested for. What can you use, how do you Use it? does it cause moisture entrainment? Leave a residue? Open or close the pore structure? Increase or collapse surface texture? Does it take multiple treatments after dryer passes (out-gassing)? Does it take multiple chemicals (you would be surprised how common this is)
- **Pre-Conditioning:** Does the substrate benefit from pre-conditioning (heat annealing or press floor temperature stabilizing)? What are its limits?
- **Adhesion and Flexibility:** make standardized adhesion tests, not just the razorblade and tape.

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