

# THE OPERATOR'S CRITICAL NEED FOR QUALITY IN TURBOMACHINERY

by

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Richard (Dick) Dubner received a B.S. degree in Mechanical Engineering from the University of California-Berkeley (1954). He worked for Tidewater Oil Company and then Phillips Petroleum Company at their Avon, California, refinery. For most of the 13 refinery years he was the Mechanical Equipment Engineer. He specialized in design, installation, operation, and maintenance of mechanical equipment. In January 1968, he

joined Chevron Corporation, then known as Standard Oil Company of California, working for the Mechanical Equipment Division of the Corporation Engineering Department. In March 1969, he became Supervisor of that division. In 1981, he was made Chief Mechanical Equipment Engineer.

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Mr. Dubner is Chairman of the API Subcommittee on Mechanical Equipment. He has also served as chairman of task groups for reciprocating compressors, noise control, vibration monitoring systems, and headed the Subcommittee's Steering Committee. He is a member of the Executive Committee of the Pacific Energy Association's Board of Directors.

## ABSTRACT

Return on major capital investments in petroleum and petrochemical facilities, both on and offshore, frequently depends on timely startup and long term reliability of major mechanical equipment systems. In recent years, operating company machinery specialist engineers have taken an active role in vendor quality assurance to achieve these two objectives. Chevron's Corporate Engineering Mechanical Systems Division developed a successful program to ensure quality in such critical machinery.

Five major steps are included:

- Vendor prequalification—which vendors have proven themselves?
- Comprehensive specifications—complete, but understandable.
- Design auditing—will the machine be suitable?
- Manufacturing quality surveillance—build it right.
- Intensive factory testing—prove that the system works.

The early history, evolution, and current procedures Chevron uses are reviewed. The results from several large projects are presented. The economics of the program are reviewed.

## INTRODUCTION

The Corporate Engineering Department (CED) of Chevron Corporation is responsible for project design and construction

management on major facilities for the company (Figure 1). This project slate includes both onshore and offshore facilities such as refineries, chemical plants, gas and liquid pipelines, gas plants, mining, geothermal, and civil works.

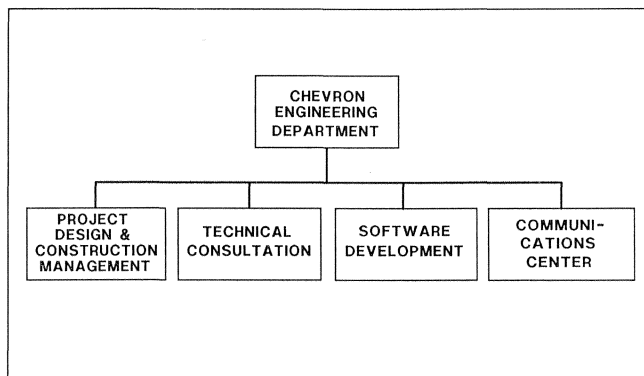


Figure 1. Chevron Engineering Department Function.

A second role of CED is direct technical consultation to Chevron's operating facilities. This counsel covers a wide range from major conversions of current equipment, failure troubleshooting and plant-wide energy conservation, to five-minute pieces of advice.

A third function of CED is developing software, such as specifications, computer programs, manuals for design of various facilities and contracts. CED serves as a center for internal and external technical communication, maintaining contact with a wide range of vendors, design contractors, consultants and other petrochemical companies.

The Mechanical Systems Division (MSD) of the Corporate Engineering Department has the following principal objectives (Figure 2):

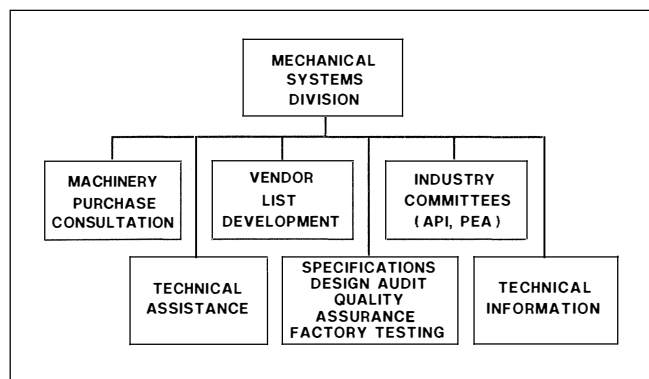


Figure 2. Mechanical Systems Division.

- Provide consultation for purchase of pump, turbine, compressor, gear, engine and gas turbine systems which enable on-time startup and safe, reliable operation. Production losses from delays in initial startup can be extremely costly. MSD's *number one objective* is putting a system in the field which will work properly the first time it is called upon.

- Lend technical and hands-on assistance to every operating area of the corporation, worldwide. This could involve improvements to existing equipment, field performance tests, upgrades, solving minor problems and analyzing catastrophic breakdowns.

- Develop acceptable vendor lists for all categories of mechanical equipment.

- Prepare all specifications, audit new machinery designs, develop and administer quality assurance for manufacturing and conduct factory or field testing programs.

- Participate in industry committees to develop standards and to share technology. The primary activity is with the American Petroleum Institute (API) Subcommittee for Mechanical Equipment. This subcommittee writes the internationally recognized API Standards on pumps, turbines, and other oil and gas industry machinery. These standards have been adopted by several other industries.

- Disseminate technical information throughout the corporation. People call from all over the company asking for help with problems or for experienced references from other company facilities or other vendors, contractors and consultants.

#### EARLY HISTORY OF CHEVRON'S QUALITY ASSURANCE SURVEILLANCE PROGRAM (QASP)

Twenty or thirty years ago, purchasing mechanical equipment systems was totally different from today. In those historical days, buying a large centrifugal compressor with a steam turbine driver, for example, was essentially just application engineering. The vendors were told what the process requirements were—flow, pressure, gravity, etc. Once the machine was purchased, the buyer more or less forgot about everything except piping and foundation details. When the machinery system was delivered, it would be installed, debugged, sometimes modified, and would normally run quite well for an acceptable period of time.

The early application of centrifugal compressors in straightforward services demonstrated that these machinery systems were very reliable. They were conservatively designed, carefully built and featured thoughtful redundancy in auxiliary systems, such as lube oil and seal oil. But machinery was becoming expensive. This demonstrated reliability, coupled with high cost, convinced most operators that redundancy was no longer vital for these critical machinery trains. While it had been common practice for years to use installed spare pumps and reciprocating compressors, the industry discovered it could manage with single, non-redundant centrifugal compressor trains (Figure 3).

The rude awakening came when infant mortality problems with such unspared machinery systems caused expensive delays in process plant startups. Even in those days, when a plant might earn only \$10,000 per day, forced outages or delayed startups could cost many times the machinery's purchase price (Figure 4). Process designs were pushing machinery toward higher pressures and higher power density, making even more demands on performance and reliability. Large ammonia plants, for example, were built with unspared, 30,000 hp steam turbine-driven centrifugal compressors.

Major breakdowns, especially during the first year of operation, began to become more and more common. Costs mounted. About fifteen years ago, several major oil companies jointly developed a way of looking at these failures to determine what

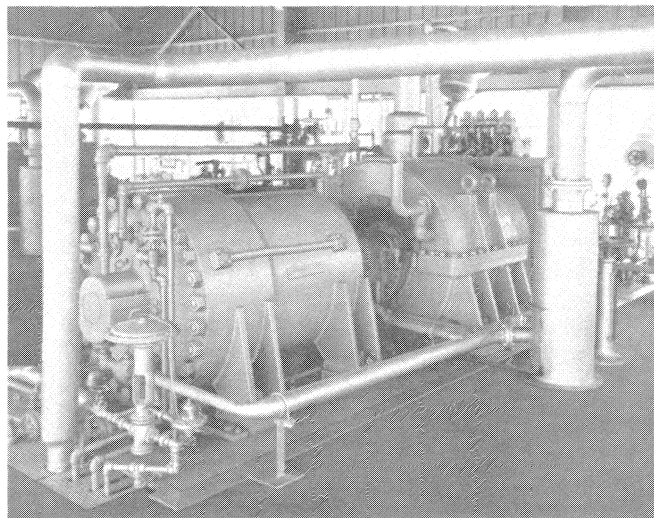


Figure 3. Centrifugal Compressor Train.

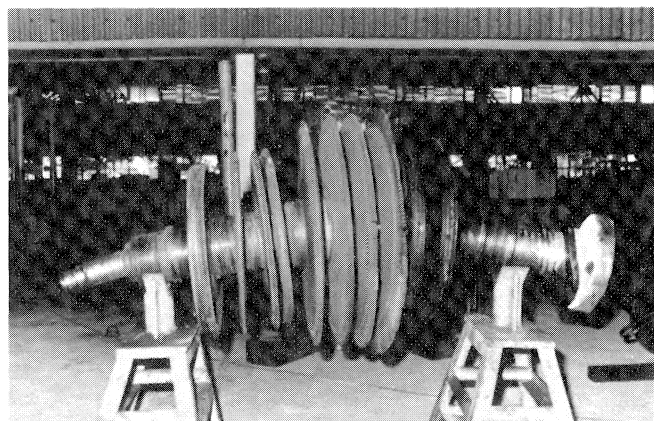


Figure 4. Wrecked Steam Turbine Rotor.

was causing them. Two indices were developed—the *Incident Index* and the *Delay Index*—both based upon the number and duration of shutdowns which occurred during the first year of plant operation (Figure 5 and Figure 6). When this data was analyzed, it was found that vendor error accounted for more than two-thirds of the big problems. The biggest single factor was design mistakes. A second major problem was the lack of manufacturing quality control (Figure 7). Subsequent evaluation showed that many of the problems were caused by communication lapses internally to the manufacturer, or between the user and the manufacturer.

Based on this analysis, Chevron started to plan for avoiding these problems in future projects. The first emphasis was on auditing the detailed design of major equipment before it was built. Manufacturing quality assurance surveillance came later.

#### MEETING THE NEED

One of the first steps in preparing to eliminate expensive machinery failures was increasing the seniority and field experience level for CED's Mechanical System Division engineers. Today, the division personnel average industry experience level is more than seventeen years.

MSD became heavily involved in working with the manufacturers to correct design and manufacturing problems with failed equipment in Chevron plants. Through this problem-solving work, basic design factors such as critical speeds and blade

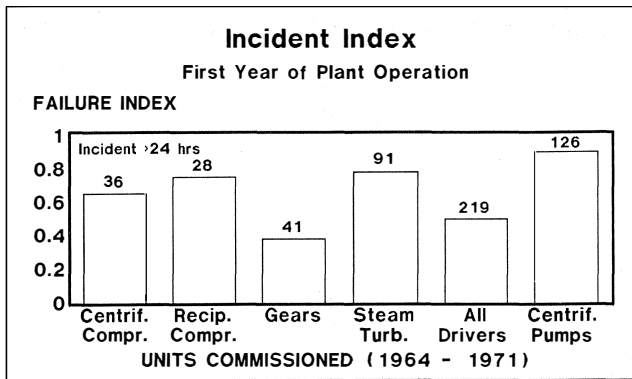


Figure 5. Major Machinery Failure Index.

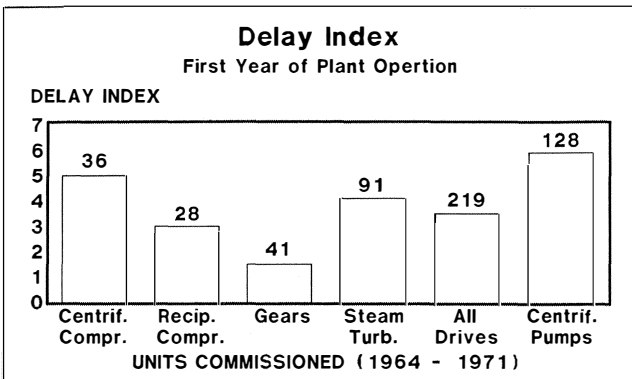


Figure 6. Major Machinery Downtime Index.

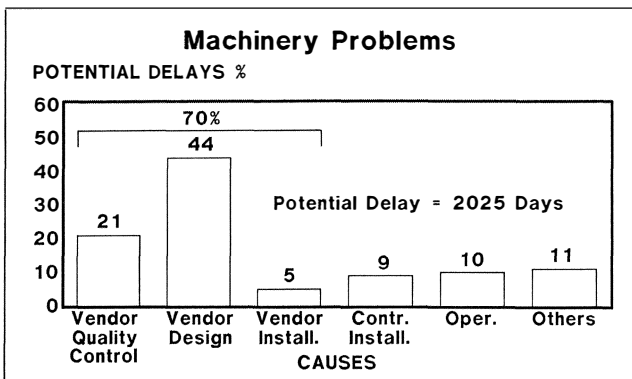


Figure 7. Causes of Machinery Problems.

stresses were understood. Many of the field problems resulted from excessive rotor vibration. In some cases, this was because the machines ran too close to the natural frequencies of the rotor-frame system. Another common difficulty, especially in steam turbines, was high-cycle fatigue blade failures.

On-line analysis of vibration spectra using noncontacting probe systems gave the first view of what was actually happening inside a high rotating speed machine. It certainly was not clear, however, what all the vibration information meant (Figure 8).

Gradually, over a period of years, machinery specialists began to replace the trial and error solutions of major field problems with technical analysis. The objective was to determine what caused the failure, and fix it right the first time.

Another development of those early years was engagement of third party consultants. These experts were usually mathematicians or former machinery designers. The industry found that some of these people could really augment their own experience

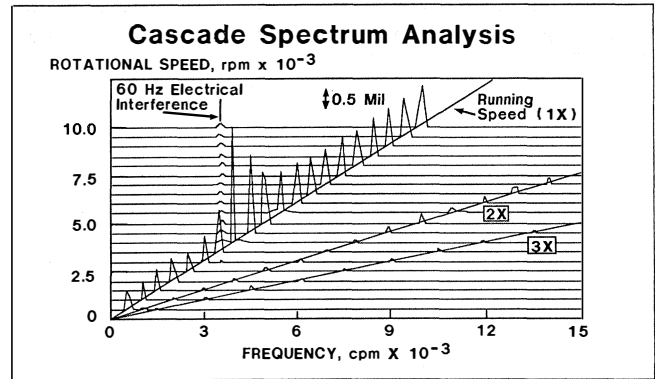


Figure 8. Cascade Spectrum Analysis of Rotor Displacement during Start-Up.

and knowledge in helping to solve machinery problems. The consultants were especially useful in looking at rotordynamics and turbine blade stresses. Later, other engineers and scientists, skilled in design and troubleshooting of hydrodynamic bearings, gears, pressure casings and foundations, were used.

Success in solving these field problems became fairly routine. And a great deal was learned about what were the typical causes of major machinery breakdown. That knowledge was put to use by auditing the design of newly purchased, multistage turbines and centrifugal compressors. Turbine blade design was the first major target. The audit made sure that in the operating range, major excitation of blade resonances was avoided. This program was quite successful.

The operators weren't really trying to design the equipment for the manufacturer. They were just making sure that all of the planned operating conditions, with their resultant stresses, were adequately covered in the design. It's true that this review forced additional conservatism into the design of machine elements such as steam turbine blades, but the increased costs were well worth it when viewed against the financial impact of lost operating time.

During these early phases of design auditing, the operators faced many arguments. Almost every manufacturer resisted incursions into their "proprietary information."

In the mid-1970s, manufacturing quality became a concern. For a period of several years, the oil business had not been buying much machinery. A number of manufacturers had cut back and laid workers off. There was concern about the adequacy of the remaining staff to build good machines for an expected upsurge in refinery plant construction.

### A NEW APPROACH

Chevron's Mechanical Systems Division developed the Quality Assurance Surveillance Program (QASP). This program was first applied to multistage steam turbines and centrifugal compressors for a major upgrade of a Southern California refinery. Just after order placement, Chevron engineers met with the vendor and agreed on what manufacturing areas were going to be looked at. The approach would be quality *surveillance*, not witnessing. This activity would be in addition to the normal witness-hold points such as hydrotesting, where a representative of the purchasing department was always given several days advance notice to be on hand. The surveillance people would very carefully check on critical machining, assembly, and balance operations. It was up to the QASP man to be at the factory at the right time—no advance notice and no stopping of production.

There was a great deal of hand wringing and soul searching in the early days. Many manufacturers strongly resisted this new

approach. They claimed that putting this surveillance man in their plant would interfere with the orderly progress of work through the shops. A few manufacturers, however, acceded readily to this new procedure.

Chevron started witnessing major equipment factory acceptance tests with MSD engineers. In the early days, there were many test stand arguments. Frequently, the acceptance parameters were poorly defined. Occasionally, it was a matter of opinion whether a machine met the requirements of the order and whether or not it was acceptable. Many delays were caused by rejection of equipment that vibrated excessively, had oil leaks, or did not perform as promised for such parameters as flow, pressure and efficiency.

The next major step was vendor prequalification. Up until that time, Chevron's list of vendors had simply grown through years of experience. The process of adding vendors and taking them out was somewhat haphazard. Chevron adopted the philosophy that only vendors who were known to be fully capable of building that particular equipment item would be asked to bid. The principle was that the products of any manufacturer that asked to bid, and responded with an offer that met our specifications, could be purchased.

### THE FIVE-PART PROGRAM

The Chevron system now consists of five individual but linked parts. These are listed in the order they are applied: vendor prequalification, comprehensive specifications, design auditing, manufacturing quality surveillance, and intensive factory testing.

#### *Vendor Prequalification*

Vendor prequalification is used by Chevron Purchasing and MSD to determine which vendors have successfully demonstrated they know how to design, build, test, and ship a system to meet all requirements for the installation (Table 1). Chevron experience and the experience of other companies accessed through user lists is analyzed to make these determinations. The quality of field service and spare parts backup are also considered important. Chevron MSD developed a formalized program which requires that the vendor demonstrate ability to meet specifications and prove that he has successfully built, installed, and has running, equipment which is similar to what the company plans to buy.

#### *Comprehensive Specifications*

Comprehensive specifications are used to ensure that project requirements are clearly stated and not subject to misinterpretation by the vendor or his subvendors. Commercial, along with technical items, must be understood and agreed upon. As with the specifications of most large oil companies, Chevron speci-

cations have become more and more bulky. The number of pages when combining the Chevron specification and the API Standard for Centrifugal Compressors, as an example, are considerably greater than they were a few years ago. Unfortunately, the oil industry has used its specifications as historical documents which defend against all of the difficulties previously experienced. This approach is based on the philosophy, "It shall never happen again!"

#### *Design Auditing*

Design auditing is used to be sure that the machinery system is designed to safely and reliably handle all specified operating conditions for the required operating life. Materials, stresses, resonance, bearing loads, deflections, and performance parameters must be accurately predicted and reviewed in detail. In some cases, Chevron uses consultants to augment the MSD staff's knowledge.

Some of the most critical items for review are turbine blade vibration and gear tooth loadings. Every stage of a multistage steam turbine blading (Figure 9) is reviewed, using such graphical displays as Campbell diagrams (Figure 10), which relate blade natural vibratory frequencies to vane passing and rotational exciting frequencies, and Goodman diagrams (Figure 11), which relate the blade's steady and cyclic stresses at resonance to the blade's material properties. Is any row of blading in resonance during any part of the operation? If it is in resonance, how high will the stresses be? Can these be tolerated indefinitely? Great care is taken to be sure that the data used by the manufacturer to estimate blade stresses and imposed loads is based on solid empirical and analytical knowledge. Gears have been one of the real weak points in major machinery trains. However, with the use of a much more conservative API Gear Standard and a thorough design review by one or two consultants, Chevron has been able to affect the elimination of most gear failures caused by poor design (Table 2).

#### *Manufacturing Quality Surveillance*

Manufacturing quality surveillance helps ensure that the machinery system parts are fabricated from the correct materials, within specified fits and finishes, properly assembled, balanced, piped and wired. Usually, machinery specialists are employed to cover these areas. Selection of the right people for this job is extremely important. Not just anyone should be used as a quality surveillance person. They must understand machining and how parts should be properly assembled. They must be able to have good working relationships with the manufacturers' people to avoid antagonism. The surveillance person should be capable of writing informative, periodic status reports. They must understand that their role is to get a good machine shipped. It is not to keep a machine hung up in the factory.

Table 1. Master Vendor List. Pumps and Turbine Drivers Pumps, Centrifugal—Heavy Duty Services, EG-983, API 610.

Vendor	Single Stage Horiz. Process	Vert. Inline Process	Multi-Stage Hi Press and Boiler FW	Pipeline	Slurry and Sulfur	Vert. Turbine	Vert. Cantilevered Shaft Type Sump	Horiz. Cooling Tower
A	X(17)	X(11)	X(19)	X		X		X
B	X(3)	X(11)(18)	X	X		X		
C							X	
D								X
E	X	X(11)	X(20)					X
F					X(10)		X	

Note: Parenthetical numbers indicate vendor limitation or special requirement included in quotation request.

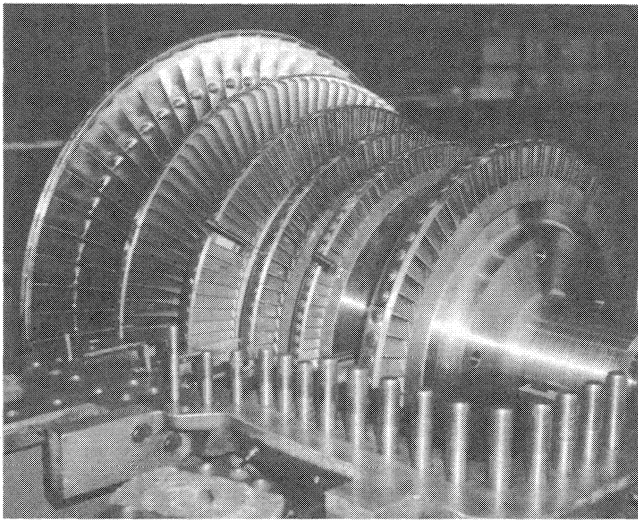


Figure 9. Multistage Steam Turbine Rotor.

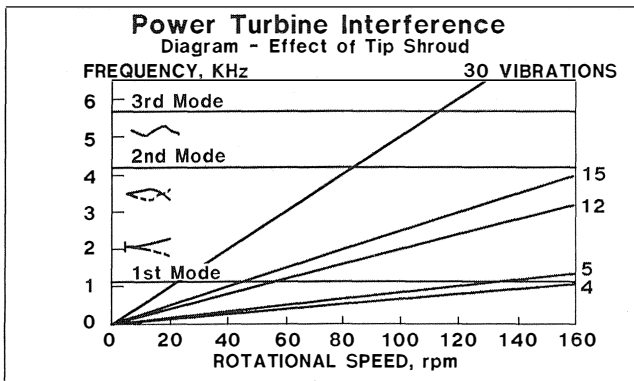


Figure 10. Typical Campbell Diagram.

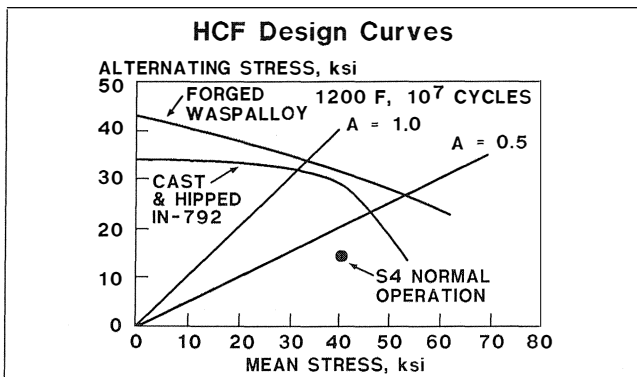


Figure 11. Typical Goodman Diagram.

Chevron has had good luck using people from its refinery and chemical plant machine shops. Also, retired machine shop foremen and a few consultants who have spent a lifetime in machinery manufacturing and servicing have worked out well.

*Intensive Factory Testing*

Intensive factory testing prior to shipment will demonstrate that the equipment is mechanically sound and performing as specified. The tests on critical equipment must be very rigorous. It is extremely important that problems are discovered and corrected before shipment. This is especially true for equipment that is going offshore or to hostile environments like the North

Table 2. Tooth Service Stress Calculations.

Item	Symbol	First Reduction	Second Reduction
Horsepower/Mesh (50% load split assumed)	P	850	850
Pinion cpm	$N_p$	504	446
Pinion Pitch Diameter	$d$	23.25	16.5
$W_t = \frac{126,050 P}{N_p \cdot d}$	$W_t$	9143	14,560
Effective Face	$F_c$	10.25	14.25
Gear Ratio	$M_g$	1.14	2.894
Tooth Contact Stress Index $= \frac{W_t [M_g + 1]}{F_c \cdot d \cdot M_g}$	K	75.4	83.3
Overload Factor	$C_o$	1.25	1.25
Mounting Factor	$C_m$	1.30	1.30
Allowable contact stress Index	$K_a$		
$= \frac{S_c \times 10^{-42}}{C_r} \times \frac{2.03}{C_o \cdot C_m}$	$K_a$	$1.25 \frac{S_c \times 10^{-42}}{C_r}$	$1.25 \frac{S_c \times 10^{-42}}{C_r}$
	Hardness		
		180	84
		200	95
		220	104
		240	115
		260	126
		280	135
		300	145
		320	158
		340	171
		360	184

Slope oil production facilities in Alaska. Field rework for problem correction is time-consuming and very expensive to the operator in terms of repair costs and lost production.

Every centrifugal compressor, even if it's an identical one of a set, is aerodynamically tested for Chevron MSD according to the ASME Power Test Code No. 10. For critical, high pressure centrifugal compressors, such as those used for natural gas injection, testing at full pressure and full horsepower, and sometimes with the specified gas, may be required (Figure 12). These tests can cost from two hundred thousand dollars to one million dollars. It is necessary to develop an economic justification for expensive testing. Usually MSD makes recommendations about spending this much test money on the basis of the machine's design, how well proven is it, how likely is it to be unstable at high pressures and high speeds, and how much will the company lose if the plant doesn't start up and operate on time.

It is extremely difficult in some cases, and very time-consuming, to make major design changes and corrections in the

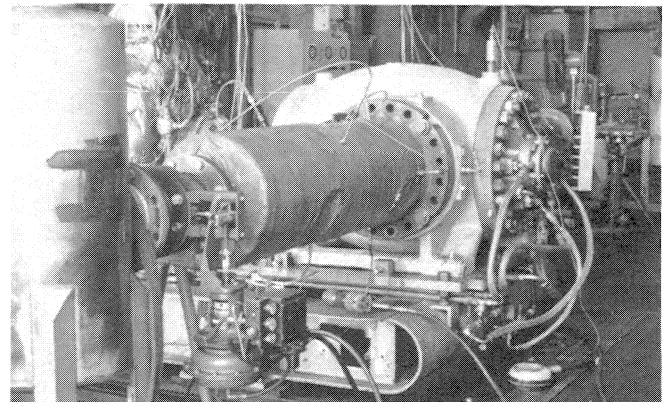


Figure 12. Centrifugal Compressor Testing.

field. Another point to remember is that having a spared machine does not always help. If you have two identical but incorrectly designed compressors, neither one of them is going to work properly.

Meaningful tests take a great deal of planning. The test procedures and acceptance parameters should not only be fully developed, but well documented ahead of time. The test stand crew should be aware of what they are going to do and what will be acceptable before the test starts. This avoids arguments and delays at the test stand.

### EXAMPLES FROM RECENT MAJOR PROJECTS

Several years ago, Chevron carried out a 1.25 billion dollar major upgrade of one of its refineries. Setting up the Quality Assurance Surveillance Program for this megaproject took a great deal of planning. As in any other endeavor, the first and most important task was getting the right people. The quality assurance effort used an organization structure which reported directly to the project manager (Figure 13). Not only were inspectors and quality surveillance people used, but, because there were so many manufacturers involved, monitors were needed to travel around and check on inspection performance from time to time.

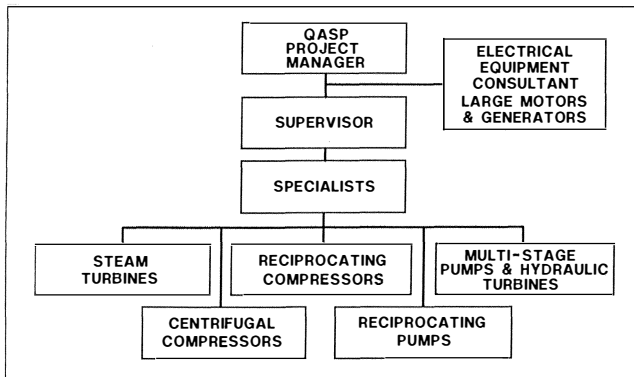


Figure 13. Quality Assurance Surveillance Program.

The organization plan for this major project worked with reasonable effectiveness. On smaller projects, the system can be a lot simpler. But in any project, administration of QASP should come right from the top. Obtaining good quality in manufacturing cannot be a secondary objective. This was graphically demonstrated in this major project. Equipment which was subjected to the quality assurance program came to the field, almost without exception, ready to install and start up. Almost without exception, it performed very well. On the other hand, dozens of items of minor equipment such as single-stage centrifugal pumps were not given the QASP treatment and could not be installed. They had connection flanges which were damaged. They had shafts which could not be turned. They had baseplates which could not be properly aligned. Many of these pumps had to be returned to the manufacturer's factories for correction.

A significant problem in a recent Chevron project was with several large, critical, multistage centrifugal pumps and hydraulic turbines. These machines were 3500 hp and 4000 hp, 3600 cpm units with double casings. There were severe and significant manufacturing problems. Incorrect materials were used. Internals would not fit into casings. Severe rubs occurred during factory testing. Numerous reworks, some essentially amounting to complete remachining, were required on these pumps before they were finally shipped. Chevron's quality assurance surveillance man worked many months and spent countless hours

helping the manufacturer find and correct the problems. This surveillance included four integral steps:

*Witnessing thermal transient (rapid heat up and rapid cool down) test at rated flow.* Pump flow, suction pressure, and discharge pressure shall be recorded. In addition, vibration, pump suction temperature, thrust bearing temperature, and pump casing temperature shall be continuously recorded for the duration of the test.

*Witnessing or observing four-hour mechanical test at minimum continuous flow.* Pump flow, pressures, power, speed, filtered and unfiltered vibration, lube oil temperature and pressure, and bearing temperatures shall be recorded at 15-minute intervals during the first hour, and at 30-minute intervals for the duration of the test.

*Witnessing or observing start/stop integrity tests, consisting of a minimum of 15 starts and stops.* Vibration, coastdown time, horsepower, suction pressure, and discharge pressure shall be recorded. Successive starts and stops shall demonstrate that no metal transfer or dimensional changes occur at close running clearance in the pump.

*Witnessing or observing complete unit test consisting of pump, gear (if any), driver, and auxiliaries.* The gear vibration on the test shall not exceed 0.15 ips (inch per second) peak unfiltered or 0.10 ips filtered at any gearbox rotating speed.

Rigorous factory testing, including an unusual multiple start-stop test to prove that mated running parts were not galling, was used to be sure that the pumps and turbines were right prior to shipment. Eventually, they were. They have been operating without trouble since 1983.

The design audit for a 10000 hp horizontally split centrifugal compressor (Figure 14) indicated this machine was going to be sensitive to unbalance going through its first critical resonance (Figure 15). Chevron raised an objection to the manufacturer. However, he showed test stand data for very similar machines which indicated that all would be satisfactory. The explanation was that his rotordynamics computer program tended to exaggerate the response of the rotor. When first tested, the machine performed just as the computer program had predicted. When opened after testing, rubbing of the rotor and internals was discovered. The actual internal damage indicated that his computer program was right.

We soon found out what was wrong. The vibration probes on the earlier machines had been installed very close to nodal points on the shaft—that is, points of little or no shaft motion. Chevron specifications had required that our probes be located just a few inches along the shaft away from nodal points outboard of the bearings.

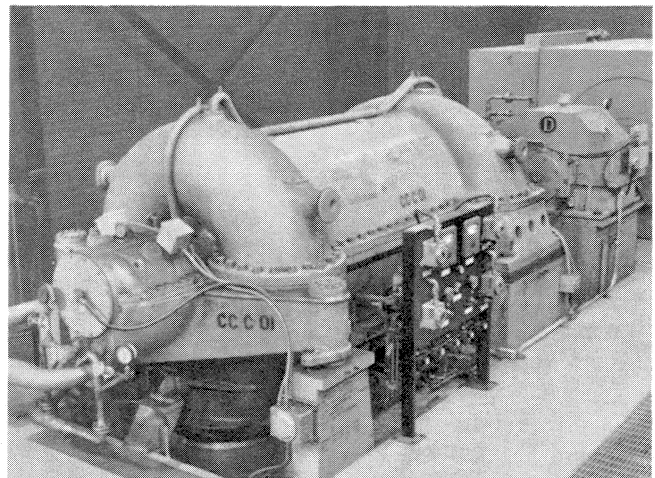


Figure 14. Large Horizontally-Split Centrifugal Compressor.

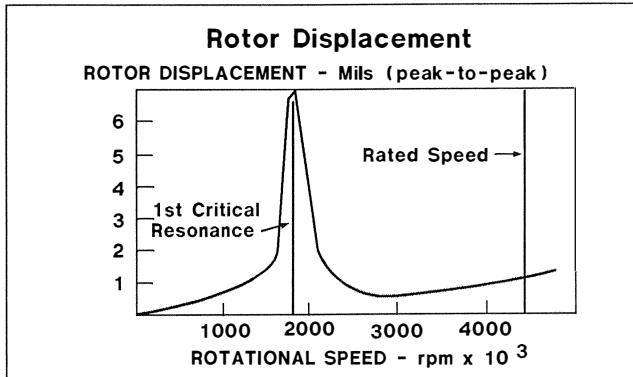
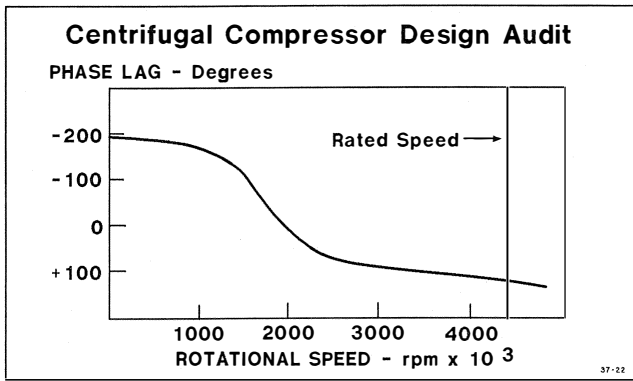


Figure 15. Centrifugal Compressor Design Audit.

Many attempts were made to solve this problem without success. We found that the impeller mounting design on the shaft was not adequate. As the machine came up to speed, the impellers shifted and ruined the good balance that the rotor had when it left the high speed balancing machine. Since it was a long rotor with not much damping at the bearings, a high response occurred going through the critical, causing the rubs. Also, we found that the older, successful compressors all used oil lubed seals. Our labyrinth seals did not provide some needed damping.

Eventually, the solution was found. A new shaft forging was made along with improvements to the design of the shaft and impellers. The assembly and balancing procedures were altered so that the rotor would stay in balance as it ran up and down in speed.

High pressure, double case, multistage centrifugal compressors must have reliable thrust bearings. In this example, the manufacturer was going to use a thrust bearing design of his own (Figures 16). This was discovered during the design audit and found to be satisfactory. Later, when the compressor was being assembled, the quality assurance surveillance man noticed that the actual thrust bearing was not the same as the one we had agreed upon during the design audit. Chevron's contractor called a stop to manufacturing.

The thrust bearing was a different design and had never been adequately tested. In order to solve this problem without being arbitrary, a mutually agreed upon third party bearing design consultant was hired. He reviewed the design and firmly concluded that it was not adequate and was probably going to allow in-operation thrust bearing failures. It was necessary to stop production, revert to the bearing which was originally approved, remanufacture the shafts, and change the bearing housings. Chevron required the manufacturer to do all of this before we would allow shipment. An operational thrust bearing

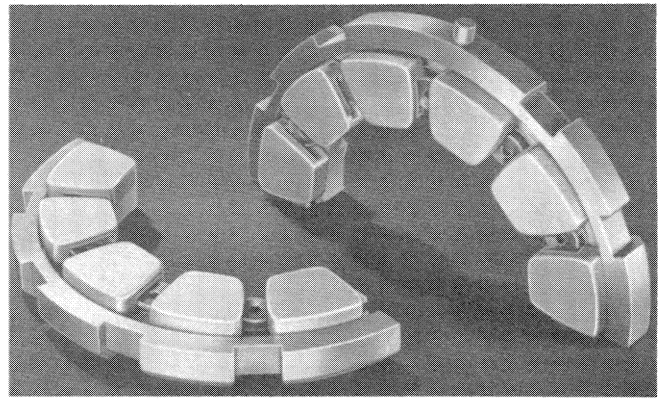


Figure 16. Thrust Bearing.

failure in a high pressure centrifugal compressor can result in total disaster.

In order to qualify manufacturers of large gas turbine electric generating sets for an upcoming cogeneration project, CED engineers traveled around the world. They visited plants for gas turbine manufacturing, gear manufacturing, electronic control systems, and electric generators, looking at their capabilities and checking into their experience. They visited several in-operation cogeneration systems using similar equipment.

Operating history and their startup and installation experiences were reviewed. This review allowed Chevron to establish an acceptable vendor list for the project. Whichever of the manufacturers is chosen, he will be able to provide a proven, satisfactory system.

QUALITY ECONOMICS

Process plant startup delays are expensive. Thirty years ago, a refinery process plant might earn \$10,000 per day. Now, for major plants, \$100,000 to \$250,000 per day earning power is not unusual. Still, major turbomachinery is typically not redundant. For a compressor train costing a million dollars as the heart of a plant that earns a quarter of a million dollars per day, it doesn't take too long to justify a full-blown quality assurance program.

Chevron has been doing quality assurance surveillance for about fifteen years, and the costs are well documented. The costs vary, depending upon the manufacturer and the complexity of the equipment. A typical range is two or three percent of the capital outlay for the machinery train (Figure 17). For a million dollar train, even if the extra cost for quality assurance surveillance, testing and design auditing is \$50,000 or \$100,000, saving one day's operation can quickly pay it out.

It must be kept in mind that quality assurance and factory testing may delay shipment. That does not necessarily delay

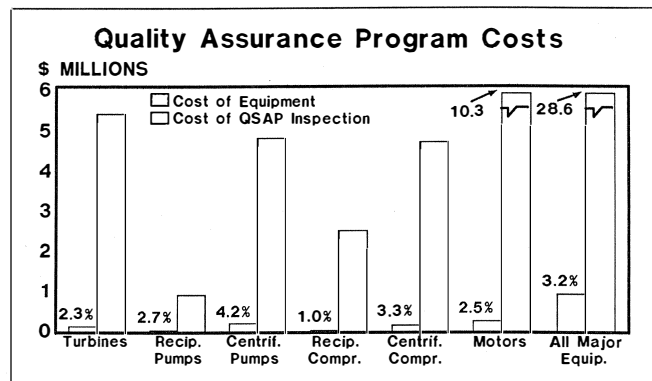


Figure 17. Cost of Quality Assurance Inspection Program.

plant startup. For major turbomachinery, it is not uncommon for the equipment train to be in place in the field for six to eighteen months before the plant actually begins operation (Figure 18). If the equipment hasn't been adequately checked during manufacturing and tested prior to shipment, it could be a time bomb ticking. All of that time while the machinery sits waiting in the plant is wasted. The latent problems manifest themselves when startup comes, or later, when trying to reach full capacity. Chevron's approach takes advantage of that lead time by being sure the equipment is right before it is installed. Consider the example of the multistage double case pumps. Delays in shipment ranged as high as fourteen months for those pumps. However, this was a large, complex project and, in spite of this delay, the plant actually started up two months early. The pumps all worked when Chevron needed them.

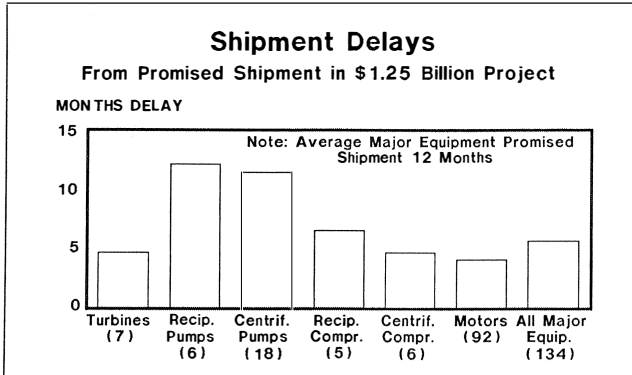


Figure 18. Major Equipment Shipment Delays.

The cost/benefit ratio for the Mechanical Systems Division Quality Program is now very well proven in the company, especially for large complex projects. Chevron's Engineering Department project managers insist on having the program. It has not been as well demonstrated for smaller projects and in some areas of work such as offshore platforms. However, the day is approaching when this will be the common method for buying major equipment for any project.

#### FUTURE OUTLOOK

Our manufacturers have begun to appreciate Chevron's critical need for well-built, reliable products, delivered on time and

in working condition, and the fact that we're willing to pay for this. They have started programs aimed at satisfying these needs. We are now asking equipment builders to submit fully developed quality assurance plans which detail all inspection and control steps. Eventually, strict compliance with their own programs may obviate the need to impose the Chevron manufacturing surveillance approach.

The company will continue actively looking for better means to obtain machinery systems which fully meet its needs. We want to do this in a manner which allows our suppliers to make a fair profit. We need them to be in business and to be financially healthy. We are trying to learn to communicate our needs even better and to work successfully with the manufacturers to achieve this mutually beneficial objective.

#### SUMMARY

The history, development, current status and operation of the Chevron Corporation Quality Assurance Program for major mechanical equipment has been presented. How Chevron's problems started and how important non-redundant equipment started to break down has been discussed. The development of the Incident Index and Delay Index analysis focused attention on first, design errors, and then, manufacturing problems. Next explained was how quality awareness was developed, through solving problems in the field, and on our own and using consultants, learning about what was important in machinery design, developing the Quality Assurance Program, witnessing tests with skilled people, and limiting vendors to those who are really qualified—all important parts of the five-part program. Examples were cited from a number of major projects about setting up a quality assurance program, design auditing, testing and vendor qualification. Hopefully, it's been demonstrated that the economics are there to support this kind of a program, especially for large projects.

There are many hopeful signs that things are improving. But even for manufacturers who are making major steps with programs to improve quality, more time will be needed. At least five years time will be required from when a manufacturer completely overhauls his approach to quality, until he can achieve these objectives.