SHOP VS. FIELD CORRECTIONS TO EQUIPMENT

by

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ABSTRACT

The objectives and types of shop testing for special purpose compressor trains are presented. Actual shop and field delays for various types of deficiencies are compared, and the period of time required to solve a problem at various stages of engineering is addressed.

INTRODUCTION

With special purpose equipment, it is very common to justify the cost of reliability against the cost of unplanned downtime. The use of American Petroleum Institute (API) specifications and vibration monitoring equipment are some items usually incorporated into designs to reduce emergency downtime.

The not-so-obvious costs incurred as the result of delays in project startup are addressed herein. The special purpose equipment is generally on the critical path of a project. Any delay in this equipment will theoretically cause the project startup to be delayed. The money invested in the project, which can range from several million dollars to over a billion dollars, is encumbered. The facilities are not operating: the invested money is idle. There is no return on investment.

Since the equipment is on the critical path, there is a temptation to compromise equipment technical review and content for project schedule, if insufficient time is allotted for equipment review. Project schedules and equipment review must be compatible. Compromises, particularly in the early stages of the equipment requisition or engineering, appear to be harmless. In reality, however, these compromises can become time bombs. Incomplete specifications are issued, generalized proposals are evaluated, and the equipment is quickly placed on order. Problem areas remain hidden until the unit is tested or started up in the field. By that time the options have been reduced and it takes considerably more time to make corrections.

The consequences of these compromises and some methods used to minimize field problems are described herein. The objectives and types of tests required by petrochemical and other users are described. Actual shop and field delays for various types of deficiencies are compared, and the period of time needed to solve a similar type of problem when the problem is uncovered at various stages from order placement to field startup is outlined.

OBJECTIVES OF SHOP TESTING

The objective of shop testing is to prevent startup delays by confirming that the equipment is mechanically and aerodynamically designed, manufactured and assembled properly.

TYPES OF TESTS

To accomplish this objective, two types of tests are performed. For compressors, aerodynamic performance is determined by running an American Society of Mechanical Engineers (ASME) performance test. This test is used to determine whether the compressor produces the quoted horsepower, flow and discharge pressure requirements. It is used also to determine the minimum flow (surge) that the compressor can compress. The lower the surge flow, the greater the horsepower savings at reduced operating conditions.

The second type of test, a mechanical run, determines the mechanical integrity of the compressor, driver and auxiliaries. The equipment train is operated at its maximum operating speed for four hours. During this test, the equipment's dynamic characteristics are determined—i.e., critical speed and vibration levels, as well as a check on the operation of the compressor bearings, seals and related auxiliaries. Extensive vibration data, as well as temperature, flow and pressure of the steam, oil and gas being used by the train, are recorded and evaluated. These data are used as a baseline against which subsequent field operation is compared.

TESTING REQUIREMENTS OF API AND USERS

A comparison of the API mandated tests, and those required by users, is shown in Figure 1. This data is based upon conversations with five manufacturers of special purpose compressors in the U.S.A., four major contractors/consultants and seven major users. The testing requirements of the seven users are compared in Table 1.

The use of the term "string test" in Figure 1 and Table 1 describes a test in which more than one piece of purchased rotating equipment is tested together as a unit. This type of test checks the interaction of the driver and driven equipment.

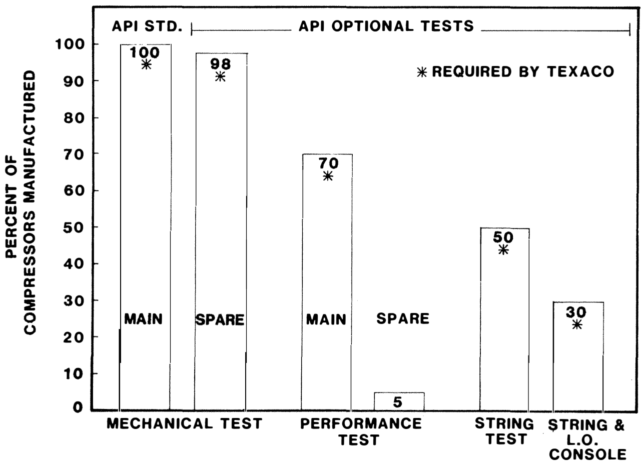

Figure 1. Shop Testing Survey Special Purpose Compressors.

Table 1. Testing Requirements of Users.

	API MECH. RUN MAIN	API MECH. RUN SPARE	PERFORMANCE TEST MAIN	PERFORMANCE TEST SPARE	L.O. CONSOLE	STRING TEST	STRING & L.O. CONSOLE
USER A	X	X	X		X	X	X
USER B	X	X	X		X	X	
USER C	X	X	X		X		
USER D	X	X	X		X	X	
USER E	X	X	X		X	X	X
USER F	X	X	X		X		
USER G	X	X	X		X	X	

"Mechanical" tests, "String" tests and "String and Lube Oil Console" tests are indicated as separate tests. This implies three different shop test setups. This is not the case. The compressor, its driver, and lube oil console are assembled in one test setup. While in this configuration the equipment is run to determine its mechanical integrity. The lube oil console is used to supply oil to the train and the oil console functions are checked. In many cases, the compressor's performance test can also be conducted while in this configuration.

These comparisons show that testing requirements agree within the majority of the industry in all cases except for the combined string and job lube console test. In this testing, the job lube and seal oil console is used to supply oil to the entire compressor train during testing. The main purpose of requiring this test is to ensure that the lube and seal oil console is manufactured on time and shipped with the compressor. Before instituting this requirement, the console was usually late. If this test is not required, the compressor manufacturer will use the shop console for the equipment tests.

To minimize field problems, the guiding philosophy should be to shop test the equipment as closely as possible to actual field operating conditions.

COMPARISON OF STARTUP DELAYS WHEN MANUFACTURING, ASSEMBLY AND DESIGN ERRORS ARE FOUND ON SHOP TEST VS. FIELD TEST

The actual time required to fix four classes of defects when uncovered during shop testing, or when found later in the field, is indicated in Figures 2 and 3. Since this equipment is generally on the critical path of the project, for purposes of illustration, any delay is assumed to result in a delay in project completion and startup. It should be noted, however, that none of the seven users queried have ever experienced a project completion delay as the result of testing or subsequent corrections made to the equipment while in the vendor's shop. Only one contrator could cite an incident of actual startup delay attributed to results of shop testing. In this incident, the compressor's aerodynamic performance was totally unacceptable. It took the compressor vendor one year to fix the problem in his shop.

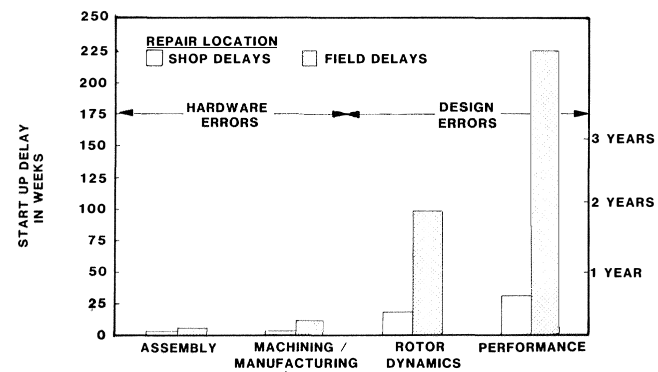

Figure 2. Average Time to Correct an Equipment Error.

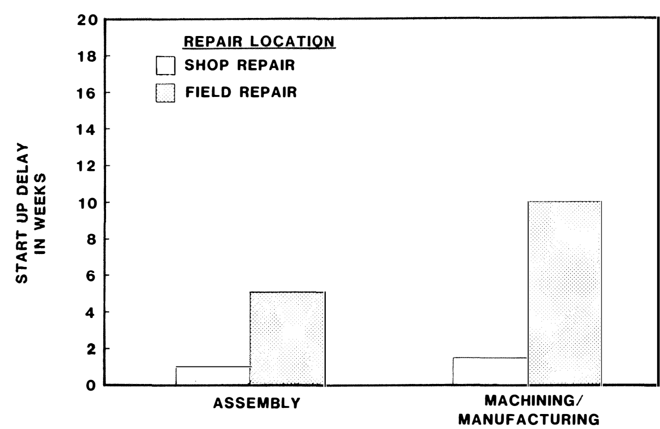

Figure 3. Average Time to Correct a Hardware Error.

Assembly errors are defined as all parts being manufactured properly but assembled improperly.

Machining/Manufacturing errors are defined as the component part not being in accordance with the manufacturer's in-house drawings.

Design errors are broken into two categories: those that affect the equipment critical speeds and rotordynamics, and those affecting the compressor's aerodynamic performance characteristics.

Shop Delays are uncovered during the assembly and testing phases in the vendor's shop. All compressor and turbine components have previously passed the vendor's in-house quality control checks. The manufacturing or assembly error found during shop testing is substantial enough to affect the equipment operation.

Discussion—Hardware Errors

To minimize the number of defective parts from getting past the vendor's in-house quality control program also requires the following:

1. Contractor's inspectors are to be in residence at the vendor shop to regularly monitor and inspect the manufacturing of the equipment.
2. Quality control checks must be performed during manufacturing and assembly.
3. Review of manufacturer's in-house quality control rejects are presented with written confirmation of rejected pieces disposition.

To minimize assembly and installation errors occurring in the field, on several projects, a contractor's field engineer has been required to closely follow the installation of this special purpose equipment. The designated engineer has been generally responsible for all mechanical equipment in an area. He, therefore, has been unable to adequately cover the special purpose equipment. Currently under evaluation is the proposal for having one contractor's field engineer assigned to supervise only the installation and run-in of all special purpose rotating equipment on future projects.

Discussion—Design Errors General

Design errors are less numerous than hardware errors. However, when they do occur, they take longer to correct. They can result in substantial delays even when found in the shop.

Performance Design Errors

Performance design errors are found during the shop performance tests. Most of the compressors that have been performance tested have actual performances different from those shown in the vendor's proposal. A survey of the seven users and four contractors indicated an average of 30 percent of the compressor performance deficiencies were severe enough to require shop modifications and retesting. Performance design errors are the most difficult to correct, and therefore generally take the longest period of time to correct.

The best means of preventing a major performance problem is to closely review, in the proposal stages, the compressor manufacturer's previous aerodynamic experience with the quoted impellers. Design limits should be set on certain aerodynamic performance parameters. The vendor's chief engineer is also required to sign the proposal, indicating that he has reviewed it, particularly with regard to compressor performance. During the coordination and design review meetings, the basis for the vendor's prediction of compressor performance should be reviewed in detail. Impeller/diffuser performance, nozzle velocities, internal losses, relative Mach numbers, and stage-diffusion ratios are reviewed and evaluated.

Due to energy conservation efforts, the trend is to use motor drivers for compressors. This generally eliminates speed as a performance correction factor. Determination of motor driven compressor performance, therefore, is critical. On two recent projects, refrigeration compressors required trimming of their impellers to make them operable. Corrections made to one of these compressors resulted in energy savings of approximately $300,000 over the pay-out period.

Performance deficiencies, if not found during shop testing, generally are extremely difficult to correct in the field. Performance deficiencies normally result in increased operating costs and reduced operating flexibility. Field performance tests are expensive and difficult to conduct.

Performance tests not only check the designer's calculations, but also confirm that the equipment is manufactured and assembled correctly. Reports of impellers installed with reverse rotation, particularly on back-to-back rotor configurations, improper impeller diameters and blocked passages are not uncommon. In fact, when close attention is paid to the designer's calculations and experience, these errors soon become the major cause of undesirable compressor performance.

Rotordynamic Design Errors

The rotordynamic design errors are found during the mechanical run of the equipment. The most common problem is the manufacturer's inability to accurately predict the frequency and severity of the equipment's critical speeds. Fifty percent of the projects during the last ten years have had vibration and/or critical speed design problems associated with the special purpose rotating equipment. This does not take into account the high vibration problems which can be easily corrected by rebalancing.

The field of rotordynamics is extremely complicated. The rotors' dynamic response can be affected by the following (based on API 617 5th Edition "Centrifugal Compressors for General Refinery Services"):

- Support (base, frame, and bearing housing) stiffness, mass, and damping characteristics, including effects of rotational speed variation.
- Bearing lubricant film stiffness and damping changes due to the bearing design (tilting pad, pressure dam, cylindrical) speed, load, oil temperatures, accumulated assembly tolerances, and maximum-to-minimum clearances.
- Rotational speed, including the various starting speed hold points, operating speed and load ranges (including agreed upon test conditions, if different from those specified), trip speed, and coast-down conditions.
- Rotor masses, including the mass moment of coupling halves, stiffness, and damping effects (for example, accumulated fit tolerances, fluid stiffening and damping, and frame and casing effects.)
- Asymmetrical loading (for example, partial arc admission, gear forces, side streams, and eccentric clearances).
- Seals.

In one recent analysis, the critical speed of a rotor could vary by several thousand cpm with a 0.001 in range in bearing clearance. In another example, the modulus of elasticity for the rotor changed from 2.7×10^7 to 1.7×10^7 the result of the temperature variation between operating and test conditions. This resulted in the rotor's critical speed dropping into the operating speed range. Gear and turbine critical speeds can be greatly affected by the horsepower being transmitted or produced. Therefore, unloaded shop tests can be misleading. This is one reason that special purpose equipment is required to be operated in the vendor's shop as close as possible to actual field operating conditions.

As with performance, the trend toward the use of motor driven compressors reduces options for corrective action. One can no longer operate at another speed when the critical is on or near the operating speed. In addition, the compressor train's complexity is increased by the additional requirement of a gear.

Rotordynamic problems that are not corrected in the shop generally have a more dramatic impact on operation than performance deficiencies. The result of improper rotordynamic performance is usually high vibration, which is a sign of machinery distress. Equipment vibration is continuously monitored in the field. Vibration trends are noted and equipment is shut down on high vibration. Performance deficiencies silently consume energy.

Field corrections for design errors are extremely time consuming, expensive, disruptive to manpower, can result in considerable lost product and increased operating cost. Quick field modifications are hampered by the unavailability of meaningful or mutually acceptable data, experienced personnel, and vendor reluctance to accept responsibility. The equipment is now on the user's foundation, with user's gas, and connected to the user's piping.

Discussion and Examples

In summary, an analysis of Figure 2 indicates:

• Field correction of design errors can substantially affect project completion. Equipment costing one million dollars can cause revenue losses of four to 180 million dollars.

• Design errors, even when found during shop testing, can result in significant project delays.

• Design errors take 10 to 20 times longer to correct in the vendor's shop than hardware errors.

• It takes approximately eight times longer to fix a problem in the field than it does to correct the same problem in the vendor's shop.

The project delays when the same type of design problem, i.e., critical speed, is discovered at various steps of the project is illustrated in Figure 4. Point A represents the time it took to resolve critical speed problems discovered during the coordination meetings for two compressor trains. One compressor was for propane service, the other one was for propylene service. It took five weeks to resolve the critical speed problems. During this time period:

• The manufacturer's data was analyzed and it was determined that a problem might exist.

• The manufacturer's analysis was examined.

• The services of a consultant were obtained.

• The consultant did an independent analysis and confirmed the existence of a problem.

• The manufacturer was informed of the consultant's results.

• The manufacturer reanalyzed his data and recommended a modification which was accepted by all parties at a subsequent meeting.

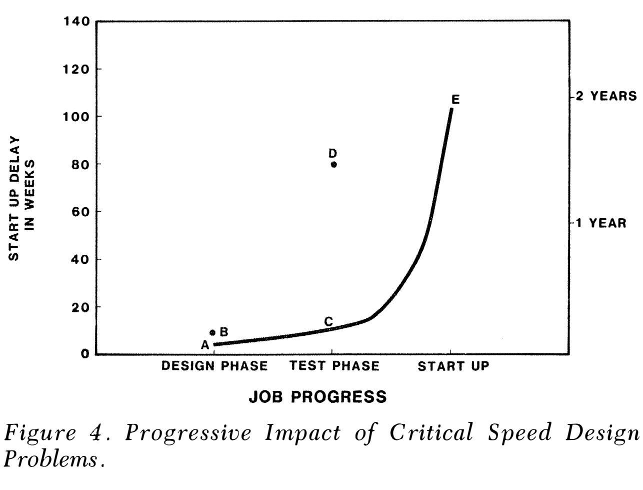

Figure 4. Progressive Impact of Critical Speed Design Problems.

Considering the coordination and analysis required, it is felt that the five week period is the minimum time in which this type of problem can be resolved at this stage of the design. For comparison, a recently purchased gear (Point B) which had critical speed problems on both the pinion and bull gears took ten weeks to resolve.

Point C represents the time it took to correct critical speed problems uncovered during the testing of two compressor drives. One was a steam turbine running on its second critical speed. The turbine manufacturer did not use the design overhung coupling moment during the solo shop runs. The problem was discovered during the compressor string test. The other turbine was well balanced and the first critical speed was discovered in the operating speed range, only as the result of unbalance response tests run during the turbine's shop mechanical tests. These were fairly straightforward corrections and, again, represented a minimum correction time. For example, it has taken over one and one-half years in another vendor's shop to correct critical speed, unbalance and instability problems on three power turbines. This example is plotted as Point D.

Point E represents the time it took to correct a critical speed problem in the field on a special purpose steam turbine. There were no design audits, unbalance response tests, or witness tests of this equipment in the vendor's shop. The turbine's initial cost was approximately \$500,000. The cost to correct the design error was over \$1,000,000, with over \$20,000,000 lost in product.

SUMMARY

The investigation indicates that testing requirements generally agree within petroleum and chemical companies.

Design errors require ten to twenty times longer to correct than manufacturing/assembly errors. It takes approximately eight times longer to correct a defect in the field than in the vendor shop.

Almost all of the special purpose compressors and turbines purchased have had manufacturing/assembly errors. These errors were found during the required shop tests.

Most of the compressors which were performance tested had actual performances different from that shown in the vendor's proposal.

An average of 30 percent of all compressors tested for the users and contractors contacted had performance deficiencies severe enough to require shop modifications and retest.

Half of the major projects over the last ten years had vibration and/or critical speed design problems on special-purpose rotating equipment.

The combined experience of all contractors and users contacted covered several hundred compressor trains. Only one incidence could be cited in which project startup was delayed due to shop testing and subsequent modifications.

CONCLUSION

The importance of reducing and/or preventing design errors from occurring is vividly illustrated in Figures 2 and 3. The examples used to determine field correction times occurred on units which were not closely audited in the equipment design phase or shop tested by the users. The emphasis, therefore, has been to closely monitor the special purpose equipment during its design phase, and duplicate, as closely as possible, field operating conditions on testing. Design audits of critical turbine blading should be checked carefully (perhaps using a numerical program) and in-house checking of the equipment vendor's rotordynamic critical speed calculations in the design phases should be performed. Continued emphasis on design audits and shop testing will assure on-time construction completion, and on-time trouble free unit startups.