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Improving the Finish Quality of Large Commercial Air Conditioners

by

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Submitted to the Sloan School of Management
and to the Department of Civil and Environmental Engineering
on May 1997, in Partial Fulfillment of the Requirement for the Degree of

Master of Science in Management
and
Master of Science

in conjunction with the
Leaders for Manufacturing Program
at the
Massachusetts Institute of Technology

May 1997

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JUL 01 1997

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Abstract

This study analyzes how quality improvement activities are assimilated into a manufacturing plant's culture. This was done by identifying a significant problem in the plant, identifying causes of the problem, developing solutions and then observing the organization's ability to implement corrective actions. The ability of the organization to apply lessons learned from addressing this problem to other problems was also characterized.

Poor finish quality was found to be a problem impacting quality, cost, delivery and environmental performance. Total Quality Management techniques were used to identify the root causes of the problem. The root causes were divided into two groups, technical and managerial. Process improvements were developed to address the technical problems. Implementation of these process improvements was quite slow.

Management systems and routines for pacing the work flow were found to be the bottleneck slowing the implementation of process improvements in the plant. The origins of the routines, perhaps once a functional approach to an older set of incentives, are addressed. The currently dysfunctional routines are described, and their effects on organizational learning are analyzed. These systems placed greater emphasis on meeting short term production targets than on making long term improvements. Recommendations to improve these management systems are presented.

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Acknowledgement

The author gratefully acknowledges the support made available to him by the industrial partners of the Leaders for Manufacturing Program at MIT.

I would like to acknowledge the moral support provided by my fiancée, Kate Vance, and parents during my stay at MIT. I would also like to thank many interested Carrier employees for helping me with the work presented in this thesis.

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1. Introduction

The Carrier Corporation, a division of United Technologies, is one of the global leaders in the manufacture and sale of heating, ventilation and air conditioning equipment. Carrier's Commercial Applied Equipment Services (CAES) division produces large air conditioning units for sale throughout the world. These units are used to provide cooling for large buildings, such as offices, hospitals, shopping malls, etc.

The market for this equipment was long considered mature. As such, little money was invested in the business to develop new product or manufacturing technology. However, two trends have developed that are increasing the demand for this equipment. The international phaseout of chlorofluorocarbon refrigerants to protect the stratospheric ozone layer is forcing building owners to replace the existing stock of equipment with new generation chillers using more environmentally acceptable refrigerants. In addition, rapid economic growth in developing countries is increasing demand for chillers overseas. This increased demand for product is forcing Carrier to re-invest in the business to increase its capacity and profitability. At the present time, approximately 70% of the equipment produced is exported.

The TR-1 plant in Syracuse, New York, manufactures chillers for CAES. The chillers are then shipped to customers throughout the world. One of TR-1's costliest quality problems is the large amount of corrosion on the finished product when it arrives at the customer site. Corroded product must be cleaned and repainted at the customer site, resulting in approximately \$875,000 per year in rework costs and damage to Carrier's reputation with its customers.

This thesis identifies the root causes of the corrosion problem. Deficiencies in both the painting process used to protect the product and the management systems used to insure that the process is followed are characterized. Recommendations for improving both the painting process and management systems are provided. The relationship between the improvements in the painting process and management systems is explored. The results obtained from implementing these improvements are included, when available.

The thesis is part of the Leaders for Manufacturing (LFM) program at the Massachusetts Institute of Technology (MIT). The LFM program is a collaborative effort between MIT and fifteen industrial partners with the goal of increasing American competitiveness in manufacturing. United Technologies, one of the partners, sponsored this project in the Manufacturing Engineering organization of Carrier's TR-1 facility.

This thesis describes the resolution of a specific problem inside of the TR-1 plant by using Total Quality Management techniques to determine its root cause, and then develop and implement solutions. The problem addressed is finding a way to eliminate the unacceptable amount of rust on chillers when they arrive at the customer site. This problem was found to be caused by both an inadequate painting process in the factory and management systems that unintentionally harm product quality. The management systems problems were found to impact much more than paint performance. The following summarizes the actions taken to address these problems.

Chapter 2 provides an overview of operations inside the TR-1 plant. Descriptions of the product line and production processes are included.

Chapter 3 provides an overview of the specific problem being addressed. First, the corrosion problem is characterized. The methods used to identify the root cause of the corrosion problem are then presented. Results of the investigation follow.

Chapter 4 provides information concerning the development and implementation of improvements to the painting process. The key process variable controlling the corrosion problem is identified as being the thickness of the paint layer applied to the chiller. Process improvements to better control this key variable are developed. The results obtained from implementing these process improvements are presented, when available. A summary of the problems encountered during implementation is included.

Chapter 5 provides information concerning the effect of the plant's management systems on performance. This investigation focussed on the effect of management systems had on the painting process. However, several management systems were found to have undesirable impacts on overall plant performance. While designed to lower costs inside of TR-1, these systems unintentionally provide incentives to lower product quality and raise total costs. Many of these dysfunctional management systems are functions of the cultural barriers to quality improvement described in Chapter 6.

Chapter 6 provides an overview of the cultural barriers to quality improvement identified during the implementation of the process changes described in Chapter 4. These cultural barriers were found to significantly delay the implementation of improvements identified during quality improvement activities.

Chapter 7 provides information concerning the anticipated benefits of this work. Improvements to the painting process will result in four primary benefits. The reduced amount of rework required to repair damaged product will lower Carrier's costs. Improved paint performance will increase the quality of Carrier products. The reduced amount of rework will lower emissions to the environment by reducing the

total amount of paint used. A less tangible, but probably more important, benefit of this work is the plant's improved ability to identify and correct problems.

Chapter 8 provides recommendations for future work to improve the performance of both the painting process and TR-1 operations as a whole. These recommendations will focus on both specific activities that are part of the painting process and the management systems and incentives that control plant wide activities.

2. Overview of TR-1 Operations

The TR-1 plant in Syracuse, New York, produces centrifugal and screw chillers with 150 to 2100 tons of refrigeration capacity. Variations of three main product lines (the 23XL, the 19XL/19XR and 19EX) provide a wide variety of capacities in this range. All chillers are composed of a compressor (and motor), two heat exchangers, connecting piping and control systems. The size of the compressor, motor and heat exchangers are varied within each product line to provide for a complete range of refrigeration capacities.

Most of the work in this thesis was focused on the 19XL (200-600 ton capacity) and its newly introduced replacement, the 19XR (350-800 ton capacity). The 19XL is the highest volume product made in TR-1 and also has the most severe corrosion problems. Figure 1 contains a picture of a 19XL chiller.

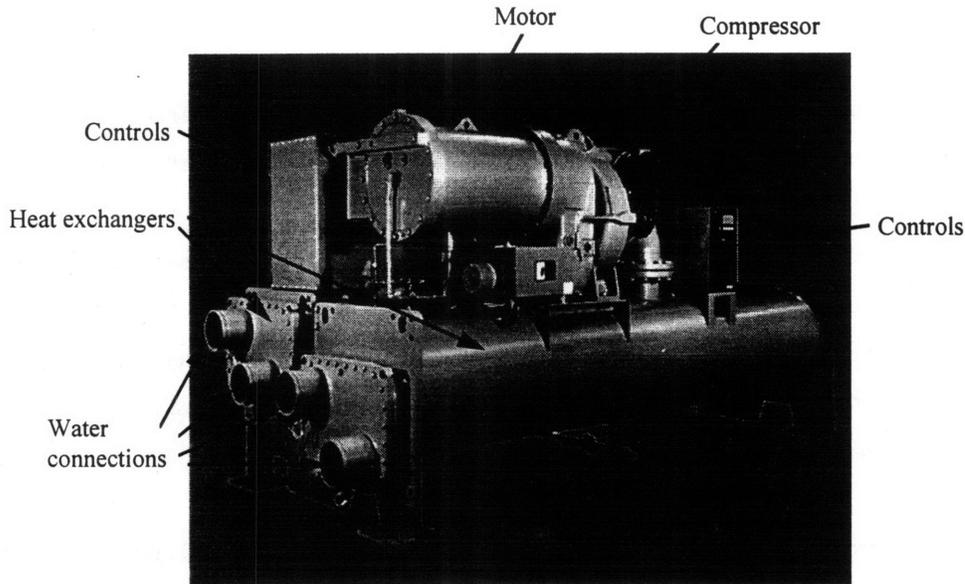


Figure 1 Carrier 19XL Centrifugal Chiller

Source: TR-1 Manufacturing Engineering

The TR-1 facility consists of a single high bay building containing three production lines for heat exchanger fabrication and chiller assembly, one production line for compressor assembly, several cells for parts fabrication, and areas for support operations (receiving, shipping, testing, storage, maintenance, offices, etc.). It is Carrier's oldest production facility. More modern production and engineering buildings are located adjacent to TR-1.

The production lines for heat exchanger fabrication and chiller assembly were the subject of this investigation. In these lines, steel plates are cut, rolled and welded to form the heat exchanger shells. The heat exchangers are cylinders approximately two to three and a half feet in diameter and twelve to nineteen feet long. Copper tubes, steel tube supports and end pieces are then added to form large shell and tube heat exchangers. The compressor (made of cast iron and steel) is then mounted on top of two heat exchangers. Piping to connect them is then welded or bolted in place. Electrical controls are added. Next, the assembled unit is pressure tested against leakage. The completed unit is then painted and shipped to the customer. Work in progress is moved between workstations by overhead cranes. Parts are supplied to the production lines from both the parts fabrication lines and from vendors.

The three chiller assembly lines are laid out in parallel. Although they are located next to each other and use similar processes, they are managed as independent entities. It is unusual for people to move between lines. There is little coordination of processes between the lines, so that similar operations are often carried out using different processes in each line. The social and technical systems have become routinized together.

The demographics of the workforce show that two distinct groups populate TR-1. The hourly workforce is characterized by its high seniority, strong union, high mobility within the Syracuse site (as agreed to in its union contract) and little opportunity for movement elsewhere within Carrier. The professional/management workforce is characterized by its low seniority and significant opportunity for movement throughout Carrier. The professional/management staff has experienced significant turnover (including the plant manager position) in the past. The relationship between the unionized hourly workforce and the professional/management staff was strongly adversarial in the past, but has significantly improved over the last several years.

TR-1 is run by its production line managers with support from the staff functions (Quality, Manufacturing Engineering, Purchasing, Human Resources, etc.). This structure provides the autonomy to line managers to quickly resolve problems with their production lines. It does not, however, lend itself to addressing plant wide problems across production lines, such as the one addressed in this thesis. Cross functional teaming is rarely used to address problems. The facility normally operates two shifts a day, five days a week. Weekend work is scheduled as needed.

The painting is done by hourly personnel with oversight from first line supervisors. These supervisors, in turn, are led by the production line managers.

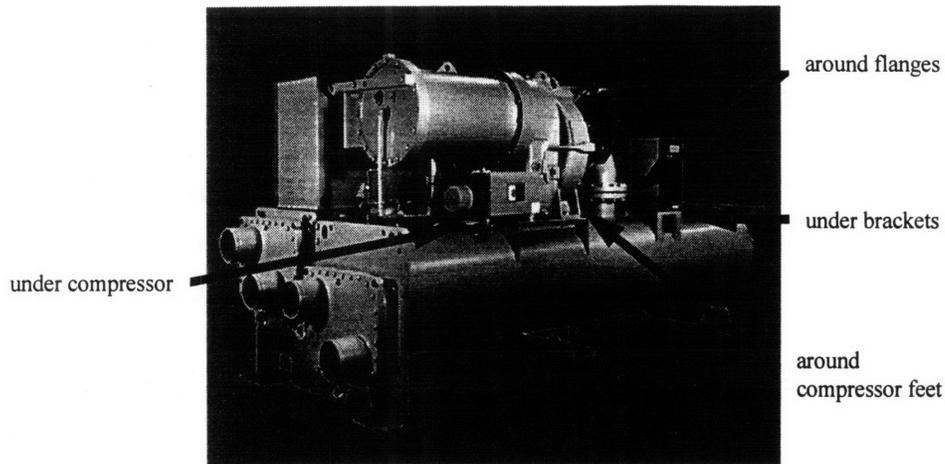
3. Analysis of Paint Quality Problems

3.1. Characterization of the problem

The specific problem addressed in this thesis is finding a way to eliminate the unacceptable amount of rust on chillers when they arrive at the customer site. Corrosion on units delivered to the customer has been a chronic quality problem for TR-1, but the severity of the problem has grown significantly as the number of units exported has grown. The rust is a cosmetic problem in that it does not affect the performance of chiller but does strongly affect the customer's perception of the overall quality of Carrier's products. Customers have become more concerned with these cosmetic issues.

After chillers are produced in TR-1, they are either shipped directly to the customer or stored temporarily at the Carrier site prior to shipment. Chillers are transported by truck to domestic customers. Exported chillers are trucked to New York City, where they are loaded on board ships for transportation to their destination. Total transportation time varies widely, from several days for a domestic customer located close to Syracuse, to as much as two months for a chiller exported to China. Chillers are held in the finished goods inventory for as long as several months before shipment. The finished goods inventory storage area is a converted parking lot, where the chillers are exposed to the weather. Rust often begins to appear on the chillers while stored in the finished goods inventory. Management of the finished goods inventory is discussed in greater detail in Chapter 5.

The rust does not appear in all places on all products, even though painting process is the same for all products. The rust problem is much worse on 19XL and 19XR's than on 19EX and 23XL chillers. While the amount of rust is highly variable from unit to unit, the rust tends to be localized in the following areas: underneath the compressor, around the flanges, around the compressor feet and underneath brackets. The 19XL is assembled on two production lines. No difference in the amount of rust that forms on 19XL's made on the different lines has been observed. The rust tended to either come through the paint or was on top of the paint. No sign of paint adhesion failures were indicated by the coating peeling off the chiller. Figure 2 shows the rust prone areas on a 19XL.



Rust is most commonly found at these locations on 19XL chillers.

Figure 2 Frequently rusted areas on the 19XL chiller

Source: TR-1 Manufacturing Engineering

The corrosion on completed chillers creates rework in two places in the delivery process. Rust spots on chillers stored in inventory are repainted prior to shipment. At current production rates, this in-house rework costs TR-1 approximately \$75,000 per year. Chillers that rust further during transportation are repainted at the customer site. Units shipped to domestic customers need little rework. Units exported require significant amounts of rework, possibly due to the longer transportation time, exposure to salt spray while on board ship, etc. Approximately one half of the exported units (one third of all units produced) must be completely repainted at the customer site. At current production rates, this costs approximately \$800,000 per year.

Figure 3 contains a flow chart describing the rework process.

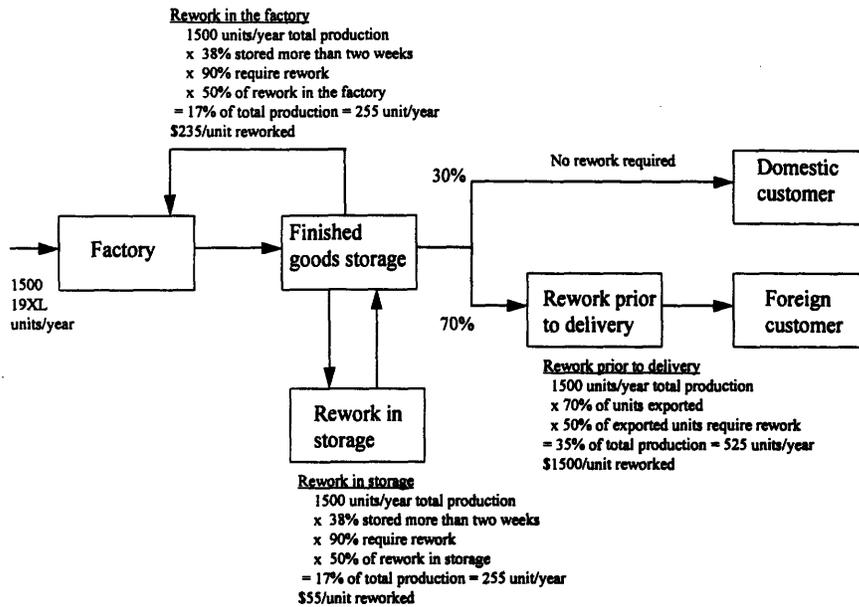


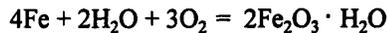
Figure 3

19XL Rework process and costs

Source: TR-1 Operations

3.2. Causes of Corrosion

The rusting of the cast iron and steel on the chiller is the oxidation of the iron in these materials. The iron reacts with water and dissolved oxygen in the following manner:



The corrosion process is an oxidation/reduction reaction with the iron being oxidized and the oxygen being reduced. [3]

The corrosion process is accelerated by the presence of water and salts, both of which are brought in contact with the chiller during the storage and shipping process. Exported units are exposed to more of these materials for longer periods of time than units produced for domestic use. This will be discussed in greater detail in Chapter 5.

3.3. Surface Preparation

The painting process is the same for all chiller models. Each of the three production lines in TR-1 has two booths used for surface preparation and painting. The chiller is moved into the first of the booths for surface preparation. Surface preparation is a two step process. The first step is an alkaline wash to remove surface contamination such as lubricants, cutting oils, chalk markings used in upstream processing, etc. The second is a combined hot water rinse and phosphating solution. Both solutions are applied to the

chiller with a manually operated spray wand. Spent solutions are collected in floor drains and stored for treatment and disposal off site. The chiller is then allowed to air dry.

After surface preparation, the chiller is moved either directly to the paint booth or to a nearby work station for insulation. Some chillers are insulated with foam to minimize condensation on the unit in service. The foam is glued to one of the heat exchangers, part of the compressor and some of the connecting piping using contact cement. Seams between the foam sheets are sealed with duct tape or an acrylic latex caulking compound. Insulation is optional feature requested by the customer. After insulation, the chiller is moved to the paint booth.

3.4. Painting

Surfaces that are to be kept free of paint are masked with masking tape and foam covers prior to painting. After masking, the unit is coated with primer and topcoat paints using hand held, air assisted airless paint spray guns. Both the primer and topcoat are water based, acrylic materials. The primer has a volatile organic compound (VOC) content of 2.2 lb/gal. The topcoat has a VOC content of 1.8 lb/gal. The primer is applied first, to a minimum thickness of 3 mils (1 mil = 0.001 inch). Either one or two coats of primer are required to achieve this film thickness, depending on the skill of the painter, the temperature, humidity, and other factors. After the primer coat has dried and has passed the film thickness inspection, topcoat paint is sprayed onto the unit to a minimum total film thickness of 5 mils. The topcoat is allowed to dry and is then inspected for film thickness and appearance (lack of runs, drip, missed spots, etc.). If the paint film is too thin, additional topcoat is applied. If the chiller is still in the paint booth, the same topcoat paint is used. If the chiller has been moved out of the paint booth to the next workstation, a solvent based acrylic aerosol paint is used instead because it dries more quickly. This material has a VOC content of 5.19 lb/gal, and is color matched with its water based counterpart. All insulated surfaces are painted. No paint is applied underneath the insulation to protect the base metal. After painting, electrical equipment is then added to the painted chiller at the last workstation. The chiller is now completely assembled.

3.5. Storage and Shipping

Some of the completed chillers are shipped directly to the customer, but most are temporarily stored outdoors in an unused parking lot on site. Storage times vary from several days to several months. The units are unprotected from the elements during storage, exposing the chillers to significant amounts of rain and snowfall. Units stored outside typically begin to show signs of rusting in the trouble spots previously noted within two weeks. Prior to shipment, rust spots are coated with the aerosol topcoat paint to restore the unit's original appearance. Chapter 5 will discuss this storage process in greater detail.

Chillers are then transported to the customer site. Upon arrival, the units are inspected for corrosion. Rusted areas are touched up with paint. When the units are severely rusted, the entire unit is repainted. Repainting is done with the water based topcoat when available, although solvent based materials are more commonly used. The unit is then installed and tested.

The flow chart in Figure 4 provides an overview of the painting process.

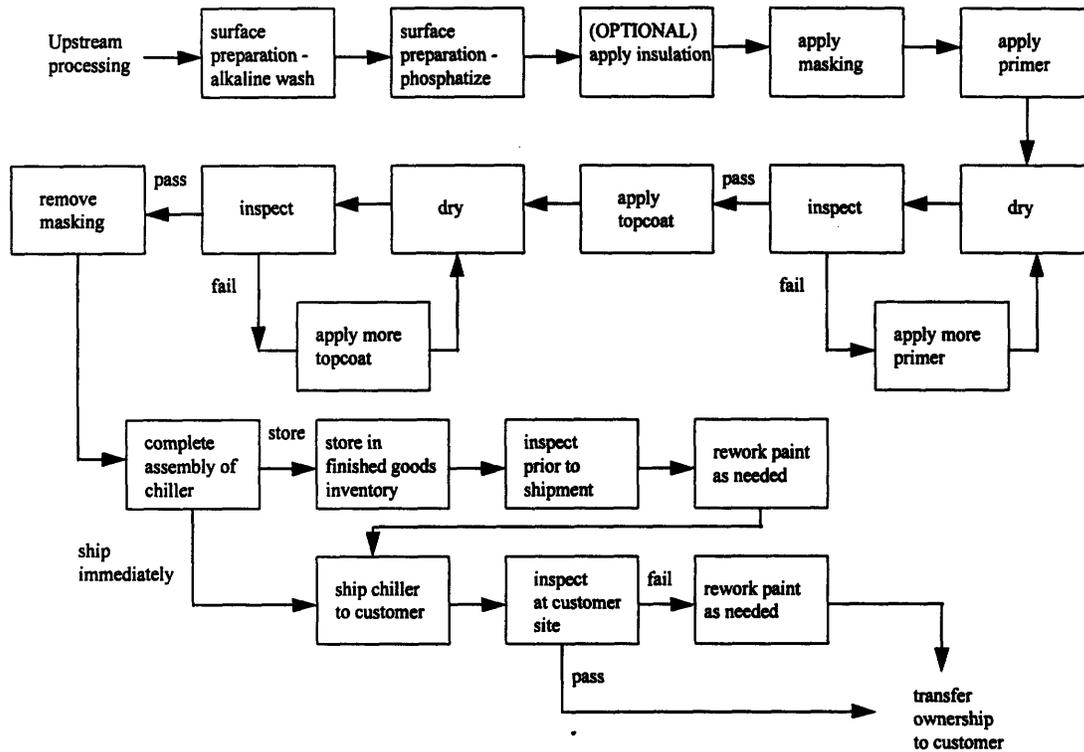


Figure 4

TR-1 Painting Process

Source: TR-1 Operations

3.6. Brainstorming

The root causes of the corrosion problem were identified using traditional Total Quality Management (TQM) tools. First, a group of employees associated with all aspects of the finishing process brainstormed a list of potential causes of the problem. Few employees had a working knowledge of the Total Quality Management process. The potential causes were grouped into four categories (materials, surface preparation, painting process and storage) and linked to process variables that could be tested. The group consisted of painters, inspectors, engineers and managers. The list of potentially responsible causes and process variables was organized into the fishbone diagram shown in Figure 5.

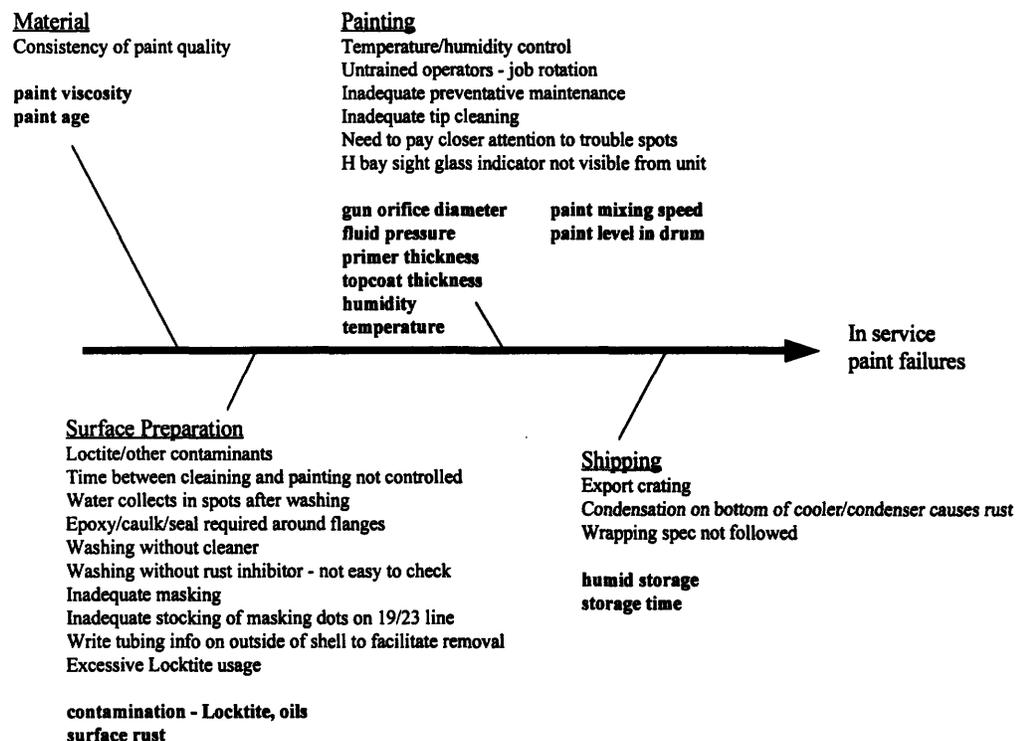


Figure 5

Potential Causes of Paint Problems
(potential causes in plain type/potentially responsible process variables in bold type)

Source: TR-1 Operations

The potentially responsible process variables were then studied to determine if they could produce a corrosion problem of the type seen in TR-1. In the category called "Materials", the process variables paint viscosity and paint age were not considered likely candidates to the the "true" root cause. The corrosion problem was worse on 19XL's than on the other products. The problem was also concentrated in specific areas of each unit. If paint viscosity or paint age were causing the problem, rust would appear more evenly across the product line and location on a chiller. In the "Surface Preparation" category, neither contamination or surface rusting were considered to be likely candidates to be the "true" cause.

Contamination would cause paint adhesion failures resulting in paint peeling off the chiller, rather than the rust coming through the paint layer as is seen in the finished product storage area and at the customer site.

In the “Painting Process” category, only the primer and topcoat thickness were considered to be the likely “true” cause. The paint gun orifice (tip) diameter, fluid pressure, level in the paint supply drum and paint drum mixer speed were not thought to be likely candidates because the same painting process was used for all products. These variables did not explain why the corrosion problem was more severe on 19XL’s. The temperature and humidity in the paint booth were ruled out because there did not appear to be any seasonal variability in the rust problem.

In the “Shipping” category, neither storage time and the humidity of the storage area were considered to be the “true” root cause. Longer storage (and shipping) times clearly made the problem worse because the corrosion problem became more severe as more units were exported to distant countries. Humid storage conditions also made the corrosion problem worse, as indicated by the larger amount of rework required on products exported in tightly sealed shipping crates. Because all products are shipped under the same conditions, storage time and humidity could not explain why the problem was worse on 19XL’s. For this reason, storage time and humidity were considered to be contributing factors, but not the root cause of the problem.

Using the process of elimination, coating thickness was thought to be the most critical process variable. This hypothesis was then tested in two ways. First, paint thickness was measured in many locations on all products to determine if the thickness tended to be different in rust prone areas. Second, an experiment was conducted to evaluate the effect of coating thickness on paint performance.

3.7. Paint Thickness Measurements

The paint thickness measurements indicated that the rust formed on areas where the paint thickness was below the 5 mil minimum required by the painting process specification. Paint thickness was measured using a Defelsko paint thickness gauge. Rusted areas on 19XL chillers in the finished goods inventory storage area consistently typically had paint thicknesses of 0.5 - 3 mils. Undamaged areas of the same units had coating thicknesses of over 5 mils. The other products made in TR-1 did not have this wide variation in coating thicknesses across a unit. Detailed “maps” of coating thicknesses were made of newly produced 19XL’s. Paint performance on these units was then tracked through delivery to the customer. Rust began to appear on areas where the total coating thickness was less than 5 mils within two weeks in the finished goods inventory storage area. An example of one of these paint “maps” is seen in Figure 6.

Test Matrix

variables	levels
cure time (hour)	12, 48
substrate	cast iron, steel
nominal paint thickness (mil)	1, 3, 6

Test panels were prepared for each combination of variables and then placed in a humidity chamber. The conditions in the humidity chamber were varied each 24 hours in the following manner. The panels were heated to 50 C at 95% relative humidity for 10 hours and then allowed to cool to room temperature and ambient humidity for 14 hours. This would simulate the environmental conditions experienced by a chiller stored in a cargo container on board a ship in a tropical climate. The panels were inspected for corrosion blisters at one and twenty days using ASTM D 714-87 (1992).

The results of the testing showed a strong correlation between coating thickness and performance. A coating thickness of approximately 1 mil failed after one 24 hour cycle in all cases. A coating thickness of approximately 3 mils passed after one cycle but showed some rusting after twenty cycles in all cases. A coating thickness of 5 mils passed after twenty cycles in almost all cases. Little difference in performance was noted between the two substrates. The longer paint cure time produced a slight improvement in paint performance, showing that the paint was not completely cured after 12 hours. A summary of the test results is listed below.

Summary of test results

Cure time	Substrate	Nominal paint thickness		
		1 mil	3 mil	6 mil
12 hour cure	cast iron	fail after 1 cycle	fail after 20 cycles	pass
	steel	fail after 1 cycle	fail after 20 cycles	pass
48 hour cure	cast iron	fail after 1 cycle	pass	pass
	steel	fail after 1 cycle	fail after 20 cycles	pass

Detailed results of the testing are included in Appendix 1.

4. Paint Quality Improvements

As discussed in Chapter 3, both laboratory testing and observation of actual production chillers identified coating thickness as the key process variable for preventing corrosion. Two complimentary causes of insufficient coating thickness were identified. The first is an ineffective painting process. Improvements to the painting process will be discussed in this chapter. The second cause is ineffective management systems that encourage dysfunctional behavior both in the paint booth and throughout the plant. These ineffective management systems slow down the organization's ability to recognize and correct this rust problem. Improvements to the management systems will be discussed in Chapter 5. A number of cultural barriers to quality improvement activities were also identified. These will be discussed in Chapter 6.

4.1. Painting the compressor bottom

Because the rust problem was most severe on the 19XL model, improvements to the painting process were evaluated on this model. As shown in Figure 3, several areas of the 19XL chiller were identified as being rust prone. They were under the compressor, under the many brackets and around the flanges and compressor feet. A way of painting that would allow paint to be applied thickly enough under the compressor and brackets without causing unacceptable drips and sags in surrounding areas had to be found. The clearance between the bottom of the compressor and the heat exchanger shells is simply too small to allow the spray gun to be manipulated in the manner required to effectively paint the bottom of the compressor. A similar problem was observed with the brackets.

Several methods of applying a thicker paint coating underneath the compressor were considered. Different models of paint spray guns, spray gun tip extensions, brushes and rollers were all investigated and discarded. Any spray gun used would have the same clearance problem. Spray gun tip extensions are commercially available that would probably be able to apply the thicker coating, but using the extension would require a separate, dedicated gun for painting this small area. The gun/extension combination would need to be carefully cleaned between uses to prevent clogging. The high amount of maintenance anticipated caused this approach to be rejected. Rollers and brushes were also rejected because they would not reach through the narrow gap between the compressor and the heat exchangers in a way that would allow painting the large surface area on the compressor bottom.

Because no effective way of painting the compressor bottom on the assembled chiller could be found, painting the compressor prior to assembly was investigated. Painting compressors not mounted on chillers is already done on a low volume basis in TR-1. TR-1 produces a small number of compressors that are

exported to other plants for assembly. These “compressor only’s” are assembled and then painted in a different paint booth prior to shipping. This paint booth had sufficient capacity available to paint 19XL compressors before assembly in TR-1. The bottom of the compressor is readily accessible using standard paint spray guns at this point. Several compressors were primed in this booth prior to assembly. This was considered the most effective means of applying paint to the compressor bottom.

4.2. Painting underneath brackets

A similar analysis was done for the problem of applying more paint underneath the brackets. All paint guns would have the same problem with access underneath the brackets. Paint gun extensions would present the same maintenance concerns. Brushes and rollers did not have the same problems as the compressor bottom, because the area to be painted under the brackets is small. Brushes and rollers were tested in production, and found to be very effective at applying paint underneath the brackets.

4.3. Protecting mating surfaces

Flanges and the compressor feet/attachment bolts were also identified by the painters and quality inspectors as rust prone areas. An inspection of chillers held in the finished goods inventory confirmed this. Both of these areas had the same problem. During assembly, metal surfaces are mated together. The gap in the mating surface is far too small to allow paint to penetrate during the painting process. Water, however, can enter this gap during storage and transportation. This water corrodes the unprotected surfaces and then flushes rust out of the gap, leaving an unsightly red streak down the side of the chiller. These red streaks give the customer the impression that large areas of the chiller are rusting.

No method of applying paint was considered to be practical for protecting these surfaces after assembly. Prepainting the surfaces of these parts prior to assembly was rejected because these parts are welded in place in upstream positions. The surfaces to be welded must be kept free of paint. Plating these surfaces with corrosion resistant materials was rejected in this analysis because of both cost and weld contamination concerns. The use of corrosion inhibiting compounds with a low enough surface tension to penetrate into the mating surface was rejected because the oily residue left on the surface would interfere with any touch up painting required without extensive cleaning.

One practical solution to this problem was developed. Applying a caulking compound to the gap after assembly sealed the unpainted surfaces from the surrounding environment. When this material is applied, water cannot enter the gap and cause the unpainted surfaces to rust. An acrylic latex caulk already used to

seal gaps in the insulation on these chillers was chosen for this application. Shop trials with this material showed that the caulking performed as desired.

Figure 7 shows a summary of the process changes implemented to address the corrosion problem.

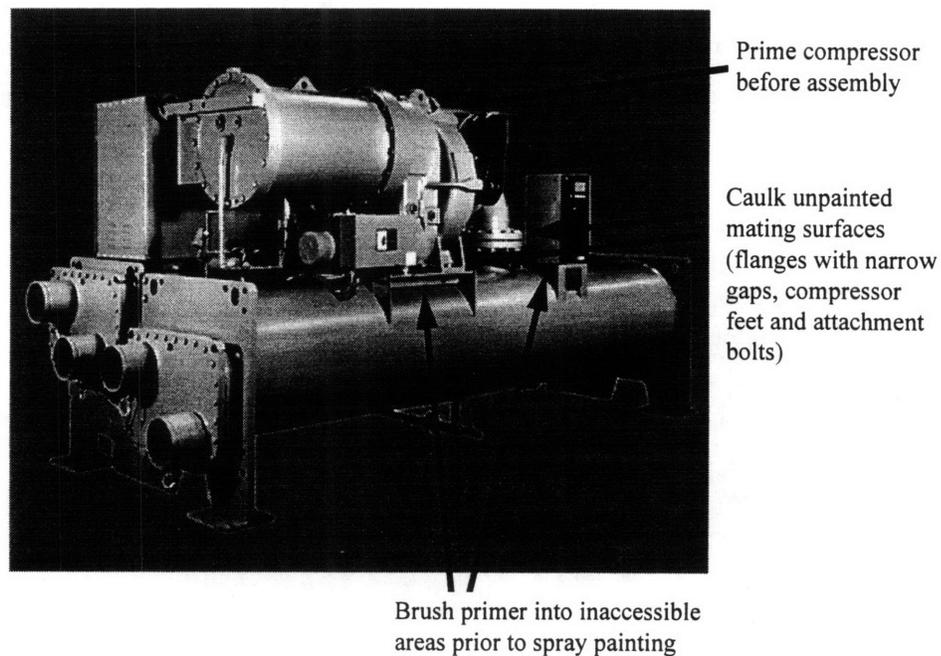


Figure 7

Process Changes

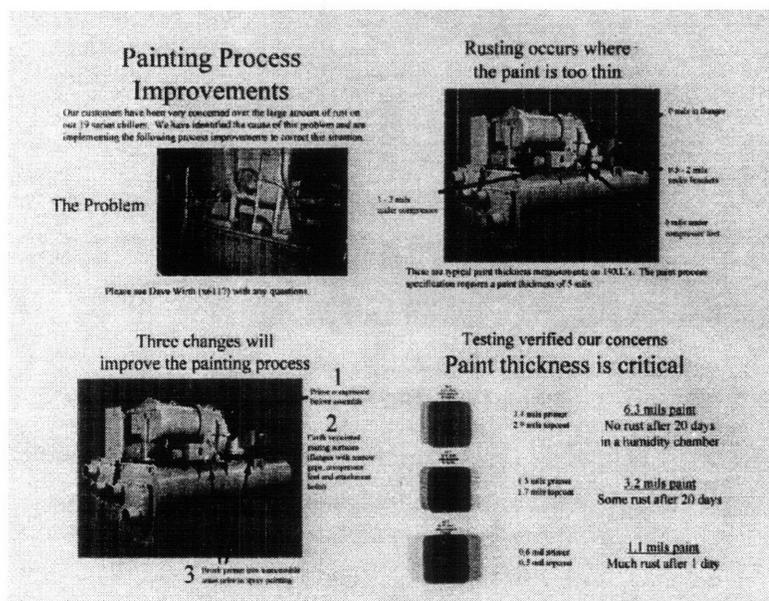
Source: TR-1 Manufacturing Engineering

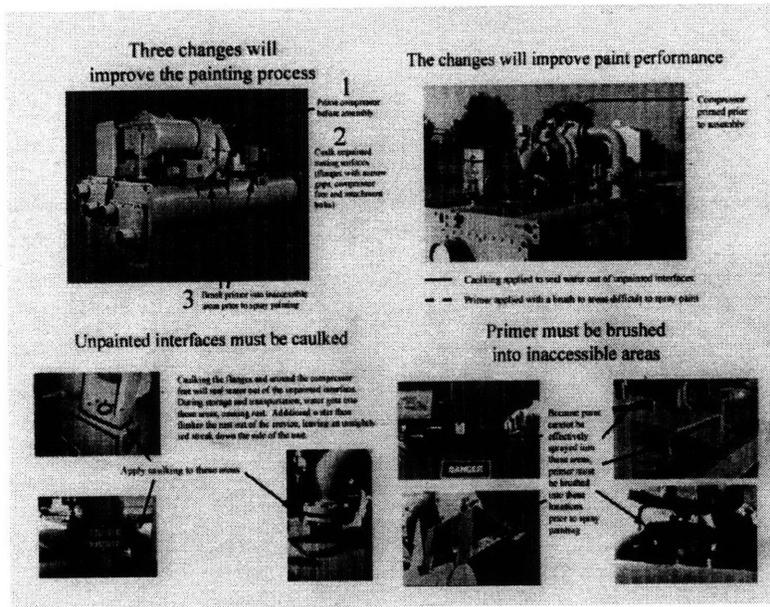
4.4. Testing

Each of the process changes identified above was tested in several ways. Ideas for process improvements were received from all stakeholders in the process: painters, assembly workers, engineers, etc.. These ideas were then evaluated in the laboratory or in the plant to determine their usefulness. If the idea looked feasible after a cursory examination, a shop trial was conducted. During the shop trial, impacts on flow time, tooling requirements and other operations were identified. Units produced using the process change and were then monitored for rust while in storage. Each of the process changes listed above dramatically reduced the amount of rust appearing on units stored in the finished products inventory when compared to units produced without the process changes. The improvement was not quantified, as no performance standard for the “acceptable” amount of rust existed. All stakeholders agreed that the process changes improved the finish quality. These units were then shipped to Asian customers along with “control” units produced without the process changes. Comparing the amount of rust on chillers manufactured using the

modified process with those manufactured with the standard process would allow the effectiveness of the modifications to be measured. Feedback from the customer sites has not yet been received due to the long shipping times and delays in the customers' required delivery dates.

Posters explaining the process improvements being made were displayed near the paint booths. The posters had three purposes: to educate shop personnel about the causes, scope and effects of the problem, to assure them that work was being done to address the problem, and to help get their support in solving the problem. It was considered particularly important to show how their contributions to the process of identifying the root causes of the problem were being used to develop and implement solutions. Getting shop personnel to "buy into" the solutions was seen as critical to the successful implementation of the process improvements. These posters can be seen in Figure 8.





Educational Posters in TR-1 H-Bay

Figure 8

Source: TR-1 Operations

4.5. Costs

The costs of each process change listed above have been identified for 19XL chillers. Priming the compressor prior to the chiller being assembled will cost approximately \$100 each, or \$150,000 per year for 19XL's. Caulking the flanges and compressor feet will cost approximately \$45,000 per year. Brushing primer underneath brackets will cost approximately \$20,000 per year. Therefore, the total cost of these process changes is approximately \$215,000 per year for 19XL chillers. This compares to an estimated cost of \$875,000 per year to repaint rusted 19XL chillers at TR-1 and customer sites (plus damage to Carrier's reputation for quality that cannot be quantified). These costs will be discussed in greater detail in Chapter 6.

5. Effects of Management Systems and Incentives

In Chapter 3, the source of the corrosion problem was identified as insufficient paint thickness in certain areas of the chiller. Two complementary causes of this problem were identified. The first is an ineffective painting process. Improvements to the painting process were identified in Chapter 4. The second cause is management systems that are intended to promote productivity but have the effect of lowering quality and raising costs both in the paint booth and throughout the plant. These management systems breakdowns are discussed in this chapter.

Misaligned management systems harm paint quality in the TR-1 plant the following four ways:

1. The absence of quality goals and plans in TR-1 implicitly makes quality a lower priority than other performance measures such as cost and schedule, which are carefully planned and communicated to the workforce. The low priority of quality is reflected in the plant's incentive pay system.
2. Workflow in TR-1 is managed to be highly cyclical, making it difficult to implement the process changes identified in Chapter 4 during the "busy" portion of cycle.
3. TR-1 is managed with a large finished goods inventory. Exposure to the elements during these long inventory storage times causes significant amounts of corrosion on chillers before they are shipped to customers.
4. The Commercial and Applied Equipment Services business unit is managed in a manner that customer concerns are inefficiently conveyed to TR-1. Delays in customer feedback hinder organizational learning in TR-1 and prevent customer concerns from being rapidly addressed.

Information supporting these claims is provided below.

While this project was focused on improving paint quality, it must be noted that the effect of these dysfunctional management systems is much broader. Making improvements to the systems identified above will have a much greater effect than simply eliminating corrosion problems on chillers.

5.1. Quality has a low priority

The absence of quality goals and plans in TR-1 implicitly makes quality a lower priority than other performance measures such as cost and schedule, which are carefully planned and communicated to the workforce. TR-1's managers are held to very aggressive cost and schedule targets. These targets are carefully communicated to employees. Corresponding quality targets do not exist, so quality is implicitly considered to be less important. Interviews with hourly associates, engineers and managers in TR-1 produced a consistent message, that when conflicts between quality and cost or schedule occur, quality

issues are almost always considered to be a lower priority. Many employees are also frustrated by their lack of involvement in and their management's perceived lack of commitment to the quality improvement process.

An example of quality concerns being considered less important is the incentive pay system used in TR-1. The incentive system rewards almost all TR-1 personnel for productivity improvements. The program distributes to employees 50% of the difference between the amount of labor currently used to produce a chiller and the amount of labor needed to produce a chiller in the 1986 baseline year (adjusted for process changes, design changes, outsourcing of parts, etc.).

This results in a strong incentive throughout the plant to ship as many units as possible each week, in order to increase the standard hours earned during the week. This increases the size of the bonus awarded to each eligible employee. Typical bonuses are approximately 15% of total pay.

Quality is not factored into the incentive system. The bonus is the same if the units shipped are perfect or not. This is particularly critical with respect to paint quality. A high quality paint job takes more time to apply than one with inconsistent thickness, surface defects, etc. Because the paint booth is almost at the end of the production line, shop management pressures the painters to paint units as quickly as possible so that they can be shipped and then counted towards the bonus. This is particularly true at the end of each week, when the paint booth becomes the bottleneck in the production line (for reasons discussed later). On Fridays, a disproportional amount of work must be pushed through the paint booths to make the weekly production targets and to maximize the bonus. The bonus program provides incentives that actually hurt the quality of the paint. Painters in all production lines in TR-1 voice these concerns.

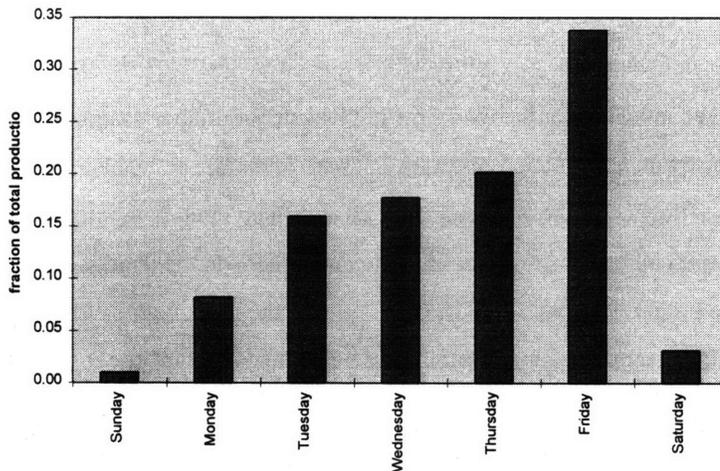
While the intent of the incentive program is good, its effect on performance in TR-1 is both good and bad. Because the system rewards employees for maximizing the production rate of chillers with the minimum amount of labor, it only results in improvements to labor productivity. By not addressing quality (or other equally important factors such as employee safety), the system hurts quality improvement efforts in order to boost short term labor productivity.

As Stephen Kerr pointed out over twenty years ago in *On the Folly of Rewarding A While Hoping for B* [1], individual and organizational behavior is strongly influenced by the reward system they operate under. As applied to TR-1, the focus on meeting short term production and productivity goals at the expense of quality and long term improvements appears to be a rational response to the reward systems used in the plant.

5.2. Widely varying workflow

Workflow in TR-1 is managed to be highly cyclical, making it difficult to implement the process changes identified in Chapter 4 during the “busy” portion of cycle. This was identified by Schwartz [2] in a 1993 LFM study of manufacturing performance measures in TR-1. Little has been done since then to address this issue. The problem is documented in greater detail below.

The problem originates in the need for production managers to maintain strict adherence to the each week’s production schedule. Midway through a typical week, a production manager realizes that the line is falling behind its schedule. To overcome this problem, the downstream end of the line is worked overtime. This accomplishes two things. The production schedule for the week is met by converting the work in progress (WIP) into finished product. However, by working the downstream half of the line faster than the upstream half, the downstream workstations are depleted of their WIP by the end of the week. This sets the line up for failure the following week. At the beginning of the following week, the downstream workstations are empty until new work flows down through the line. Few chillers are actually completed early in the week. This forces the downstream workstations to work even more overtime at the end of the week to meet the weekly schedule. This becomes a vicious cycle that transforms what should be level loaded production into alternating waves of quiet and frenzied activity. Figure 9 documents this by plotting TR-1’s production by day of the week over a two and a half year period. The figure shows that approximately 34% of TR-1’s output was completed on Friday, while only 8% was completed on Monday.

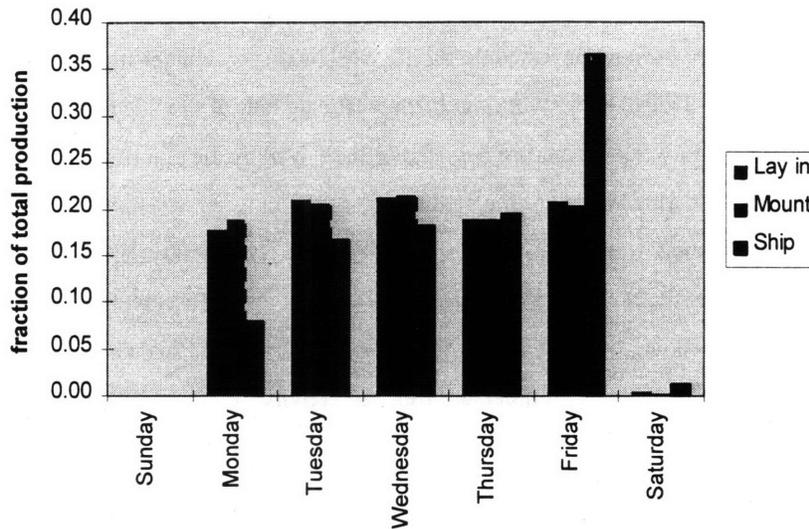


Distribution of Production by Day of the Week
(All TR-1 Production 1/1/94 through 6/15/96)

Figure 9

Source: TR-1 Manufacturing Engineering

The source of this variation was investigated. Workflow variation data at the beginning (lay in), middle (compressor mount) and end (shipping) of the TR-1 H-bay production line was evaluated. Figure 10 shows that the variation in workflow originates in the last half of the production line, after the compressor is mounted. This was not investigated further, as it was outside the scope of this study.



Distribution of TR-1 Production by Day of the Week
(TR-1 H-bay production 8/94 through 1/96)

Figure 10

Source: TR-1 Manufacturing Engineering

There are large penalties involved in managing the workflow in this manner. Labor costs are increased, because employees in the downstream half of the production lines are often idle at the beginning of the week but are worked overtime at the end of the week. Quality also suffers. Interviews with hourly associates, engineers and managers all tell of strong pressures to cut corners on the quality of the work being done in order to meet the production schedule during the “end of the week rush”. Employee morale is also hurt, as the problem is universally recognized but little is being done to eliminate it.

The cyclical nature of the workflow is particularly damaging to paint quality. Because the paint booths are almost at the end of the production line, they are subject to the widest variations in workflow. During periods of peak flow they become the line’s bottleneck. When this occurs, painters are placed under extreme pressure to push work through the booths as quickly as possible, even at the expense of quality.

Every painter interviewed expressed frustration with their management's desire to trade off quality for speed at these times.

The low priority given to quality under these conditions also hurts quality the rest of the week. When painters see quality standards being lowered on Friday to meet production schedules, they begin to apply "Friday quality" standards to the rest of the week, too. This, in turn, leads to more cynical views of quality improvement efforts in general.

Some of the painting process improvements presented in Chapter 4 have not yet been widely implemented because of these workflow variations. Brushing primer under the brackets adds flow time in the paint booth. This flow time increase is unacceptable on Fridays. Caulking around the flanges and compressor feet is also not done on Fridays because of the high workload. These flow time increases would not be a problem if the production line was level loaded.

5.3. Large finished goods inventory

TR-1 is managed with a large finished goods inventory. This occurs for two reasons. First, the absorption method of cost accounting used to measure TR-1's performance results in product being built before it is needed. Second, the resulting large finished goods inventory is controlled by Marketing, not TR-1, so the factory is not penalized for creating the large inventory. This problem was also well documented by Schwartz. The large inventory of finished goods negatively impacts both paint quality and overall plant performance.

Finished goods storage

When a survey was done on October 4, 1996, 170 completed chillers worth approximately \$11.5 million were stored on the plant site. While TR-1 actually "owns" the finished goods inventory, the Marketing organization controls the storage area and manages the inventory. The storage area has been nicknamed "Shang-ri-la" at the plant because it is an unused parking lot located in a rarely visited corner of the site. These chillers are classified into three different categories, "Bill and store", "Sold" and "Inventory". Bill and store units comprise approximately \$5.2 (45%) million of the total. Customers have paid for these units, but want Carrier to store them until they can be installed. This would occur if the construction schedule for a new building has slipped, delaying the installation of the building's HVAC system. The customer is charged a portion of the unit's selling price per month as storage fee. A picture of chillers stored in Shang-ri-la can be found in Figure 11.



Shang-ri-la

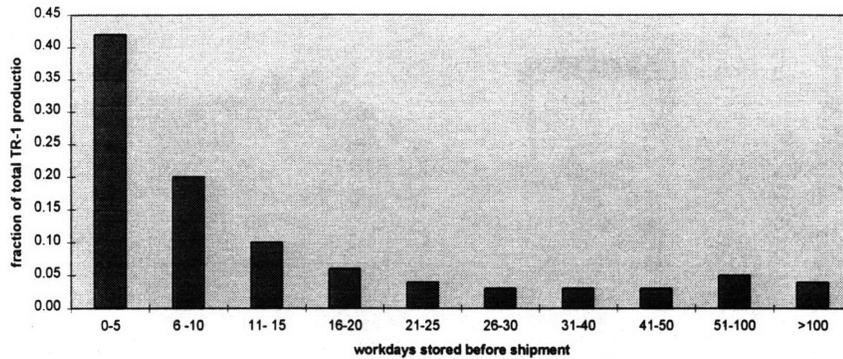
Figure 11

Source: TR-1 Manufacturing Engineering

Sold units are chillers ordered by customers but not yet paid for or shipped. They comprise approximately \$2.6 million (23%) of the total. Shipment of these units has been held up for a wide variety of reasons, including delays in obtaining export papers, financing, etc. An internal transfer price of a portion of the unit's selling price per year is charged to the local Carrier sales office responsible for the unit, but that charge is rarely passed on to the customer.

Inventory comprises approximately \$3.7 million (32%) of the total. Inventory is a combination of stock units and units built before customers need them. Marketing maintains a stock of finished chillers available for quick shipment to customers. No information is available concerning the relative amounts of stock units (a desirable thing) and units built too soon (an undesirable thing). Marketing owns all chillers in this category.

The stored chillers are held for a wide range of time prior to shipment to the customer. Figure 12 summarizes these storage times for all of TR-1's production over a two and a half year period. No data breaking these storage times down into the categories listed above was available.



Finished Goods Inventory Storage Times
(total TR-1 production 1/1/94 through 6/15/96)

Figure 12

Source: TR-1 Manufacturing Engineering

Cost accounting methods

The absorption method of cost accounting creates strong incentives to maximize factory output in the short run. In the absorption method, overhead costs are allocated to products using labor hours as the allocation base. The plant “absorbs” these overhead costs as units are produced. Plant performance is measured by comparing the total absorbed costs to a budgeted amount. The plant is considered “successful” if the total absorbed costs exceed the budgeted amount (a positive variance to the plan). A plant can be made to appear more “successful” in the short run by increasing production above the planned amount, absorbing more costs than planned to produce a positive variance. This “success” has little or nothing to do with a business’ true profitability, because the absorption metrics only measure units built, not sold.

Output is maintained at high levels by building chillers earlier than is needed by customers. In 1993, Schwartz [2] documented the practice of “pulling in” units, where chillers are built even though they are not needed until some time in the future. This maximizes production in the short run, making the plant’s performance appear better. This practice continues at TR-1 today.

Costs of storage

The finished chillers are stored in a converted parking lot. Exposure to the elements during storage in Shang-ri-la causes significant amounts of corrosion on chillers before they are shipped to customers. Approximately 90% of the chillers stored for more than two weeks have sufficient corrosion damage to

require rework. Some of the rework can be done in the storage area, but most of the chillers must be brought back into the factory. Rework in the factory is expensive and disrupts the normal workflow. The cost of this rework is documented in Chapter 6.

The chillers experience other weather related damage while in storage. Insulation often tears away from the chiller. Tape pulls away from the insulation seams. Gauges become fogged with water. Some of this damage can be repaired in the storage area. Other damage must be corrected in the factory.

The Marketing organization manages the storage area. Two full time hourly associates are assigned to manage the storage area. The organization is not charged anything for use of the space, because it is an unused parking lot. Transporting chillers between the factory and storage area costs approximately \$20,000/month.

A long term plan is being developed to eliminate the outdoor storage of completed chillers. The plan would convert unused space inside of TR-1 into a storage area. This would eliminate the transportation charges between the plant and storage area, as the plant's overhead cranes could move the chillers instead of flatbed trucks. Weather related damage would be greatly reduced with indoor storage. Other policies are being modified to reduce storage times.

5.4. Inadequate feedback from customers

The Commercial and Applied Equipment Services business unit is managed in a manner that customer concerns are inefficiently conveyed to TR-1. Delays in customer feedback hinder organizational learning in TR-1 and prevent customer concerns from being rapidly addressed. The corrosion problems addressed in this thesis became an issue with Asian customers over a year before this work began. Shop personnel were not made aware of the problem for over a year. Feelings of being "kept in the dark" help contribute to the alienation of the hourly workforce. This lack of information about the existence of the problem is largely responsible for the lack of action to correct it. Rapid feedback between supplier and customer is required for continuous quality improvement to occur.

6. Cultural barriers to quality improvement

Three cultural barriers to quality improvement were observed in TR-1. These barriers impeded the implementation of the process improvements previously discussed, and also the overall process of improving the quality and productivity of TR-1 operations. The TR-1 culture places greater value on achieving productivity goals than quality goals. The second barrier is that the plant culture places greater value on achieving short, rather than long, term goals. The third cultural barrier is the high degree of distrust between the hourly workforce and the plant's management.

The TR-1 culture places a much higher priority on the quantity, rather than the quality, of its output. This is demonstrated by the highly visible production targets that drive activities throughout the plant. Corresponding quality targets do not exist. The Operations function in the plant is responsible for meeting the production targets, but is not held accountable for product quality. TR-1 support organizations (Quality Assurance, Manufacturing Engineering, etc.) are held accountable for product quality and quality improvement activities. The productivity incentive system discussed in Chapter 5 reflects these priorities.

The TR-1 culture places a much higher priority on achieving short, rather than long, term goals. There is no long term plan outlining the changes to be made within TR-1 to support the CAES business unit's goal of achieving profitability. Without this plan, the workforce focuses almost exclusively on meeting the most recently published production targets. Interviews with TR-1 employees in a wide variety of job functions (hourly, engineer, manager, etc.) demonstrated that this lack of long term vision is a concern at all levels of the organization.

The third cultural barrier to quality improvement identified in TR-1 is the high degree of distrust between the hourly workforce and management. Interviews with both hourly associates and managers showed that each group feels highly threatened by the other. Management often views the hourly workforce as uninterested in improving the plant's performance. The hourly workforce often views management as trying to eliminate their jobs to improve the plant's productivity. As a result of this distrust, little information is shared between the two groups. This information sharing is a necessary part of any quality improvement activity. Shop floor based quality improvement teams that are so effective in other manufacturing operations are not found in TR-1. As a result, few ideas for quality or productivity improvements from hourly employees are implemented in TR-1. The three improvements to the paint process identified in Chapter 4 were all originated by hourly employees, but no mechanism for evaluating and implementing these ideas existed until this study was initiated. Aligning the incentive systems for both

the hourly workforce and management with the business unit's goals would do much to break down the distrust between the two groups.

7. Anticipated Benefits

The improvements to the painting process discussed in chapter 4 will result in three primary benefits. The reduced amount of rework required to repair damaged product will lower Carrier's costs. Improved paint performance will increase the quality of Carrier products, improving the company's reputation with customers. The reduced amount of rework will lower emissions to the environment by reducing the total amount of paint used.

The benefits of improving the management systems discussed in Chapter 5 are not as readily quantified. These dysfunctional systems clearly have a significant effect on paint quality. They also have a much broader impact on quality and productivity throughout TR-1. Quantifying the impact of these management systems is beyond the scope of this thesis. Recommendations to determine the scope of the problems caused by these systems and to mitigate these adverse impacts are contained in Chapter 8.

7.1. Cost savings

The three painting process improvements presented in Chapter 4 are clearly cost effective. Defective paint on completed chillers is reworked in three locations. Prior to shipment to the customer, paint can be reworked either in the finished goods storage area (for relatively small problems) in the factory (for relatively large problems). Reworking in the factory is much more expensive, because of the need to transport the unit to and from the storage area and the disruption to the normal manufacturing process caused introducing reworked units to the factory flow. Defective paint is also reworked at the customer site. This is the most expensive type of paint rework, because large amounts of rust must be removed and then the unit is completely repainted with topcoat.

Corrosion typically begins to appear on chillers in the storage area within two weeks. Sixty eight percent of TR-1's production is stored for two weeks or more prior to shipment, of which approximately 90% require rework. Approximately half the rework can be done in the storage area at a cost of \$55/unit (for 19XL's). The remaining half must be done in the factory at a cost of \$235/unit (for 19XL's). At a nominal production rate of 1500 19XL chillers per year, reworking rusted 19XL chillers on the TR-1 site costs approximately \$75,000 per year.

Reworking paint on the customer site is much more expensive because the chiller is completely covered with a new layer of topcoat. Approximately 70% of 19XL chillers are exported. Of these, half must be completely repainted after arriving in their destination country. The repainting work is usually contracted

to vendors at an approximate cost of \$1500/unit. Few chillers shipped to domestic customers must be reworked. Exported chillers are usually transported by ship. The long shipping time and contact with warm, salt air are assumed to account for the difference in paint performance between chillers shipped to domestic and foreign customers. At a nominal production rate of 1500 19XL chillers per year, reworking rusted 19XL chillers on customer sites costs approximately \$800,000 per year, for a total rework cost of \$875,000 per year.

Figure 3 contains a flow chart describing the rework process.

The cost of implementing the process improvements is much lower than the cost of the rework. Priming the compressor prior to assembling the chiller is the most expensive of the three improvements, at a cost of approximately \$100/unit (or \$150,000 per year for a production rate of 1500 19XL's/year). Caulking around the flanges and compressor feet will cost approximately \$30/unit, or \$45,000/year. Brushing primer into inaccessible areas will cost approximately \$12.50/unit, or \$18,750/year. Therefore, the total cost of the process improvements is approximately \$215,000/year.

Appendix 2 contains a spreadsheet documenting the process used to estimate the cost of the rework and the process improvements.

The total cost savings resulting from implementing the process improvements can only be estimated at this time. No data is available to measure the amount of rework that can be eliminated by the process improvements. A small number of chillers were made using the process improvements. These were stored for a short time on site and then shipped to customers in China. Paint performance was noticeably better in storage than on chillers made without the improvements. Feedback has not yet been received on the condition of the units upon arrival in China. The small number of units shipped would also preclude quantifying the improvements with great precision.

The amount of rework that would be eliminated by the process improvements was conservatively estimated at 60%. This would result in a net cost savings to the company of approximately \$300,000/year, as shown in Figure 13. The process improvements would "break even" if they only eliminated 25% of the rework. The general consensus of TR-1's management was that the improvements would easily surpass the "break even" point. The actual amount of improvement will be measured over time.

<u>Current rework costs</u>		<u>Cost of process changes</u>	
within TR-1	\$ 75,000/yr	priming compressor	\$150,000/yr
at customer site	\$800,000/yr	caulking flanges	\$ 45,000/yr
		brushing primer	\$ 20,000/yr
total	\$875,000/yr	total	\$215,000/yr
assuming the process changes eliminate 60% of the rework the Net savings = \$300,000/yr			
Estimated Cost Savings from Process Improvements			

Figure 13

Source: TR-1 Operations

7.2. Environmental benefits

In addition to cost impacts, the rework adds a significant amount of emissions to the environment. Applying additional paint during rework steps results in increased emissions of volatile organic compounds (VOC's). VOC's are photochemically reactive materials that contribute to the formation of tropospheric ozone, or smog. Approximately seven gallons each of primer and topcoat are required to paint a 19XL chiller. This results in emissions of approximately 29 pounds of VOC/unit. Total emissions from 19XL painting are approximately 43,000 lb/yr of VOC (assuming 1500 produced per year). Reworking the paint on a 19XL in the storage area results in additional emissions of 166 lb/yr of VOC. Reworking the paint in the factory results in additional emissions of 395 lb/yr of VOC. Reworking the paint at the customer site results in additional emissions of 27,000 pounds/yr of VOC. This number is large because solvent based paints are commonly used for rework at the customer site instead of the water based materials used in TR-1. The rework is increasing VOC emissions from the process by approximately 65%.

A more detailed analysis of these emissions estimates can be found in Appendix 3.

Implementing the process improvements will add little or no VOC emissions to the process. By eliminating a portion of the rework, the process improvements will also yield significant environmental benefits.

7.3. Other benefits

Implementing the process improvements discussed previously will have other benefits. These benefits are real, but more difficult to quantify. The net result of the improvements will be to reduce the amount of paint rework required. This will minimize disruptions to the production line in TR-1 caused by completed chillers being returned to the line for rework. Delivery schedules will become more predictable as completed chillers can be shipped to customers without allowing for the time to potentially rework the paint at a customer site. Because the process improvements were originally suggested by hourly employees, implementing them will provide feedback to the hourly workforce that the company is serious about improving product quality. This feedback will help develop a more cooperative relationship between hourly employees and management in TR-1. Finally, Carrier's reputation with its customers will be improved by improving the quality of the paint on its chillers.

Perhaps most importantly, the lessons learned from correcting the problem addressed in this thesis can be used to solve other problems in TR-1. Organizational learning capabilities are becoming much more important competitive weapons.

8. Recommendations

The paint problems in TR-1 arise from management systems that fail to provide incentives for identifying and correcting product quality problems. These management systems reward TR-1 employees for minimizing labor costs within TR-1, while ignoring more important issues like minimizing total product cost and quality. Changing these management systems to align TR-1 employees' and the business unit's objectives will increase the rate of pace of change in the plant, and help the business unit achieve its goal of becoming profitable.

As a result of this study, the following recommendations were developed to improve the performance of manufacturing operations within TR-1. The recommendations are provided in two groups, those that impact specific operations and those more general in nature.

The following recommendations apply to specific operations within TR-1:

1. The effect of implementing the recommended painting process changes should be documented. Further improvements can then be planned using this information.
2. The size of the finished goods inventory should be reduced. This will both reduce the amount of weather related damage to the paint and free up capital for more productive uses. This can be done in the following two ways.

The factory should be given "credit" for building a unit only when it is either shipped to the customer or entered into "bill and store", "stock" or "sold" inventories. Currently, TR-1 receives credit for building a unit when it leaves the factory door, regardless of when the unit is actually needed by the customer. There are no penalties for the factory building units too soon, because Marketing manages the finished goods inventory. To optimize production rates, TR-1 must be responsible for the finished goods inventory, so it can balance the benefits of level loading the factory with the costs of creating excess inventory.

The amount charged to local sales offices for holding "sold" inventories should be increased to reflect the true costs of holding the inventory. The sales offices are currently charged only a small portion of the value of the "sold" inventory each year. This transfer price reflects the cost of the capital tied up, but does not reflect the costs of managing the inventory. The costs associated with providing space for the inventory, staffing for the storage area and reworking weather related

damage should be passed on to the sales offices. This increase in the cost of “sold” inventory will decrease the demand for it.

The following recommendations are made to address broader problems in TR-1:

1. The chiller assembly lines in TR-1 should be managed as level loaded production lines. Each chiller should have an assigned completion date. This is possible because of the relatively small number of units produced. Performance should be measured by comparing the actual production schedule with the planned schedule, instead of the currently used weekly quota system. These changes will eliminate much of the workflow variation, excessive cost and quality degradation previously discussed.
2. A quality metric should be incorporated in the incentive pay system. The current system provides incentives only for minimizing the labor content of the product. This is often done at the expense of quality. Rewarding employees for both minimizing costs and maximizing quality would better align the incentive system with the business unit’s goals. Changes to this incentive system will need to be negotiated as part of the Syracuse site wide collective bargaining agreement.
3. A long term plan should be developed to focus all efforts in TR-1 on supporting the plant’s role in the CAES business unit’s turnaround. The plan must contain detailed descriptions of the actions to be taken and the schedule to be followed. Most employees interviewed in this study did not know what their role in the turnaround was. Without this plan and its emphasis on long term goals, achieving short term production targets has become the primary goal of the TR-1 organization.
4. Cross functional quality improvement teams should be formed to identify the root causes of production problems, and then to develop and implement solutions as needed. All levels of employees should be involved in these teams, from the shop floor to the plant manager. These efforts should be modelled after the many shop floor based quality improvement efforts that have produced significant quality and productivity improvements elsewhere in United Technologies and in a wide variety of industries throughout the world. These cross functional teams will both improve TR-1 operations and break down the barriers between the hourly workforce and plant management.

An excellent place to start using this approach towards quality improvement would be to attack the problem of workflow variation. The daily variations in workflow in the latter half of TR-1’s production lines are both expensive (through the wasteful use of overtime at the end of the week) and damaging to quality (the “Friday quality” discussed in Chapter 5). The broad scope of this

problem will require many different people to become involved in the quality improvement process. Level loading production in these areas will both reduce costs and improve quality.

9. Appendix 1 Paint Thickness Test Matrix



To: [REDACTED] (A)
 [REDACTED] (C)
 [REDACTED] (C)

Date: July 2, 1996

From: [REDACTED]

Office: Technical Services

Subject: Coating Evaluation: Final Report

We have completed the evaluation of the 12-hr cure and 2-day cure samples (Cast iron and Hard rolled steel) that you sent to us.

The coupons were subjected to a Humidity/Condensation cyclic test with a total test time of 24 hrs for each cycle. Each cycle included two phases: 10 hrs of heating at $50 \pm ^\circ\text{C}$ followed by 14 hrs of cooling at room temperature. The test was performed for a total of 20 cycles (20 days). A total of 30 samples were tested. The samples with Top coat thickness less than 1 mil rusted after one cycle. The rest of the samples held up till the end of the 20 cycles. Also, the 2-day cure samples appeared to perform better than the 12-hr samples. Samples with the following topcoat thickness and cure time showed blisters at the end of the 20 cycles:

<u>Samples with blisters after 20 - cycle exposure</u>	<u>Topcoat thickness (mils)</u>	<u>Cure time</u>
Cast iron	1.64	12 hrs
Hard rolled steel	1.66	12 hrs
Hard rolled steel	1.7	12 hrs
Hard rolled steel	1.76	12 hrs
Hard rolled steel	1.4	2 days
Hard rolled steel	1.46	2 days
Hard rolled steel	1.48	2 days

The blisters were classified according to ASTM D 714 - 87 (1992) designations. The results are summarized in the attached tables and pictures.

In all, premature corrosion failure of the samples can be reduced by increased (or proper) coating thickness and longer curing times prior to encapsulation of the chiller.

Please let me know if you have any questions. I can be reached at X6981.

[REDACTED]

Coating evaluation.
Humidity exposure testing.
12-Hr cure. After exposure results.

Coupon	Top coat thickness (mils)	Type	Appearance of topcoat after exposure
HC1	2.86	Cast iron	Intact
HC2	3	Cast iron	Intact
HC3	1.66	Cast iron	Intact with rust spots
HC4	1.64	Cast iron	Intact with few blisters (size 6)
HC5	0.5	Cast iron	Failed after one cycle
HC6	0.44	Cast iron	Failed after one cycle
HC7	1.66	Hard rolled steel	Intact with medium blisters (size 6) and rust spots
HC8	1.76	Hard rolled steel	Intact with medium - dense blisters (size 6)
HC9	1.7	Hard rolled steel	Intact with medium blisters (size 6) and rust spots
HC10	3.44	Hard rolled steel	Intact
HC11	3.18	Hard rolled steel	Intact
HC12	3.24	Hard rolled steel	Intact
HC13	0.64	Hard rolled steel	Failed after one cycle
HC14	0.58	Hard rolled steel	Failed after one cycle
HC15	0.6	Hard rolled steel	Failed after one cycle

Coating evaluation.
Humidity exposure testing.
2-Day cure. After exposure results.

Coupon	Top coat thickness (mils)	Type	Appearance of topcoat after exposure
HC16	0.54	Cast iron	Failed after one cycle
HC17	0.6	Cast iron	Failed after one cycle
HC18	1.48	Cast iron	Intact
HC19	1.64	Cast iron	Intact
HC20	3.02	Cast iron	Intact
HC21	3.06	Cast iron	Intact with rust spots
HC22	0.48	Hard rolled steel	Failed after one cycle
HC23	0.48	Hard rolled steel	Failed after one cycle
HC24	0.5	Hard rolled steel	Failed after one cycle
HC25	1.4	Hard rolled steel	Intact with few blisters (size 6) and rust spots
HC26	1.48	Hard rolled steel	Intact with few blisters (size 6) and rust spots
HC27	1.46	Hard rolled steel	Intact with few blisters (size 6) and rust spots
HC28	3.08	Hard rolled steel	Intact
HC29	3.5	Hard rolled steel	Intact
HC30	3.38	Hard rolled steel	Intact with rust spots

Coating evaluation.
Humidity exposure testing.
12-Hr cure.

Coupon	Spray point 1	Spray point 2	Spray point 3	Spray point 4	Spray point 5	Thickness (mls)		Type
HC1	3.4	3.4	3.5	3.4	3.5	3.44	Primer	Cast iron
	2.9	3.1	2.8	2.5	3	2.86	Topcoat	
HC2	3.5	4.1	3.9	4.1	4.2	3.96	Primer	Cast iron
	3.1	2.9	3	3.1	2.9	3	Topcoat	
HC3	1.5	1.4	1.7	1.5	1.4	1.5	Primer	Cast iron
	1.4	1.6	1.8	1.7	1.8	1.66	Topcoat	
HC4	1.7	1.3	1.7	1.6	1.7	1.6	Primer	Cast iron
	1.5	1.6	1.6	1.7	1.8	1.64	Topcoat	
HC5	0.7	0.8	0.8	0.4	0.4	0.62	Primer	Cast iron
	0.5	0.4	0.4	0.6	0.6	0.5	Topcoat	
HC6	0.7	0.7	0.7	0.7	0.8	0.72	Primer	Cast iron
	0.4	0.4	0.5	0.4	0.5	0.44	Topcoat	
HC7	1.5	1.6	1.4	1.8	1.8	1.62	Primer	Hard rolled steel
	1.6	1.4	1.7	1.8	1.8	1.66	Topcoat	
HC8	1.3	1.5	1.6	1.3	1.4	1.42	Primer	Hard rolled steel
	1.8	1.6	1.7	1.8	1.9	1.76	Topcoat	
HC9	1.5	1.5	1.2	1.7	1.4	1.46	Primer	Hard rolled steel
	1.7	1.6	1.7	1.7	1.8	1.7	Topcoat	
HC10	3.7	3.8	3.9	3.9	4	3.86	Primer	Hard rolled steel
	3	3.2	3.1	4	3.9	3.44	Topcoat	
HC11	3.7	3.8	3.7	3.5	3.5	3.64	Primer	Hard rolled steel
	3.1	3	3	3.2	3.6	3.18	Topcoat	
HC12	3.5	3.7	3.8	3	3.6	3.52	Primer	Hard rolled steel
	3.4	3.1	3.1	3.6	3	3.24	Topcoat	
HC13	0.6	0.7	0.6	0.5	0.6	0.6	Primer	Hard rolled steel
	0.5	0.6	0.7	0.7	0.7	0.64	Topcoat	
HC14	0.8	0.3	0.4	0.4	0.6	0.5	Primer	Hard rolled steel
	0.5	0.7	0.6	0.7	0.4	0.58	Topcoat	
HC15	0.5	0.7	0.5	0.7	0.6	0.6	Primer	Hard rolled steel
	0.6	0.5	0.7	0.5	0.7	0.6	Topcoat	

Coating evaluation.
Humidity exposure testing.
2-Day cure.

Coupon	Spray point 1	Spray point 2	Spray point 3	Spray point 4	Spray point 5	Thickness (mils)		Type
HC16	0.5	0.8	0.7	0.8	0.8	0.72	Primer	Cast iron
HC17	0.6	0.5	0.5	0.5	0.6	0.54	Topcoat	Cast iron
	0.7	0.7	0.8	0.7	0.7	0.72	Primer	
HC18	0.6	0.7	0.4	0.6	0.7	0.6	Topcoat	Cast iron
	1.7	1.9	1.6	1.6	1.8	1.72	Primer	
HC19	1.4	1.5	1.4	1.5	1.6	1.48	Topcoat	Cast iron
	1.6	1.6	1.8	1.3	1.8	1.62	Primer	
HC20	1.5	1.8	1.6	1.8	1.5	1.64	Topcoat	Cast iron
	3.9	3.8	4	3.9	3.9	3.9	Primer	
HC21	3	2.8	3	3.1	3.2	3.02	Topcoat	Cast iron
	3.9	3.9	4	3.5	3.9	3.84	Primer	
HC22	3.1	3	3	3.1	3.1	3.06	Topcoat	Hard rolled steel
	0.6	0.7	0.7	0.7	0.6	0.66	Primer	
HC23	0.5	0.6	0.4	0.4	0.5	0.48	Topcoat	Hard rolled steel
	0.7	0.7	0.6	0.7	0.6	0.66	Primer	
HC24	0.4	0.6	0.5	0.4	0.5	0.48	Topcoat	Hard rolled steel
	0.7	0.7	0.8	0.8	0.7	0.74	Primer	
HC25	0.6	0.5	0.5	0.4	0.5	0.5	Topcoat	Hard rolled steel
	1.9	1.8	1.9	1.9	1.9	1.88	Primer	
HC26	1.4	1.5	1.5	1.4	1.2	1.4	Topcoat	Hard rolled steel
	1.9	1.9	1.8	1.9	1.8	1.86	Primer	
HC27	1.4	1.5	1.6	1.4	1.5	1.48	Topcoat	Hard rolled steel
	1.8	1.9	1.8	1.8	1.9	1.84	Primer	
HC28	1.4	1.6	1.4	1.5	1.4	1.46	Topcoat	Hard rolled steel
	3.8	3.9	3.7	3.7	3.8	3.78	Primer	
HC29	3.1	3	3	3.1	3.2	3.08	Topcoat	Hard rolled steel
	3	3.5	3.6	3.7	3.7	3.5	Primer	
HC30	4	3.4	3	3.1	4	3.5	Topcoat	Hard rolled steel
	3.5	3.7	3.6	3.7	3.8	3.66	Primer	
	3	3.5	3.2	3.2	4	3.38	Topcoat	

10. Appendix 2 Paint rework cost analysis

		labor cost =	\$25.00	per hour	from [redacted]
annual 19 series production	store < 2 weeks before shipping				
1500		62% from database			
	annual total				
		930			
	store in Shang-n-la > 2 weeks	% of stored units requiring paint rework =			90% from CIA audit
		38% % of reworked units repaired in SRA =			50% guess
	annual total				
		\$70			
		cost of rework in SLA			
		labor	2 (hrs/unit)	estimate	
		labor	50 (\$/unit)		
		materials	5 (\$/unit)	estimate	
		total	55 (\$/unit)		
		cost of rework in TR-1			
		labor	5 (hrs/unit)	from [redacted]	
		labor	\$125 (\$/unit)		
		materials	\$10 (\$/unit)	estimate	
		transportation	\$100 (\$/unit)	estimate	
		total	\$235 (\$/unit)		
	TR-1 rework cost =		\$74,385	per year	
	% of units to domestic customers	% of domestic units requiring repainting =			0% from [redacted]
		30%			
	% of units exported	% of exported units requiring repainting =			50% from [redacted]
		70%			
		cost of repainting domestic units =			\$0
		cost of repainting exported units =			\$1,500 from [redacted]
	cost of repainting at customer site =		\$78,500	per year	
	paint warranty costs =		\$0	per year	
	total annual paint rework costs for 19 series =		\$861,885	per year	

11. Appendix 3 Volatile organic compound emissions estimates

estimate of VOC emissions from 19XL painting process

model 19XL as three heat exchangers because the surface area of the compressor is difficult to estimate

- 3 number of heat exchangers
- 19 length (ft)
- 3.5 diameter (ft)
- 684 total surface area including ends of exchangers (ft²)

- 0.006 estimated average final paint thickness (inch)
- 36 % solids in paint by volume
- 50 % transfer efficiency of painting process (estimated)
- 7.5 gal/ft³ conversion factor

14 estimated total amount of paint applied (gal)

assume this is half primer and half topcoat

- 2.2 lb/gal VOC in primer
- 1.8 lb/gal VOC in topcoat
- 1500 annual 19XL production rate
- 29 total VOC emissions per unit (lb)
- 42780 annual VOC emissions from 19XL painting (lb/yr)

estimate of VOC emissions from rework processes

rework in storage area

- 16 estimated amount of aerosol touchup paint used (ounces)
- 5.2 lb/gal VOC in aerosol touchup
- 255 19XL units/year reworked in storage area
- 166 total VOC emissions from rework in storage area (lb/yr)

rework in factory

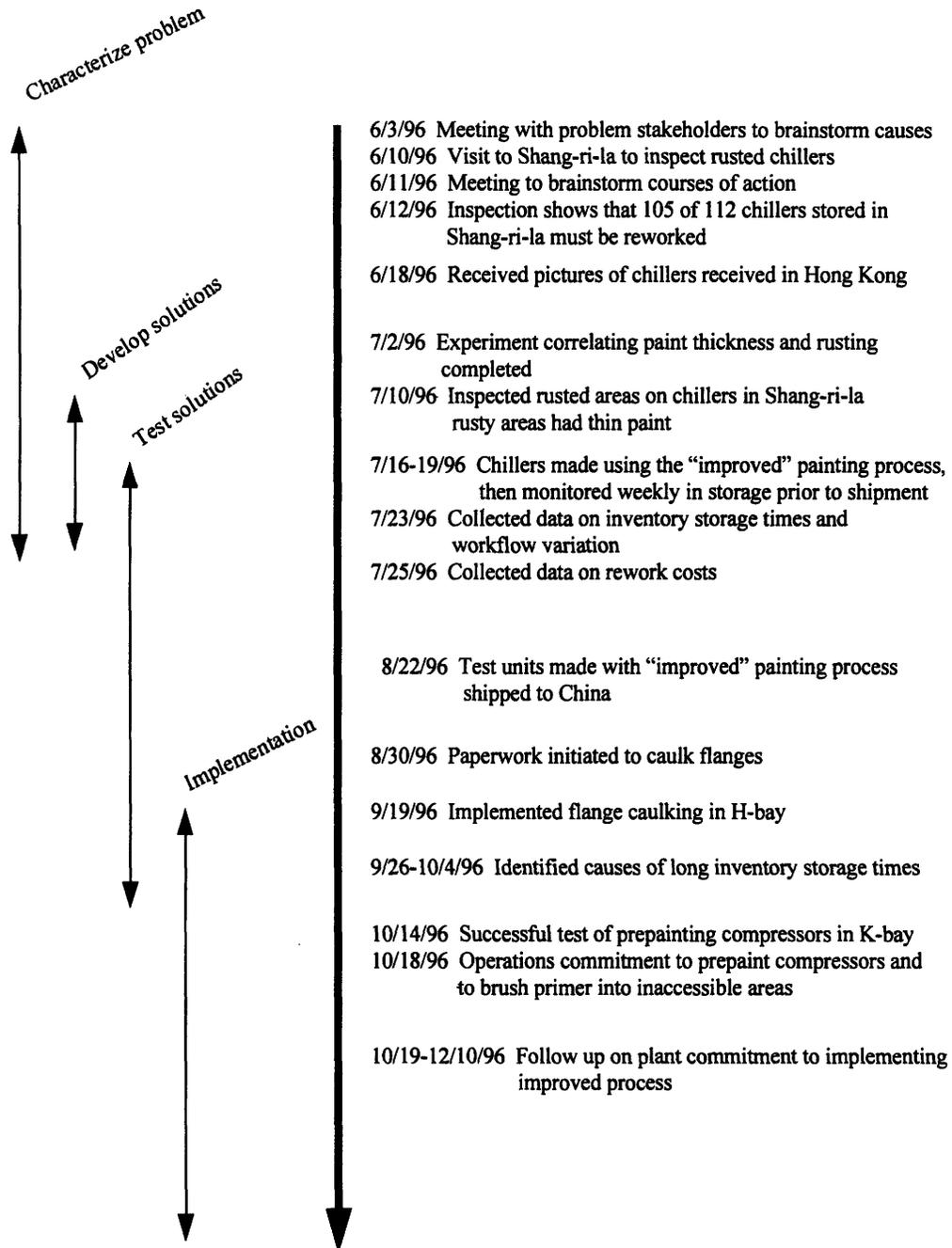
- 16 estimated amount of aerosol touchup paint used (ounces)
- 0.5 estimated amount of topcoat used (gal)
- 255 19XL units reworked in the factory
- 395 total VOC emissions from rework in factory (lb/yr)

rework at customer site (assuming 3 mils paint solvent based paint applied, 50% transfer efficiency, 25% solids by volume)

- 10 estimated amount of touch up paint applied (gal)
- 52 VOC emissions per unit (lb)
- 525 19XL units reworked at customer site
- 27300 total VOC emissions from rework at customer site (lb/yr)

- 27861 estimated total VOC emissions from rework (lb/yr)
- 65 % increase over normal production emissions

12. Appendix 4 Time Line for Research Activities



13. Bibliography

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