PLANNING TURBOMACHINERY OVERHAULS AND DOCUMENTING THE RESULTS

by

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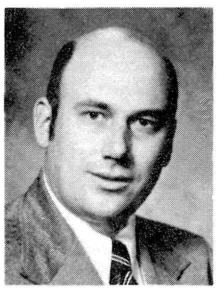

John D. Houghton is currently assigned as the manager of the Mechanical Equipment Department at Shell's largest manufacturing plant, Deer Park, Texas. He received his B.S. degree in Mechanical Engineering from the University of California, Berkeley, in 1966. Previous assignments with Shell include work in both the Maintenance and Operating Departments at the Martinez, California plant; work in the Heat Transfer Department at Emeryville, California; five years in the Mechanical Equipment Department, Engineering Services, Head Office — Houston; and one year as group leader, Mechanical Equipment, Houston Refinery. He is now involved in predictive and preventive maintenance programs, troubleshooting and failure analysis, and design, modification and performance improvement for rotating equipment at the Deer Park Manufacturing Complex.

ABSTRACT

The paper covers the subject of overhauling turbomachines with particular emphasis on practical field procedures and proven concepts. It does not dwell on one type of machine, but multi-stage centrifugal compressors and steam turbine drivers will receive most of the coverage. The paper represents data gathered from approximately 30 machine overhauls conducted over the past three years and the efforts of 16-20 engineers with varying levels of experience. Specific examples of what can go wrong are included with correction tips from our experiences.

The paper is divided into three main sections. 1.) Planning; 2.) The Actual Overhaul Work and 3.) Documenting the Results and Planning for Future Overhauls. Step-by-step suggestions and recommendations are offered in each section. The paper generalizes in many areas to avoid being a simple rewrite of a given machine manufacturer's manual. It deals with overhaul work from the eyes of the engineer in charge of the work.

INTRODUCTION

Modern turbomachines can run reliably for many years if designed, applied, and operated correctly.

Indeed, the periods between inspection and overhaul on machines in clean, noncorrosive service can be so long that memories will dim on just how much time and effort are required to successfully plan and execute an overhaul of a particular piece of equipment. A proper overhaul involves preplanning and teamwork among Plant Engineering, Warehouse, Purchasing, Safety, Operations, and Maintenance forces, as well as with original equipment manufacturer and other non-company sources. In the case of sophisticated problems, consultants and laboratories may also come into play to achieve a reliable, smooth-running, efficient machine. Managing these resources and documenting the results present a real challenge to those assigned the task of heading up the overhaul effort.

PREPARATION AND PLANNING

When preparing for an overhaul of a major piece of turbomachinery, it is important to know as much as possible about the machine and why it needs to be taken out of service. There are several obvious sources of information, including the operating and maintenance personnel, the equipment file folder, and vibration history record. If sufficient information is not found in the file folder, which is all too often the case, this fact should reinforce the resolve to do a proper job of documenting the planned overhaul.

Before proceeding, one question needs to be answered: "Is a complete overhaul *really* necessary?" To properly answer this question, you will obviously need to evaluate the symptoms. Has the vibration steadily increased over a long period of time or have you witnessed a step change? What does an analysis of the vibration signature reveal? Has the performance gradually fallen off or taken a dramatic drop? Problems such as a locked gear coupling or soluble deposits inside the machine can be corrected without opening the machine at a considerable savings of time and effort.

Another obvious source of information is the manufacturer's manual. The good ones provide detailed, step-by-step instructions with clear illustrations, others assume prior knowledge or place undue reliance on the manufacturer's service representative.

Since a detailed manual is often too bulky for constant reference, we reduce portions of it to a critical item list. Certain steps, clearances, methods, etc., are vital to doing a good job. These items should be summarized and kept for ready reference during the course of the overhaul.

It is important to assign the responsibility for the overhaul to one person so that conflicting positions do not occur. We appoint an engineer to oversee the job and require that all decisions and compromises be made by him, regardless of on which shift the question arises. He is responsible for the engineering coverage, interface with the maintenance and operating departments, interface between our company and the original equipment manufacturer, and for documenting the overhaul. It is a responsible assignment, one that requires judgment, maturity, and initiative on the part of the engineer.

Safety

Work safely. Be sure all power is off, blinds in, purging procedures followed, etc. A pre-work safety item check list is strongly recommended, as is a list of locations of all blinds. The latter item is important at the beginning of a job to ensure all necessary lines are secure, and, at the end of the job, to check off the removal of all installed blinds. Failure to install or remove a blind at the appropriate time could lead to a disaster.

It is important to establish teamwork and proper communications among the Operations, Safety, Engineering, and Maintenance personnel at the start of the job so that each can fulfill his role in the total effort. A list of key players and phone numbers where they can be reached during the overhaul period should be made available at the start of the job.

Planning

If this is a planned overhaul, as opposed to forced outage, so much the better. Take full advantage of the planning period to make a visual inspection of the machine before the shutdown. Pay particular attention to the condition of the foundation, anchor bolts, piping, instruments, and look for leaks. It is a good idea to keep an "evergreen" list of required maintenance items in the equipment folder. Encourage personnel who frequently go on the machinery deck to make note of any problems.

Take a final set of vibration, performance, alignment, and mechanical health data just prior to the shutdown. We have found that a small shirt-pocket size tape recorder is particularly useful to record notes; it leaves the hands free to manipulate instruments, etc. The data can then be transferred to paper back in the office. If you are working a forced outage, the most recent set of data will have to do. Compare the most recent information to previous readings and develop a list of anticipated problems.

In our experience, machines are normally shut down for overhaul due to fouling (restricted performance); excessive vibration (ingestion of a liquid slug, a loose piece of hardware, the failure of a mechanical component or misalignment); misoperation (surge, lube oil supply failure, etc.); or when the whole process unit is shut down for a turnaround. In general, we do not open machines that are running satisfactorily just for inspection. At every convenient opportunity we will inspect externally available components, such as couplings, and check readily accessible items such as rotor float and shaft alignment, as well as all tripping devices and general instrumentation.

In the case of steam turbines, the overspeed trip bolt and the steam trip and throttle valve have proven to be the least reliable — and most important — safety devices in the train. A check of these two components is mandatory during major shutdowns, and checks should be made at every other opportunity. I am of the opinion that these checks are the most important checks performed during a shutdown. In addition, we "exercise" the trip and throttle valve weekly by moving the stem in and out manually several turns on the hand wheel to preclude the buildup of deposits that would prevent the machine from tripping during a shutdown condition.

As an example of the penalty associated with the failure of a trip circuit, a 10,000 horsepower, steam turbine-driven compressor train failed to trip during a condition which allowed the compressor to fill with liquid while at full speed. The resulting loads caused a catastrophic failure of both the compressor, as seen in Figure 1, and coupling and allowed the steam turbine to overspeed to destruction. The repair bill for parts and labor came to well over $1,000,000. The cause of the wreck was eventually traced to the buildup of deposits on a brass piston in the hydraulic shutdown system which was in a hot deadened oil circuit. The heat caused the oil to decompose over a long period of time causing the piston to stick. As a result, we now check trip circuits more frequently, have installed backup trip devices on many trains, and are evolving new design practices in this area.

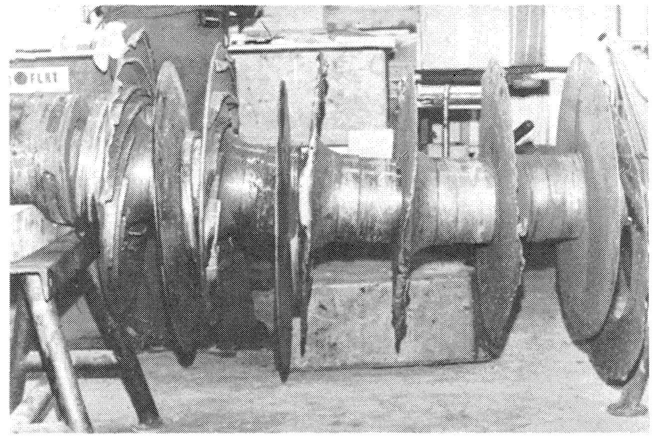

Figure 1. Severely Damaged Compressor Rotor.

Spare Parts

The time to check spare parts is *not* in the middle of the night following an emergency phone call from the Operating Department Manager. Most large companies have some degree of computer control on the warehousing and reordering of spare parts. But how many times have you been lied to by a computer? There is no substitute for a hands-on check of parts by a knowledgeable individual. Parts numbers must be checked because an item on the shelf does not necessarily mean it was filed in the right slot.

We are considering the use of boxes devoted to major machinery spare parts storage. The box would have individual compartments for labyrinths, seals, bearings, etc. A list on the lid would detail all parts inside, their location in the box, the manufacturer's part number and our company's stock number. Once filled, the box would be sealed and stored in the usual manner. During an overhaul, the box would be taken to the field and some or all of the parts consumed. The box would be returned to the warehouse with a list of consumed parts to be replaced. A call-file system is used to keep tabs on rotors that are out of the plant for repairs and delivery of other critical spare parts.

When checking spare parts, it is important to recognize that not only must the part be the right size, it also must be in good condition. Handling and improper storage, as well as deterioration with time, are a few of the hazards associated with a warehousing operation. A nicked "O" ring or a carbon seal face out of flatness could require a second shutdown to correct the problem. The use of an optical flat, a set of micrometers, and a knowledgeable pair of eyes can be invaluable in detecting a defective part. Also remember that just because the part came from the factory, it may or may not be the right one for your machine. While equipment manufacturers have various quality control procedures, they too rely on human beings, and errors — hopefully infrequent — do occur. In addition, some parts have a finite shelf life (case split line sealant is an example) and must be fresh when the time comes to use them.

This is also the time to check on the availability of special (custom fabricated) tools. These should be kept in a separate box, inventoried at regular intervals, and generally managed as a valuable spare part or other essential resource. The delay of an overhaul for several hours to fabricate a special seal nut wrench is time and money wasted. Alignment brackets and coupling "solo" plates fall into this category.

The Spare Rotor

By far the most critical single spare part is the spare rotor. Most companies purchase the spare rotor at the time the machine is purchased. We follow this practice and require a four-hour mechanical test to ensure integrity prior to acceptance of the machine. It is our opinion that the spare rotor should be checked after every movement. This means a "truth" or rotor bow check upon receipt from the manufacturer, as well as a check of the preservatives used for completeness of coverage. A truth check is also performed at the time the rotor is check-balanced and prepared for installation. Be sure to obtain a rotor runout diagram and a balance report at that time.

Our lighter rotors, up to 2000 pounds, are hung vertically in a remote temperature controlled storage building as shown in Figure 2. The larger rotors are stored on substantial stands and turned 180 degrees once a month. These stands employ rollers rather than lead or Teflon bearings at the support points. (During a previous Turbomachinery Symposium discussion group, a user discussed the problem of sheet Teflon placed between the storage cradle and the rotor filling the microscopic pores of a shaft journal which prevented the formation of an adequate oil film on startup and caused a bearing failure.)

Rotors must, of course, be handled with great care. Nylon slings should be used to prevent damage and all lifts should be made under the watchful eye of a competent individual. Never hesitate to call a halt to a lifting operation if a possibility of damage exists. You are being paid to look out for the company's interests and a rotor worth from 100,000 to 1,000,000 or more dollars is well worth a lot of care and concern. The rotor must be slung such that it is horizontal and its center of gravity centered under the hook, and it must be moved very slowly. Consider your vibration monitoring probes when removing a rotor from storage in preparation for installation. We record the rotor's serial number and verify that it is not positioned such that it will interfere with a thrust position eddy current probe. Some users also report success with degaussing and/or micropeening techniques to minimize electrical runout in the areas viewed by the radial eddy current probes. We have had some success rolling the rotor on a balance stand with the areas under the probes directly on the balance rollers.

Diagrams

A critical dimension diagram (APPENDIX A) has proven invaluable in the middle of the night during a complicated overhaul. This is a single sheet of paper with items such as bearing and labyrinth clearances, rotor float, seal clearances, coupling advance, coupling bolt torque, etc., clearly shown with maximum and minimum values, as well as spaces for "as found" and "as left" conditions. Any warning notes such as internal bolts, left-hand threads, or other super critical steps should be clearly flagged on this sheet. Clearances should be properly labeled as to diametral or radial, metric or English units, to avoid confusion.

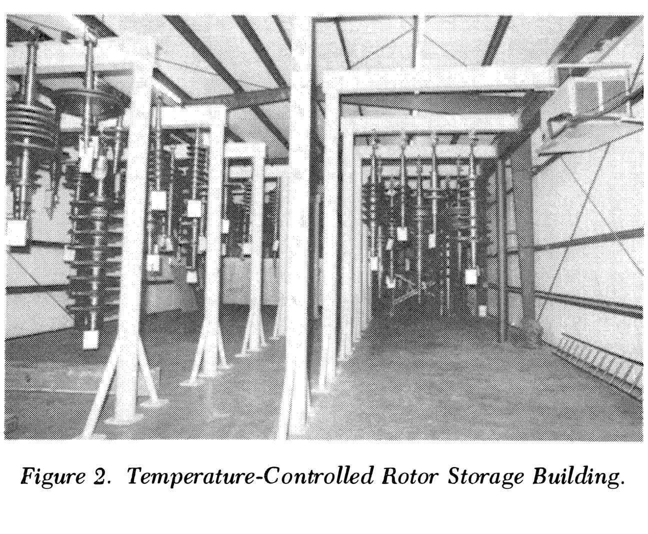

Figure 2. Temperature-Controlled Rotor Storage Building.

An alignment diagram, as shown in Figure 3, complete with estimated thermal growth and desired readings, is mandatory. This should be available from previous alignment work. If it is not, and if reverse dial indicator alignment techniques are not well known and practiced at your plant, I would strongly recommend implementation of such a program. The techniques and procedures have been the subject of many papers [1]. We have developed a simple algebraic program card for a hand-held, programmable calculator which has proven to be a useful check on the graphical method used with the alignment diagram. The techniques described above have proven to be time and, hence, money saving, and are well worth the effort. Another useful item involves preplanning the allowable limits on the desired shaft position. It is impractical to expect the field crew to precisely place a compressor or turbine in the exact position as shown on the alignment graph. If allowable limits are known in advance (not necessarily by the field crew, but by the engineer in charge of the overhaul), a decision or compromise can be made in a rational manner depending on need for the machine and time available to achieve acceptable alignment. Under no circumstances should alignment be compromised beyond a few thousandths of the desired position nor excessive pipe strain be permitted on the machine. The search for absolute perfection will generally be rewarded with time consuming frustration and an ultimate compromise in any case.

Miscellaneous Items

Any good shutdown/overhaul plan should include an inspection of auxiliary components. During the overhaul period is the time to clean lube oil coolers, replace filters, overhaul lube oil pumps, etc. But beware of introducing dirt into the system. Many a clean lube set and newly overhauled machine have been damaged by a few seconds of careless maintenance activity.

The instrumentation associated with the machinery train should also be checked and calibrated. Again, a list and adequate record keeping practices are a must. The list should include all set points and complete information on any rebuilt instruments placed back in service. The engineer in charge of the overhaul will normally delegate this task to the Instrument Group after collaborating on the list with this group and the Operating Department to pinpoint any troublesome items. Key shutdown instruments such as low oil pressure and high discharge temperature should, of course, receive as accurate a test as practical.

The Factory Serviceman

Most machinery manufacturer's manuals recommend the use of a factory serviceman. It is most important to know who you are getting and what his qualifications are. I had the unsettling experience of shaking the hand of a serviceman from a major supplier of gas turbines while he told me he normally worked on steam turbines and this would be his first gas turbine. The point is, after several years in the field, assuming continuity of plant personnel, the user many times will know more about the machine than its manufacturer. The factory field serviceman leads a rough life; 16- to 20-hour or more shifts are common, as well as being away from his home city a great deal of time. Attrition is high. We have had some very

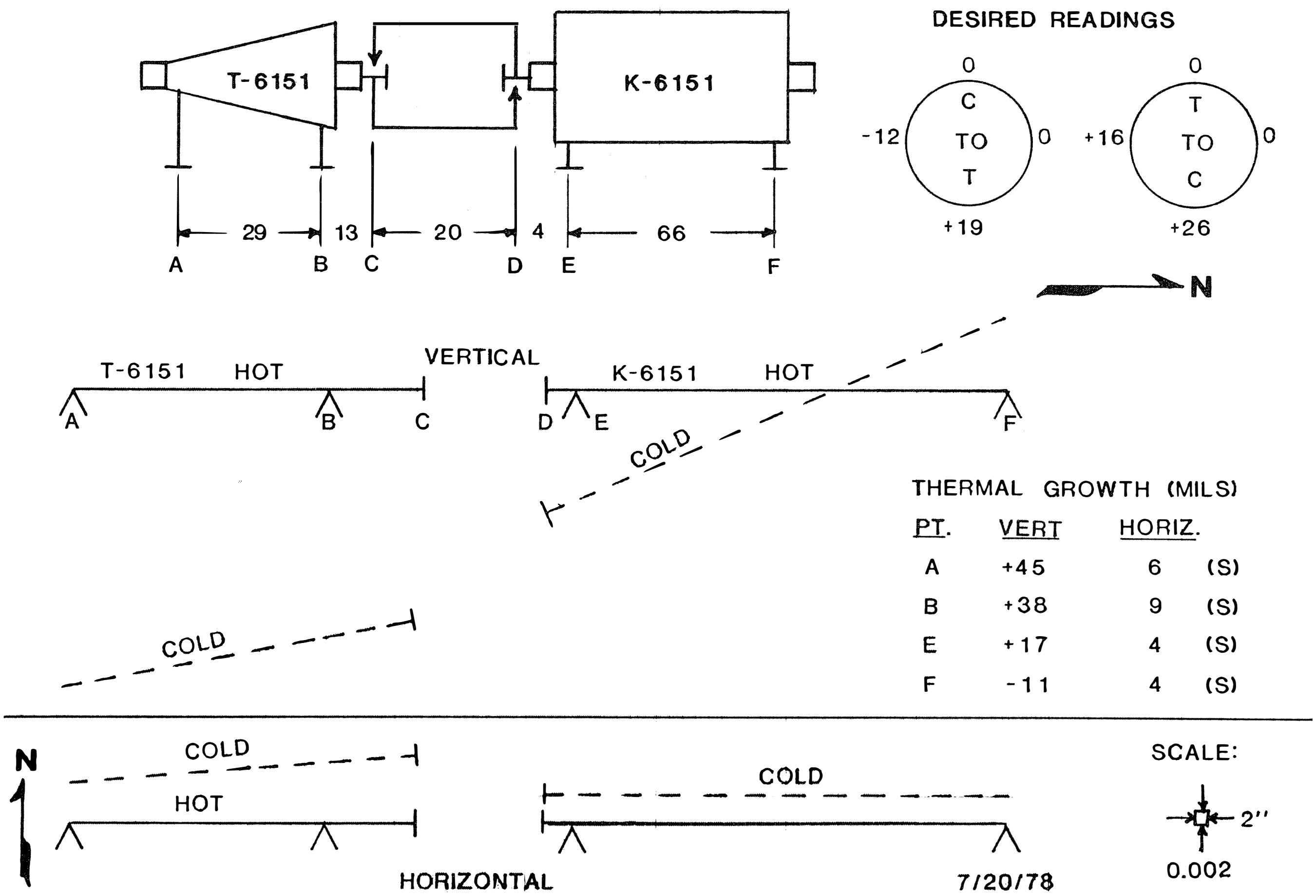

Figure 3. Alignment Diagram.

good and some very bad ones. I keep a list of those to invite back, as well as of those I would rather not use again. We have conducted many successful overhauls without using factory service personnel. The ability of a given plant's engineering staff, the time available for the overhaul, the complexity of the machine, and warranty considerations all play a part in this decision.

THE OVERHAUL

During the course of the overhaul, it is very important to keep track of the job on an hour-to-hour, shift-to-shift basis. We use a shift log or diary for this purpose and it has proven an invaluable communications tool. The critical dimension diagram and the alignment diagram should likewise be kept available for ready reference.

The use of a good quality camera and a professional photographer to document details of the overhaul is strongly recommended. After all, if you do a good job, it will be three to five years or longer before anyone sees the inside of the machine again. We use both a 60-second color and 35-mm single lens reflex camera, and have considered using a video tape camera to provide training films for Maintenance.

Before the actual shutdown of the machine is the time to take a final set of hot alignment data, if such a program is currently in use at your plant. There are, of course, several accepted methods for checking hot alignment. The use of eddy current probes, either inside the coupling guard or on the machine cases, the optical method using a transit and targets on the machine train, or the use of a telescoping measuring rod and reference points on each machine and benchmarks on the foundation are three currently used systems. If you don't currently check *running* hot alignment (as opposed to the old method requiring a shutdown/alignment check, which has proven to be both inaccurate and unreliable), I would strongly recommend evaluating the various systems to see which one best fits your needs. As with reverse dial indicator alignment, a good hot alignment method can be a real money saver. We favor the benchmark/telescoping rod method, as shown in Figure 4, as it is simple, easy to teach to plant personnel, reliable, does not require expensive equipment, has been proven in many field situations, and is adaptable to most machinery trains.

After the machine has stopped turning, but before the actual disassembly begins, is the time to check several items:

1. The coupling. If it is a gear coupling, is it free to move on the gear teeth?
2. Look for broken coupling bolts. Broken bolts can indicate several problems, the most likely being incorrect bolt torque on installation, the wrong bolt material, or mismachined coupling flanges.
3. Get a sample of coupling grease, if a grease packed coupling is used.
4. When removing the coupling, remember to turn the

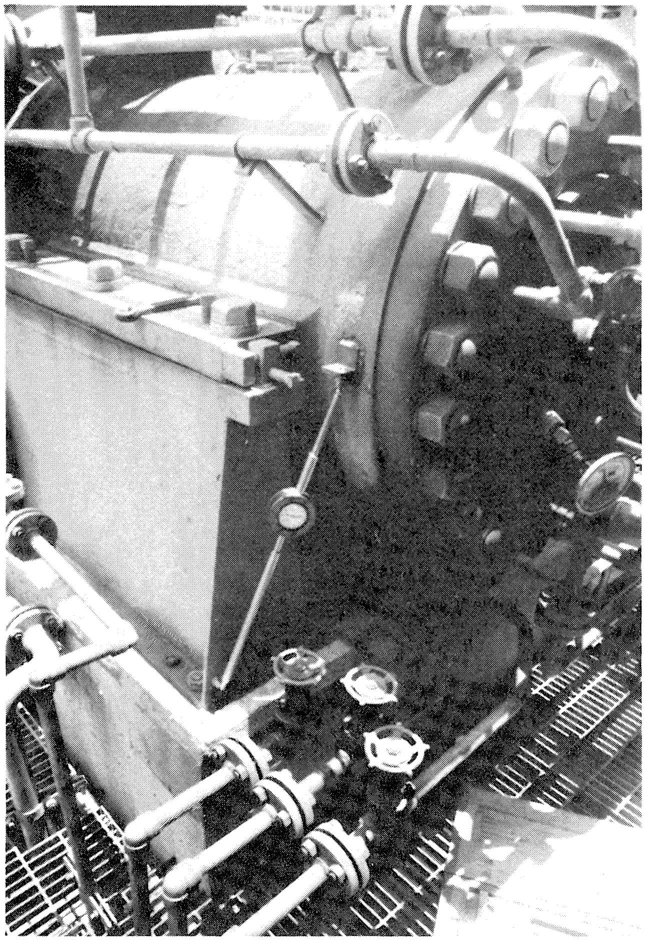

Figure 4. Hot Alignment Check.

nuts and hold the bolt head from turning so as to avoid wearing the body-fitted bolts. In a doubled keyed coupling, be sure to check that the keys are marked as to their location.

5. Be sure to keep the coupling bolts and nuts together as individual assemblies. Do not plan to reuse the nuts more than 10 times. If any doubt exists in this area, a new set of match weighed nut and bolt assemblies is cheap insurance. A more complete treatment of the subject of coupling failure analysis appeared in the Proceedings of the 4th Turbomachinery Symposium [2].
6. Check and record rotor float within the thrust bearings and shaft end spacing.
7. Check the total rotor float with the thrust bearing removed and the relative rotor position in the machine case. Check nozzle stand-off in the case of a steam turbine, or position between diaphrams in the case of a compressor.
8. When removing the thrust bearing, be sure to measure and tag any thrust shims used for thickness and location (inboard or outboard).

Opening the Machine

Before actually opening a major piece of machinery, take time to review the critical steps in the operation. Attempting to remove an upper half casing without first removing internal (nonexposed) bolting or lifting the casing without using guide pins can result in a much longer and more expensive overhaul. Be especially careful when opening lube oil lines. The loss of a flow control orifice or the introduction of dirt into the system can cause serious problems during the machine startup.

As the machine comes apart, take lots of pictures, make written notes, and/or use a tape recorder to document what you see. It's amazing how much detail will be lost and how difficult it is to accurately reconstruct events, hours or days — let alone years — after they have occurred.

In this vein, we have four large (nominally 20,000 horsepower) identical steam turbines which, due to a series of blade problems, have been opened a total of 31 times in an eight-year period. It is vital to know which rotor modification is installed in what case when a given modification fails in another machine. In this particular instance, we have prepared a rotor chart to keep track of rotor movements and modifications, as shown in Figure 5. When the first blade in the first rotor failed, it was not apparent that we were in for such a lengthy problem. The rotor movement chart was laboriously constructed from memory when we were halfway into the program and had added a sixth rotor to the system (four installed and two spares).

If you plan to remove compressor diaphrams, be sure to match mark them as to their position in the case. Inadvertent mixing of inlet guide vanes could alter machine performance! Be careful to stone down any match marks which are placed in a machined area, such as the casing split line. When the top half of a horizontally split compressor is removed, it is a good idea to position the rotor with its thrust bearing as it was before shutdown and check to see if the impellers are centered with the diffuser flow passages.

ROTOR HISTORY CHART

DATE	MACHINE NUMBER				SPARE
	300	350	500	550	
5/70 (NEW)	A-1	B-1	C-1	D-1	E-1
7/70			E-1		C-2
9/70		B-2			C-2
10/70			C-2		E-2
10/70				E-2	D-3
10/70			D-3		C-3
10/70				C-3	E-3
11/70				E-3	C-4
1/71		B-3			C-4
4/71				C-4	E-4
5/71		E-4			B-4
6/71			B-4		D-5
6/71			D-5		B-5
7/71	B-5			C-5	A-7
8/71		E-5			A-7
9/71	B-6				A-7
6/72	A-7		C-5	F-8	B-10, D-9
2/74		D-9	B-10		C-9, E-12
9/75	C-9				A-12, E-12
12/75	C-9/6				A-12, E-12
6/76	A-12		E-12		B-12, C-12
10/78		B-12		C-12	D-12, F-12

NOTE: LETTER CORRESPONDS TO MFG. ROTOR SERIAL NO.
NUMBER REFERS TO SPECIFIC DESIGN MODIFICATION

Figure 5. Example of a Rotor Movement Chart.

Inspection

As the machine is being opened, pay particular attention to visible deposits. On machined sealing surfaces you may find telltale tracks of a leak or wire drawing. Such leaks may indicate a need to check the flatness and fit of the surfaces with lead wire or plasti-gage or simply better attention to bolt torquing requirements. Fouling inside the flow passages of the machine will likely not be distributed uniformly from one end to another. In a compressor, the gas will get hotter with each successive stage. With some gases this will bake the deposits in the latter stages; with other gases, heavy, wet deposits will form in the first stages of the machine. Get a sample of the deposits to determine, first, what they are in order to see if they can be eliminated from the process. Failing that, test to see if they can be dissolved in some suitable solvent, for either on-line or off-line washing, in order to delay a subsequent machine overhaul. While compressor manufacturers shy away from on-line full-speed washing, we have had very good luck with both this technique and with off-line washing when the machine is slow rolled while half full of the wash liquid. When choosing a wash fluid be sure it is compatible with all components in the machine, such as "O" rings, etc., as well as the process. On-line abrasive cleaning with walnut hulls, etc., has found wide acceptance with gas turbine users, but is not without its problems. Plugged orifices, airbleed passages, and the like are common. The total subject of on-line or off-line cleaning is beyond the scope of this paper, but it is well worth consideration in specific situations as it is a real time and money saver. An interesting paper on the subject was presented at the 2nd Texas A&M Turbomachinery Symposium [3].

The bearings, journals, and seals should be checked visually for signs of distress. An analysis of journal bearing damage appeared in the Proceedings of the 4th Texas A&M Turbomachinery Symposium [4]. The most common problem in our experience has been that of babbitt fatigue. While the after-market has been offering bearings with babbitting less than 0.010 of an inch thick for a number of years, some machinery manufacturers have resisted change in this area. Our experience with thin babbitt bearings has been excellent to date. We plan to try a set of thin babbitt bushing-type seals shortly.

Labyrinths can also tell a story which needs to be read and analyzed. Deep grooves in the impellers or shaft spacers are indications of a shaft excursion at some time in the operating cycle. Worn or corroded labyrinths indicate loss of efficiency, and, if found over the balance piston, could lead to a thrust bearing failure. As with bearings, new materials are now coming into the after-market which can combat the corrosion problem. Rubs could indicate misoperation, such as running at or near a rotor critical speed or in surge; a rotor dynamics problem; a thermal bow; or similar difficulty. The location, depth, and distribution of the rubs are the keys to a proper analysis.

Cleaning

When cleaning fouled components — rotors, diaphrams, etc. — make sure the work is done in a remote location. Sand or hulls used for this purpose will usually find a way of invading the wrong parts of the machine, such as bearings and seals. The rotor should be carefully checked at this time for debris lodged in the gas passages. We have had several instances where a rag or piece of metal was jammed in an inaccessible place in an impeller. The use of a small dental mirror and a thorough inspection by hand can reveal most of this sort of debris.

One of our most spectacular problems involved a rather unusual foreign object which has subsequently been dubbed "The Million Dollar Bolt." The compressor, an 8000-horsepower, 8600-rpm, multi-stage, horizontal split machine, had run very well for seven years since startup and had not been opened for inspection during that period of time. One night, the vibration level suddenly took a large step change from 1 mil to well over 8 mils. The machine is not on automatic shutdown, so we continued to run at this level for several hours and were able to analyze the vibration signature. All signs pointed to imbalance since the predominant vibration peak was at operating speed. We thought a piece had come out of an impeller and were planning an orderly unit shutdown when a loud bang was heard from the machine. The vibration level immediately dropped to 4 mils. We opened the machine and found that a six-inch-long, ¾-inch carriage bolt had passed through the first stage impeller and had lodged in the diffuser channel. This situation was all the more remarkable as we have a permanent suction screen welded into the inlet line which was still intact. This meant the bolt lay on the upstream side of the screen for seven years before traveling the last 30 feet of pipe and entering the machine. We suspect the bolt was one of those used to hold the temporary shipping blind in place and fell into the inlet line during installation.

It is fairly common practice to inspect a rotor using magnetic particle or dye penetrant techniques. This is a strongly recommended step, as it can turn up defects which could otherwise prove to be highly damaging during a subsequent running period. In one such instance we uncovered an undesirable manufacturing technique which has been practiced for many years. The magnetic particle and subsequent dye penetrant inspections showed several cracks around the eye of the fifth stage impeller in a multi-stage barrel compressor rotor installed in relatively clean hydrogen service. Up to this point the overhaul had been a routine matter, but now took on far more serious implications. It seems that this particular compressor manufacturer has been in the habit of overspeed testing impellers and then trimming the eye labyrinth area to size, thus weakening the most critical structural area of the impeller. The explanation given (to compensate for bore stretch during overspeed) is, of course, unacceptable. Most manufacturers will now readily guarantee maximum allowable expansion in the diameter of the eye of an impeller as a function of the diameter before the overspeed test. This is the only acceptable way to buy compressor impellers, either as part of a new machine or as a replacement part.

Reassembly

Once the machine has been opened and all parts cleaned and inspected, the reassembly procedure can begin. There are many critical phases involved with this operation, one of the most important being care in handling the rotor. Large, heavy rotors (over approximately 2500 pounds) require special handling and, in some cases, special guide fixtures should be fabricated to avoid damaging components. This is particularly necessary with gas turbines which have many exposed, fragile parts. A solid rotor cradle is also a very necessary item. Do not shortchange your most valuable spare part by failing to protect it during the course of an overhaul or during transit to or from the storage warehouse.

When fitting housings and other components with multiple "O" rings in blind areas, we have found that it is usually beneficial to first remove the "O" rings and fit the housing by hand to check the alignment of the assembly. Blind dowels or concealed shims can be located in this manner with pencil marks. The "O" ring fits should be touched lightly with 600 wet or dry paper to remove any burrs and then checked carefully by hand. Lubricate the "O" rings with a suitable grease or oil. A cut "O" ring, worth very little in itself, can bear heavily on the success of an overhaul.

Bearing clearance is one of the most important checks during reassembly. We have found that after several years of operation the pads of a tilting pad journal bearing will wear small depressions in the housing which can open the clearance beyond specifications. Also, replacement pads may not be within tolerance. The only proper way to check bearing clearance with this type of bearing is by using a mandril the size of the journal and a flat plate as shown in Figure 6. The clearance in a sleeve-type journal bearing can be checked with plastigage. Be sure to torque the bearing cap bolts correctly or you may get a false reading.

When assembling bearings, be sure the antirotation dowels are in place and look to be sure the oil dam (if used in that particular bearing) is in the correct direction of rotation. Some of these steps will sound obvious, but each one results from a problem experienced in the field. It is also useful to check the alignment of oil supply holes in the housing with oil feed grooves in the bearing. For want of a 3/8-inch groove in the housing of a replacement bearing, we recently lost a high-speed shaft and impeller assembly in a plant air compressor package.

Before the upper half of the casing of a horizontally split machine is bolted in place, a final rotor mid-span bow check is recommended. This is particularly useful if you, as the responsible engineer on an overhaul, have not been able to personally witness all rotor movements during the course of the job.

Coupling half fit is another area requiring consideration. The assumption that the taper is correct provides a false sense of security. By lightly bluing the shaft and transferring the bluing to the coupling half, the fit can be properly checked. We require 85% contact. If the contact pattern is not acceptable, the dilemma to lap or not to lap rears its ugly head. We will not lap using the coupling half for obvious reasons, but will lap using a ring and plug gauge set. The advance of the coupling on the taper must be correct and should be witnessed and recorded by a knowledgeable individual. Coupling bolts must be torqued to the coupling manufacturer's specifications as the clamping force, not the bolt body, is generally the means of transmitting the torque.

As the machine goes back together, fill in the information on the critical dimension diagram. Labyrinth and bearing clearances, total rotor float, thrust clearance, coupling advance, bolt torque, etc., should all be measured and logged. Shaft alignment and cold baseline data for comparison with hot growth data taken after startup should also be logged on the appropriate sheet. Remember to check the shaft end gap, as not all rotors are created equal and the wrong dimension could damage your coupling. When leaning into an open machine, it is well to remember to remove all loose objects from shirt pockets!

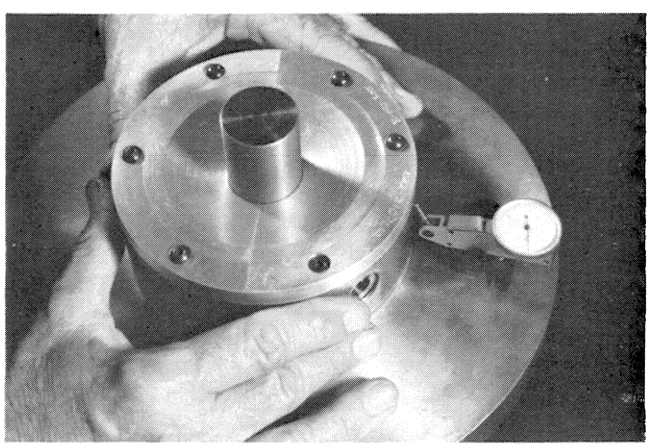

Figure 6. Checking the Clearance in a Tilting Pad Journal Bearing Assembly.

There are some other checks which may or may not have been incorporated on the critical dimension diagram, most notable of them being whether the rotor is free to turn and whether oil is flowing to and from the proper places. This latter item can be viewed just prior to bolting bearing caps or covers in place, assuming the oil lines have been reconnected. On some machines with internal oil tubing, it is possible to have oil flow showing in the main oil drain sight flow indicator while no oil is reaching the bearings or seals!

DOCUMENTING WHAT YOU'VE DONE

Following the overhaul, the startup will need to be monitored. We use a Real Time Analyzer and a multi-channel FM tape recorder to obtain baseline vibration data for comparison with previous operating information. Hot alignment readings can usually be taken several hours after startup. Machine performance will normally be checked after the process has stabilized which, on some machines, can be as long as one or two days after startup. All of this information provides a very useful check on the success of the overhaul and should be taken at the outset of a run and not delayed until a "convenient" time several weeks from startup.

As soon as the machine is operating satisfactorily, do the paper work. Many engineers shy away from this duty and use the press of day-to-day business to delay or even forget this very necessary chore. While the events are still fresh in your mind, sit down and finish the job. In documenting an equipment overhaul, we use the following format:

1. Basic machine data.

   A brief description of the machine, including manufacturer model number, number of stages and other physical parameters, serial number, date purchased, date of last overhaul, and reason for current overhaul.

2. Performance, vibration, and mechanical health data. A comparison of pre- and post-overhaul levels.

   Performance and vibration data for the train, including process flow, pressure and temperature, machine case and eddy current probe vibration levels, as well as oil supply pressure and temperature and oil return temperature. The performance data should be sufficient to accurately assess the machine's condition. Calibrated instruments are required.

3. Spare parts.

   A complete list of spare parts for the machine, as well as a list of parts actually consumed. Include machine manufacturer's part number, as well as company warehouse stock number.

4. Critical dimension diagram.

   Complete with factory specifications, as-found dimensions (logged during disassembly), and as-overhauled dimensions. This information must include such items as total rotor float, thrust clearance, rotor position within the total float, labyrinth clearance, radial bearing clearance, nozzle stand-off, coupling bluing check, coupling advance, etc.

5. Rotor run-out diagram and balance report.
6. Shaft alignment diagram.
   A shaft alignment diagram showing desired readings based on anticipated thermal growth data, "as found" readings (prior to overhaul), "as left" readings after overhaul, and actual measured thermal growth data.
7. Photographs of the overhaul.
8. A discussion of the overhaul. Refer to appropriate photographs throughout.
9. Recommendations.
   - For future overhauls.
   - For reconditioning worn but reusable parts.
   - For on-line cleaning, if applicable.
   - For redesigned parts, if applicable.
10. Shift logs and backup data as required.

In writing up a report, decide what went right and what went wrong. Fully identify the causes in each case so that your successor can benefit from your experiences. Send a list of spare parts used in the overhaul to the warehouse controller. While you hope you won't need parts in a hurry, don't bet on it! Decide if you plan to invite the factory serviceman back for a subsequent overhaul. In either case, put his name on your report so no confusion exists on this point. Go back to the machine manual and make notes in the margin on any obvious errors that appear in the printed material.

Nonstandard Parts

Once the first year of operation of a new machine is up, it is well to remember that the guarantee is also up. In addition, bear in mind that the original equipment manufacturer's parts were generally a design compromise to a competitive marketplace and existing, available designs in his shop. Any parts that fail to stand up should not necessarily be replaced by standard parts. There are many excellent after-market manufacturers of components and many specialized tools such as multi-plane milling machines and overspeed spin pits for individual components. Aerospace technology and materials are beginning to filter down to the after-market also. None of the above should be construed as an indictment of the equipment manufacturer, but when his spare part pricing, policies, and failure to solve design problems mount to a point where it becomes necessary to put properly engineered after-market components into a machine, we do not hesitate to do what is best for our company.

CONCLUSION

Successful machinery overhauls result from careful planning, teamwork, and attention to details. A proper overhaul report will document the effort and prepare the way for more efficient overhauls in the future.

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3. Turner, Brian, "On-Stream Cleaning of Turbomachinery," Proceedings, 2nd Turbomachinery Symposium, Gas Turbine Laboratories, Texas A&M University.
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APPENDIX A

CRITICAL DIMENSION DIAGRAM

PAGE 1 OF 3

GENERAL

MACHINE NO. K-6251 DATES OF OVERHAUL ________ (INCLUSIVE)

SERIAL NO. 2-6-2264

INSTALLED ROTOR SERIAL NO. ________

REMOVED ROTOR SERIAL NO. ________

ENGINEER IN CHARGE ________

MISCELLANEOUS

WEIGHTS: TOP HALF OF CASE 11,700 LBS. ROTOR 1390 LBS.

ROTOR: LENGTH (O.A.) 78 IN. LARGEST DIA. 25 1/2 IN.

ROTOR: 1ST CRITICAL 4000 RPM 2ND CRITICAL ________ RPM

ACCEPTABLE CLEANING MATERIALS: BLASTING: WALNUT HULLS

CLEANING: INHIBITED COLD CLEANER

CASE BOLT TORQUE:	DIAMETER	ELONGATION	TORQUE (FT.LBS.)
MAIN	2 1/4 IN.	0.025 IN.	8000
ENDS	1 5/8 IN.	0.018 IN.	3500

CASE SEALANT COMPOUND: RTV-60

DATE OF MANUFACTURE ________ AMOUNT REQUIRED FOUR 1/4 LB

COUPLING

		SPECIFICATION	CHECK	
			INITIALS	AMOUNT
DRIVER HUB:	ADVANCE	0.144 IN.		
	BOLT TORQUE	27 FT LBS		
	BLU CHECK	85%		
DRIVEN HUB:	ADVANCE	0.168 IN.		
	BOLT TORQUE	27 FT LBS		
	BLU CHECK	85%		
SHAFT END SPACING		18 IN ± 1/64		

MAXIMUM HYDRAULIC PRESSURE 25,000 PSIG EXP./4000 PSIG PUSH

CRITICAL DIMENSION DIAGRAM

JOURNAL BEARINGS

	SPECIFICATION	CHECK	
		INITIALS	AMOUNT
H.P. END: DIAMETER	**4.125 IN.**		
CRUSH	**0.000 TO -0.001**		
CLEARANCE	**0.005 TO 0.0075**		
L.P. END: DIAMETER	**4.125 IN.**		
CRUSH	**0.000 TO -0.001**		
CLEARANCE	**0.005 TO 0.0075**		

NOTES: 1. USE MANDRIL TO CHECK CLEARANCE
2. CLEARANCES ARE DIAMETRAL

THRUST BEARING

	SPECIFICATION	CHECK		
		BEFORE	AFTER	INITIALS
AXIAL CLEARANCE	**0.015 TO 0.022**			
COLLAR RUN OUT	**0.0005 MAX**			
COLLAR FIT	**0.000 TO -0.001**			
OIL CONTROL RING CLEARANCE	**0.005 TO 0.009**			
TOTAL ROTOR FLOAT	**0.480 IN.**			
% TO H.P. END	**60%**			
% TO L.P. END	**40%**			

ACTIVE DIRECTION: **OUTBOARD**

THRUST NUT THREAD: **LEFT HAND**

OIL SEALS

	SPECIFICATION		CHECK	
LABYRINTHS	DIAMETER	CLEARANCE	AMOUNT	INITIALS
LP INNER STEP	**5.250 IN.**	**0.008 TO 0.0105**		
LP OUTER STEP	**5.000 IN.**	**0.008 TO 0.0105**		
HP	**5.000 IN.**	**0.008 TO 0.0105**		
SEALS				
HP INNER RING	**4.500 IN.**	**0.003 TO 0.004**		
HP OUTER RING	**4.500 IN.**	**0.015 TO 0.017**		
LP INNER RING	**4.500 IN.**	**0.003 TO 0.004**		
LP OUTER RING	**4.500 IN.**	**0.015 TO 0.017**		

NOTE: CLEARANCES ARE DIAMETRAL

CRITICAL DIMENSION DIAGRAM

PAGE 3 OF 3

DIAPHRAM LABYRINTH CLEARANCE

	SPECIFICATION		CHECK		
	DIAMETER	CLEARANCE	AMOUNT	INITIAL	
STAGE 1 LARGE	17.125 IN.	0.022 TO 0.027			
STAGE 2 LARGE	15.575 IN.	0.022 TO 0.027			
STAGE 2 SMALL	7.500 IN.	0.012 TO 0.016			
STAGE 3 LARGE	14.200 IN.	0.022 TO 0.027			
STAGE 3 SMALL	7.000 IN.	0.012 TO 0.016			
STAGE 5 LARGE	14.200 IN.	0.022 TO 0.027			
STAGE 5 SMALL	7.500 IN.	0.012 TO 0.016			
STAGE 6 LARGE	12.950 IN.	0.022 TO 0.027			
STAGE 6 SMALL	7.500 IN.	0.012 TO 0.016			
STAGE 7 LARGE	12.950 IN.	0.022 TO 0.027			
STAGE 7 SMALL	7.500 IN.	0.012 TO 0.016			
			BEFORE	AFTER	INITIAL
BALANCE PISTON	14.375 IN.	0.012 TO 0.016			
			AMOUNT	INITIAL	
FINAL MID SPAN RUN OUT	0.001 TIR MAX				

NOTE: CLEARANCES ARE DIAMETRAL

SPECIAL NOTES OR PRECAUTIONS: ____________________