MACHINERY FAILURE PREVENTION: A FUNDAMENTAL ASPECT OF PLANT SAFETY

A program that combines analytical review, detection, and maintenance in a coordinated attack on mechanical failures is given, as well as a description of monitoring techniques and new failure detection devices.

James J. Zimmerman
Mechanical Technology Inc.
Latham, N. Y.

Any unscheduled and unanticipated event occurring in the operation of a processing plant constitutes a potential hazard. Additionally, such events inevitably represent a potentially significant loss; loss from consequent damages, loss resulting from lost production, loss as represented by resulting increased insurance costs.

Until lately, the problem of machinery failure has generally been accepted as an inevitable operating hazard. The logical attempts to reduce the likelihood of failure involved design improvements based on experience, plus preventative maintenance programs formulated on the basis of combined experience of the machinery manufacturer and the plant operators.

These measures notwithstanding, mechanical failures continue to plague plant operators. In fact, the possibility of component failure has increased in recent years. Much of this has been the result of large scale processes which have been able to utilize completely rotating type equipment.

The new applications, coupled with the differences in machinery, have added to the complexity of the program. Processes themselves which encompass extremes of pyrogenic and cryogenic temperatures and extremely high pressures have added to the problem. Requirements for greater efficiency and greater output have resulted in higher loading, higher speed and in general, higher stress levels.

Proposed program

A full scale program needs the proper coordination of initial review of requirements, selection of equipment, analytical techniques, previous field experience and an enhanced plant maintenance program. Obviously, the scope of such a program in minute detail would require a thorough knowledge of an individual plant. It would also require a treatise on each individual item which would not be practical for a presentation, such as this one.

However, there are many items which are common regardless of the process or plant, which can significantly improve on-stream performance. In a simplified form we can discuss these under five basic areas:

1. *Properly detailed purchase specification:* This will insure that equipment purchased for a given application has, in fact, been designed for realistic operating conditions in all respects, and manufactured with proper quality control and inspection criteria being applied. This item gives preliminary insurance that the machine is adequate for the function intended, and that it will integrate into the system without catastrophy.
2. *Design audit:* The equipment should receive a design audit to check performance capability, to establish mechanical integrity, and to determine the adequacy of critical items.
3. *Proper engineering analysis* of all of the machinery to an interconnected system.
4. *Incorporation of monitoring instrumentation:* This instrumentation is designed to detect the functioning of the critical elements and sense incipient failure; i.e., before it progresses to become the initiator of a catastrophic failure involving a component, a whole machine, or even an entire system.
5. *Preventative maintenance programs* to encompass *all* factors requiring inspection and maintenance.

Based on the previous comments, it will be noted that Item 1 seeks to determine if the equipment is proper for the purpose intended. It goes a step further in that it seeks to establish a more through meeting of the minds between the manufacturer and the ultimate user so as to eliminate items which can affect performance, but may, in some cases, be omitted from the specification. Item 2 is a further review of potential mechanical problems which can often, by minor modification, be removed prior to the fabrication stage. At the very least, it will provide certain guidelines and areas to watch during operation, even if a meeting of the minds cannot be established with regard to their initial implementation.

Item 3 is self-explanatory and takes into account that many of the salient features of individual machines are lost by improper installation and formulating into the final train. Item 4 recognizes that certain unforeseen problems can arise during operation and that conventional means for monitoring do not have the sensitivity nor the absolute discrimination to pinpoint a problem before it has reached serious and damaging proportions. Item 5 seeks to extend the preventative maintenance program to encompass considerable additional knowledge which can be determined regarding the particular equipment. The sections which follow review these five items and discuss several of the key aspects.

Detailed purchase specification

The specification should include such items as:

1. Complete engineering description of equipment. This should include such factors as: aero-thermodynamic performance, efficiencies specified, surge and instability limits, etc., preferably indicated by a series of curves.
2. Basic materials of construction. Stress levels at design speed and operating temperature of all critical components, i.e., impellers, turbine blades, gears, etc.
3. A description of important "fits," particularly as regards seals, bearings, balance pistons, and shaft-disk contact locations.
4. A list of limiting operating conditions, i.e., maximum vibration; maximum oil temperature; transient conditions, move-

ments, etc.
5. Detailed description of control and auxiliary equipment.
6. Minimum content of operating instructions and maintenance manual.
7. Details of acceptance test, load schedule and list of test data to be taken.
8. Guarantees.

In addition to this, the user or potential user should request the following:

1. Sufficient information to establish the mechanical integrity of equipment:
   A. Layout sufficient to define mechanical relation of components.
   B. Mass and inertia distribution for rotating machinery.
   C. Bearing type, size, clearance (spring and damping characteristics).
   D. Seal type, size, clearance.
2. Lateral and torsional analysis of equipment train (where applicable).
3. Material certification - shafts and impellers:
   A. Test report of test sample (tensile and metallurgical).
   B. Heat treatment report.
   C. Hardness test reports; impellers, gears, shafts, etc.
4. Wheel overspeed certification.
5. Closed loop test at full system pressure:
   A. Various speeds.
   B. Endurance test 24-48 hr.
6. Specific service examples.

Design audit

A design audit should be instituted during the purchasing process in order to compare major design features of competitive equipment. Alternatively, an audit may start once the equipment vendor has been selected. The design audit may be conducted in depth so as to include such things as aerodynamic performance, electrical performance, etc., or it may be restricted to concentrate on the mechanical design and the dynamic performance. The audit should certainly be accomplished by other than the manufacturer to insure maximum objectivity.

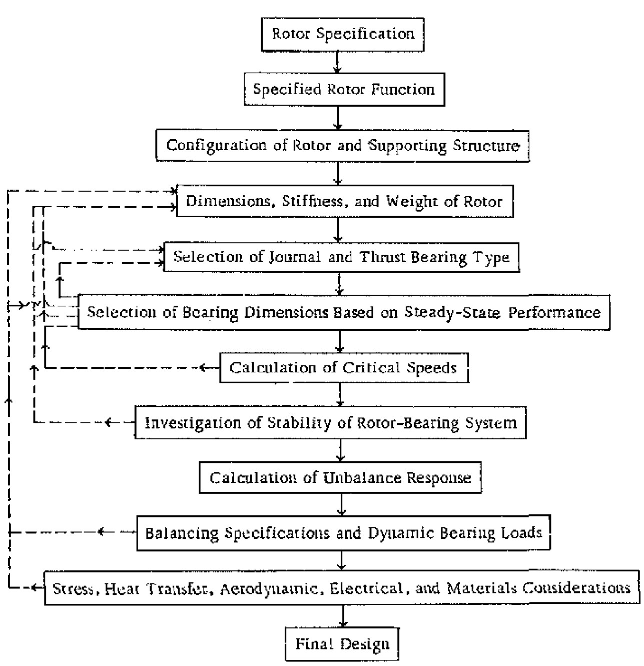


Figure 1. Logic diagram of design procedure.

Figure 1 illustrates the interrelation of factors influencing machine design. As part of the audit it is necessary to review those items most prone to failure. Major components include bearings, seals, balance pistons, couplings, gears - all of which contribute to the operation of the machinery from the standpoint of vibrations, loading, performance and operating temperature. These items individually must be carefully reviewed and their operating characteristics established.

The bearings, for example, must be evaluated for their ability to carry load, their susceptibility to unstable operation, their compatibility with the rotor system, and for their compatibility with the available lubrication system. As part of the review on the bearings, spring and damping coefficients should be determined. These coefficients are used later to define rotor-dynamic behavior.

The seals should be examined from two standpoints; firstly, with respect to their primary function of keeping process fluid or gas restricted to particular areas, and secondly, to determine if the seal may act to influence the rotor-dyamic behavior. A typical example of this is oil buffered type seals. These seals are essentially plain cylindrical journal bearings which have a tendency toward instability at higher speeds. It is therefore possible that a rotor supported on inherently stable bearings may be caused to exhibit instability by virtue of the influence of the seals.

The remainder of the components should also be examined for their ability to transmit torque, adequacy of lubrication, and adequacy of the material selection. In the case of balance pistons, for example, the construction and materials should be evaluated in terms of the discharge pressure and temperatures which act upon them. Couplings should be evaluated for size, torque rating, misalignment tolerance, lubrication, and material properties. In the latter case, hardness of teeth may well be the difference between a satisfactory operation and one which suffers deterioration.

Importance of stability

Rotordynamic behavior should be concentrated upon because of the high incidence of equipment which exhibits undesirable vibrational characteristics in many applications. Review the procedure of evaluation. As previously stated, the spring and damping coefficients for the bearing system are a necessary prerequisite for the analysis of rotordynamic behavior. Next, the mass and elasticity of the shaft should be used to define the various system critical speeds as a function of support stiffness. It should be noted that the support stiffness consists not only of a consideration of the bearing fluid film stiffness, but also considers any series stiffness such as the stiffness of pivots in the case of the pivot shoe-type bearing, as well as housing stiffnesses, etc.

For a first approximation, superimposing of the bearing stiffness—including elasticity of the pivot as a function of speed—will show the interaction with critical speeds during acceleration and at the operation point. A presentation of this type is shown in Figure 2. It is well to concentrate on this figure for a moment. Very often the information provided by the vendor will include critical speed data, which considers the mass and elasticity of the shaft, but which ignores the effect of the spring stiffness of the bearing. Thus, a rigid bearing critical speed will essentially be presented. In essence, this corresponds to Figure 2 with the support stiffness approaching infinity.

Based on these values, most operating machinery will be construed to be operating above the first bending critical, but well below the second. As the effect of bearing support stiffness is introduced, it will be noted that it is possible to operate above the second critical in proximity to the second and third, or well above the third critical speed. This is valuable information in terms of long-term reliable operation. Where the system will exhibit changes in balance with operating time, operation in some of these regions may be extremely sensitive and be the cause of future difficulty. Because the above treatment does not consider the effect of bearing damping, it is necessary to further refine the analysis to determine the response of the rotor to excitation such as unbalance.

To determine the response of the rotor to residual unbalance, the spring and damping characteristics of the bearing must be considered, as well as the influence of damping in other components, such as oil buffered seals. Unit balances are placed at

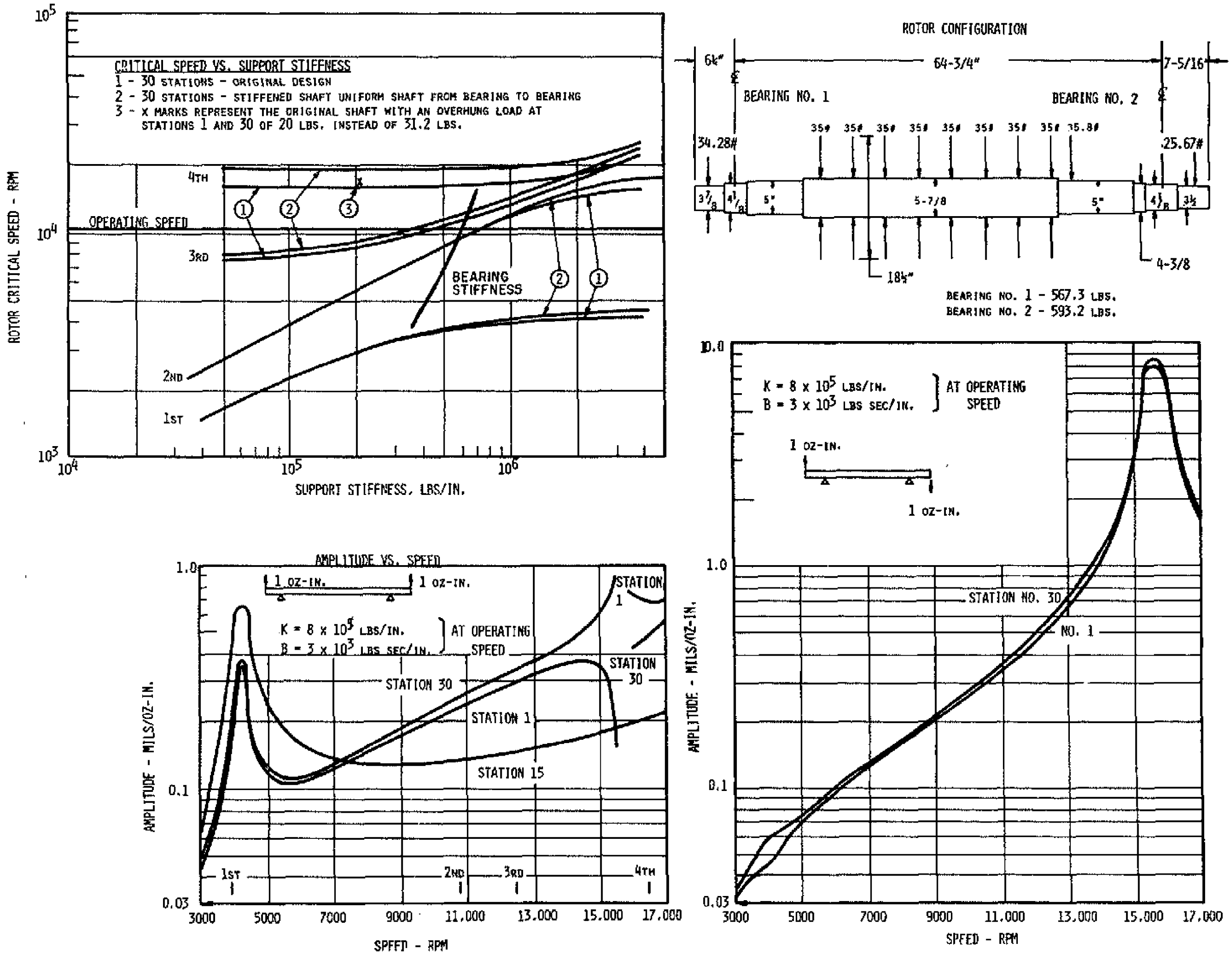


Figure 2. Typical unbalance response analysis for unit unbalance.

regions likely to change balance with time. Typically, these would be at couplings, at the mid-point of the impeller assembly, and in regions where large additional members have been added to the rotor.

Figure 2 shows a typical unbalance response analysis for unit unbalance. This then, defines the anticipated amplitude of vibration for the actual system, and in the case of the first critical speed demonstrates where this would shift because of the addition of bearing damping.

As part of the mechanical review of the rotor, consideration must be given to the type of material to be used for both shaft and impellers, the way in which the assembly is mounted and the locking means used to prevent rotation. The fitting practice is important in terms of the stress induced in the wheel as well as its potential for inducing fricitional type instabilities and/or permitting movements of parts - both of which result in deterioration of vibration performance. The suggested request for the material certification and certification of over-speed test is basically a spot check on which should be standard practice.

Effects of thermal gradients

It is also often advisable to check impeller stresses in order to assess the ultimate reliability of the design. Such stresses should be calculated to include both centrifugal effects and thermal effects. Figure 3 shows the results of such an analysis on a turbine wheel and demonstrates the value of including thermal effects as well.

The foregoing comment with respect to thermal effects on stress indicates that there very frequently is a need to ascertain the temperature gradients existing in the machine. The analysis of temperature and temperature gradients requires an evaluation of all heat sources—thermal conduction, convection, and radiation paths—and the generation from this data of a so-called thermal map, which shows temperature distribution, point by point, throughout the machine. A typical map generated for a turbocompressor is shown in Figure 4. For the particular case shown, the bearing clearances were critical and the generation of a thermal map was mandatory in order to insure satisfactory operating clearances.

In the previous discussion, the use of the rotor response was defined with respect to amplitudes of vibration. Other information deduced from this analysis is the actual rotor mode shape under the assumed conditions of unbalance. With this established, it is possible to specify whether amplitude measurements should be made so as to define satisfactory operation. The availability of rotor mode shape also permits interpretation of various amplitude measurements which might be made.

Analysis of machinery in coupled systems

A common cause of machinery failure in processing plants is vibration resulting from the fact that the dynamics of an entire machine train or system were not throughly checked as described previously. This system check is strongly recommended for those cases where individual rotating machines will be connected in trains.

Vibration suppression is a vitally important aspect of the design of any high-speed or high-power geared transmission system. Geared systems are subject to torsional vibration of the whole

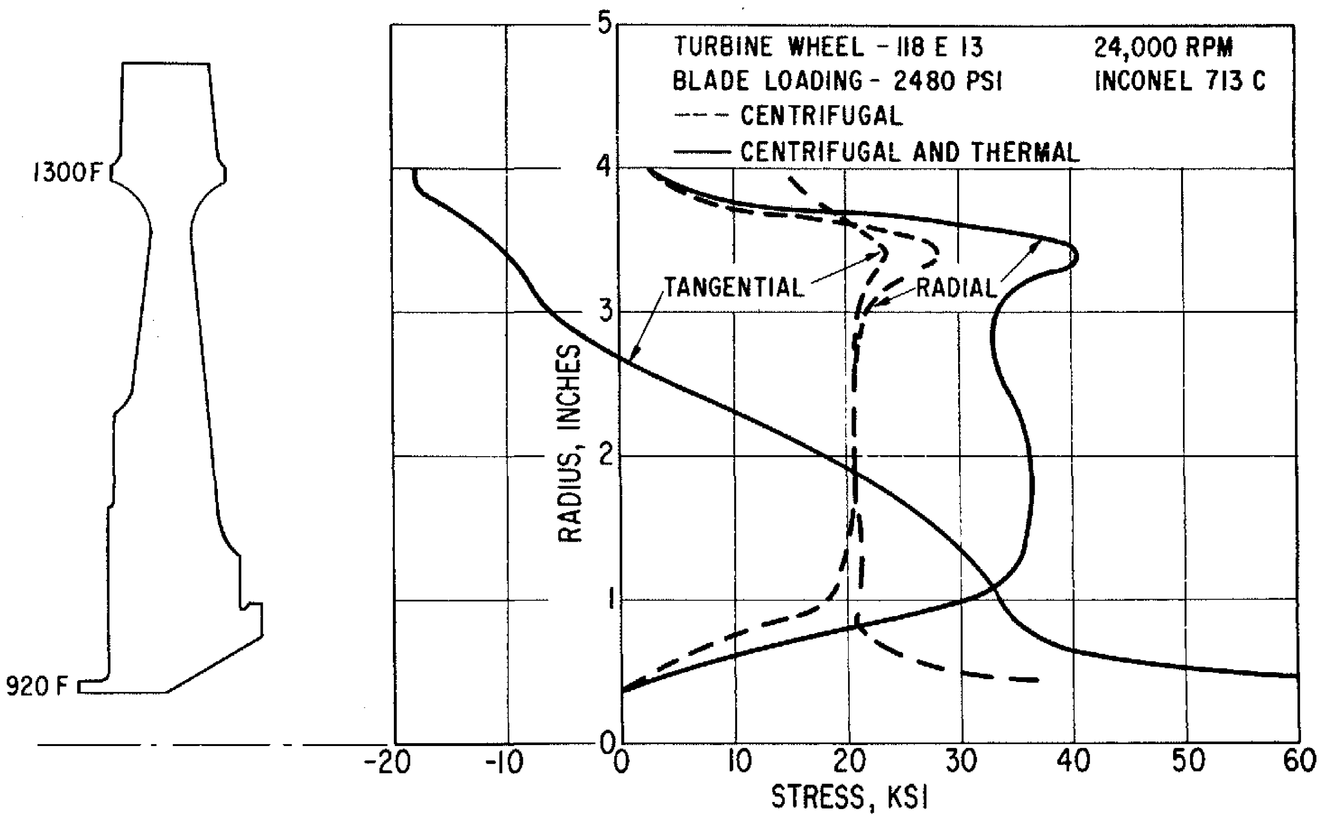


Figure 3. Results of analysis on turbine wheel.

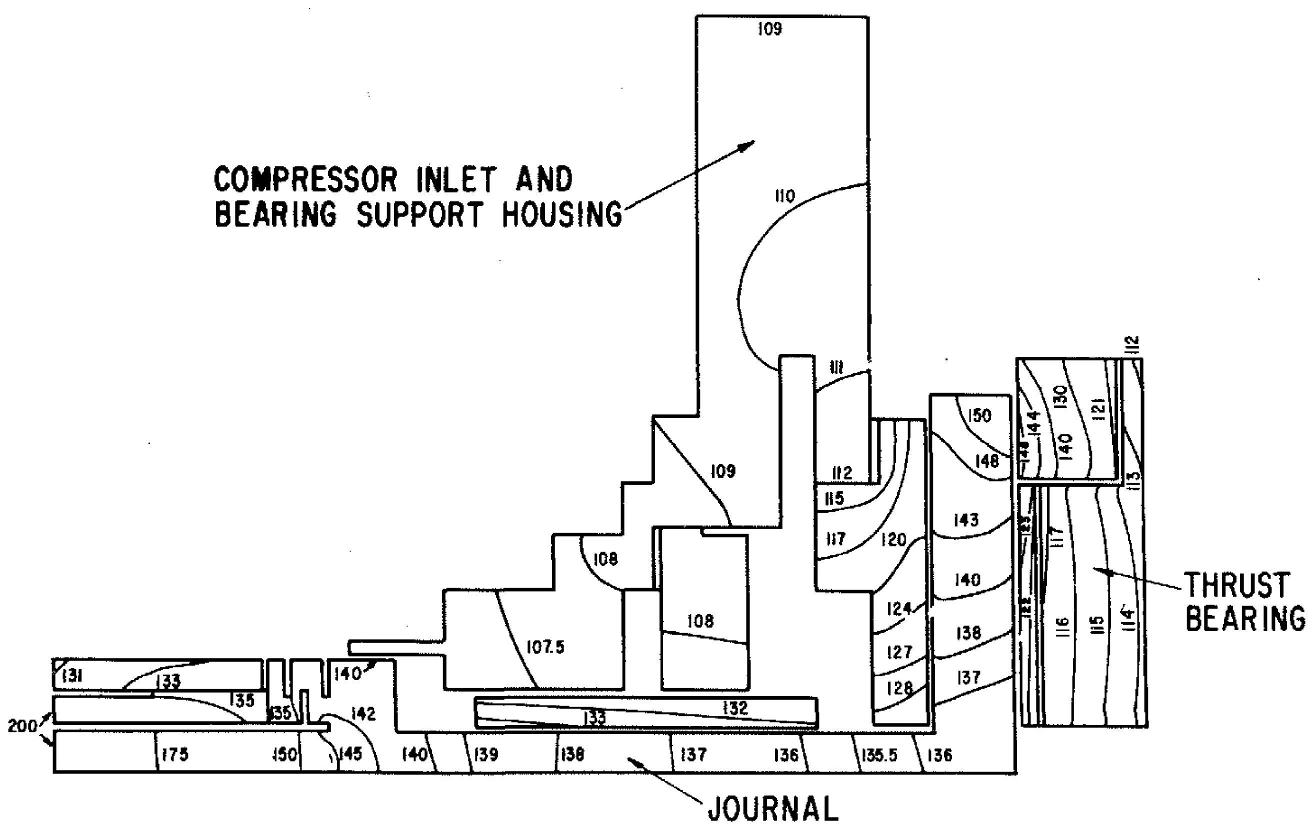


Figure 4. Typical temperature map generated for a turbocompressor.

system, bending vibrations of drive shafts, plate vibrations of gears, axial motions of certain subassemblies and various combinations of these vibration modes.

Three principal factors promote vibration problems in powered systems: (1) High power flow, (2) high speed, and (3) system complexity. In Table 1 these factors are evaluated in terms of their potential hazardous effect on system or operator.

It is obviously impossible to determine definitely at the design stage whether a system will encounter hazardous vibrations during operation. Within limits, however, Table 1 may be used as a reasonably effective guide, to ascertain preliminarily, the extent to which the system will probably be adversely affected by dynamic influence.

Table 1. Degree of Potential Hazard

Factor	Degree of Hazard			
	Name	Slight	Quite Probable	Almost Certain
Horsepower				
1	X			
100		X		
1,000			X	
10,000				X
Pitchline Velocity				
1,500 ft./min.	X			
4,000		X		
10,000			X	
25,000				X
Arrangement				
Single mesh		X		
Multiple reduction			X	
Multiple inputs or outputs				X
Flexibility and Accuracy				
High-accuracy teeth, light masses, flexible shafts		X		
Medium-accuracy teeth, heavy masses, stiff shafts				X

A reciprocating engine prime mover in a system with its inherent unbalance harmonics of torque entering the rotational drive will worsen any situation. Alternatively, the absence of such a vibration source is no indication that troublesome vibrations will not occur. These may still result from either a speed or power high enough so as to be capable of exciting heavy vibrations leading to failure without any other stimulus.

Figure 5 shows certain groupings of environmental factors which may be used to determine whether or not a problem is likely to exist. These charts are essentially qualitative, but when used together with discretion they can be of value in evaluating the need for more specific information. Ideally, a complete system or train of equipment should be assembled on the equipment vendors' test floor and should actually be operated as a system prior to delivery.

Monitoring instrumentation

It is very distressing to realize that a large proportion of disasters resulting from mechanical failure would not have occurred had monitoring instrumentation been installed which would have detected and given warning of incipient failure.

In most instances, a machinery component which is in danger of failing gives obvious warning signs; for example, the bearing oil and piston ring temperature rises, if either component is overloaded or wearing, pedestal vibration and noise levels increase in a turbine or compressor, and in many instances, there is a marked deterioration in operating performance.

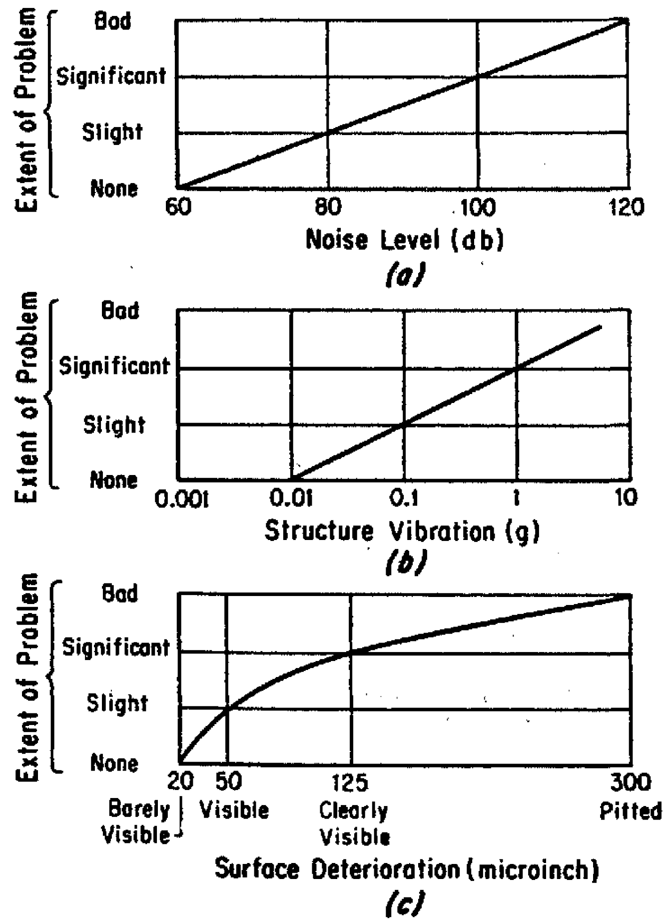


Figure 5. Groupings of environmental factors.

To a significant extent, mechanical failures can be traced to a high proportion of failures occurring in a few critical or "failure sensitive" components; bearing, gears, seals, rings, pistons, etc. These components contain certain obvious locations where incipient failure may be monitored in any machine. Research to a very significant extent has provided a basic understanding of the failure process in these critical components; the effect of variables on the process, how deterioration of these components affect system performance, and importantly, what type of instrumentation will detect impending failure.

The tools are at hand to develop diagnostic systems which will detect failure and/or deterioration in any given piece of machinery. These systems will comprise an integration of various internal and external measurements.

To design the optimum monitoring system, it is necessary for the machinery manufacturer to correlate data on the way in which components fail under operating conditions, including failure time and overload tolerances. Figure 6 shows the correlation of design information with respect to detection systems. Figure 7 shows the relationship existing between analysis, detection, and control. Acquisition and correlation of complete data relating to failures would result in more adequate failure detection equipment. It would also lead to improved design of critical components, superior equipment, better maintenance programs, and eventually substantially reduced failure histories.

Pinpointing causes of failure

Failure analysts are aware that it is rare for failure to occur due to a single cause. In most cases, a complex of interacting circumstances conspire to cause the final catastrophy. Figure 8 illustrates this fact. It follows that complete answers to the following questions are a fundamental necessity in the development of an adequate monitoring system:

1. What is the sequence of events which lead to failure?

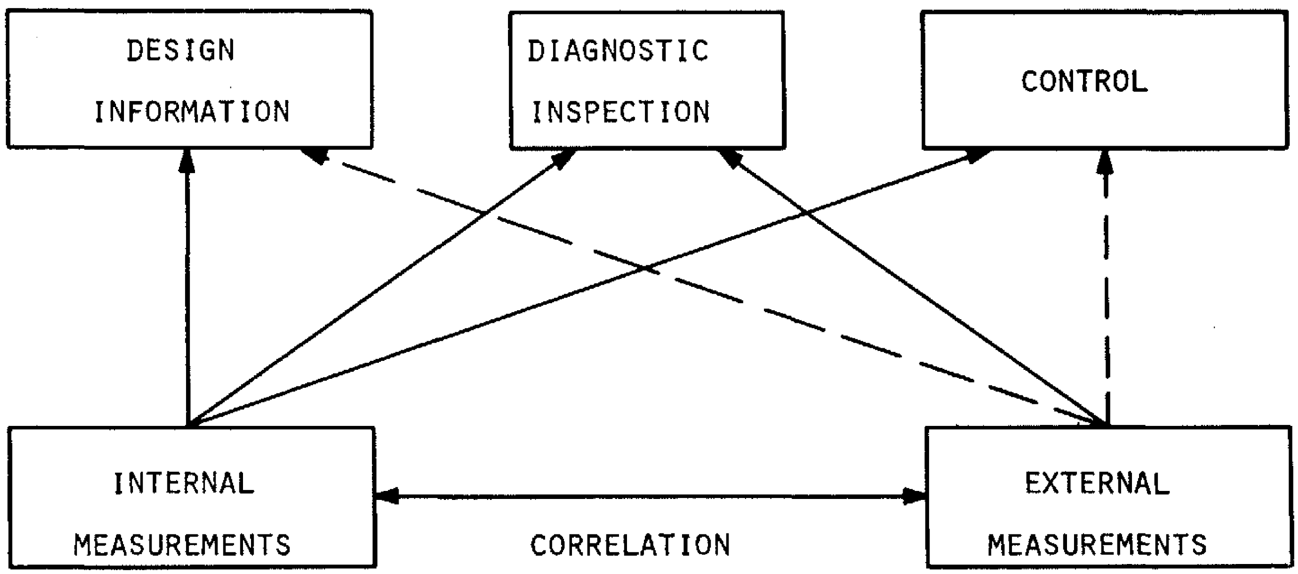


Figure 6. Detection systems.

ANALYSIS	DETECTION	CONTROL
BASIC MECHANISMS	COMPONENT INSTRUMENTATION STUDIES	IMPROVED DESIGN
WEAR FAILURES		REDUCED VULNERABILITY
VIBRATION & FATIGUE		FAIL-SAFE DESIGN
CORROSION & EROSION		MATERIALS
CREEP & FRACTURE		
COMPONENT FAILURES	FAILURE TRANSDUCER DEVELOPMENT	IMPROVED MAINTENANCE
FAILURE ANALYSIS		DIAGNOSTIC INSTRUMENTATION
INFORMATION ANALYSIS		CONTROL INSTRUMENTATION
		MODIFY OPERATING CONDITIONS
		IMPROVED MANUFACTURING
		QUALITY CONTROL
		TEST PROCEDURES

Figure 7. Mechanical failures.

WEAR PROCESSES IN ENGINEERING COMPONENTS

A CAUSE OF WEAR FAILURE	B PROCESS OF WEAR FAILURE	Journal Bearing	Thrust Bearing	Rolling Contact Bearing	Bushings	Pivots	Seals	Brakes	Clutches	Piston Rings	Electrical Contacts	Wear Plates	Gears		C RESULT OF WEAR
Dirt Corrosion	Material Removal			X	X	X	X			X					Seizure
Misalignment	Surface Damage 1.	X	X		X		X				X	X	X		Improper Position
Faulty Design	Thermal Instability 2.	X	X	X				X		X			X		Undesired Friction
Improper Materials	Fatigue	X	X	X											Breakage Noise
Over-Heating	Material Distortion or Breakage			X			X						X		Diminished Performance
Lubricant Interruption	Material Deterioration										X				
Improper Lubricant	Frictional Instability 3.				X			X	X						

1. Damage to the surface from relative motion while in contact.
2. Wear generated fails lubricant, etc.
3. Friction to high or low, variable friction, vibrations.

Figure 8. Wear processes in engineering components.

2. What effects would the operating variables have on the failure process?
3. What was the affect of design variables?
4. Which measurements are best able to sense impending failure and what degree of accuracy is required?
5. What steps can be taken to arrest the failure process once it is started?
6. How do impending failures and proceeding failures affect overall machine operation?

Considerable instrumentation is involved in obtaining this information. Figure 9 shows an instrumented turbomachine in a test cell. Figures 10 and 11 show the read-out instrumentation. It is not suggested here that plant operators have all of this instrumentation. The purpose of the illustration is to demonstrate the depth of analysis required by either manufacturers or consultants in order to be able to adequately answer the foregoing six questions.

Several new monitoring techniques have recently been developed and are currently being introduced into use in the processing industries. These techniques satisfy the first requirements for instrumentation used in processing plants. Namely, they combine required sensitivity with ruggedness, reliability, simplicity and physical size enabling placement in correct locations.

New monitoring techniques

These techniques enable internal measurements to be made which, when correlated with external measurements; for example, vibration, sound, oil sampling, etc., provide a comprehensive diagnostic monitoring system.

Shown in Figure 11 are several Micro-Dyne console analyzers which were developed jointly by MTI and Millivac Instruments Inc. The unit replaces a combination of general purpose electronic instruments previously required to monitor shaft motion under dynamic operating conditions in high-speed rotating machinery. The system will discriminate motion with an accuracy of ± 5 microin. as sensed by non-contacting capacitance probes. It faithfully indicates and displays motional vibrations ranging from steady-state or DC up to 10,000 cps.

Magnetic inductance transducers are currently in production and available in a variety of configurations to suit practically any mounting requirement. A magnetic transducer pickup sys-

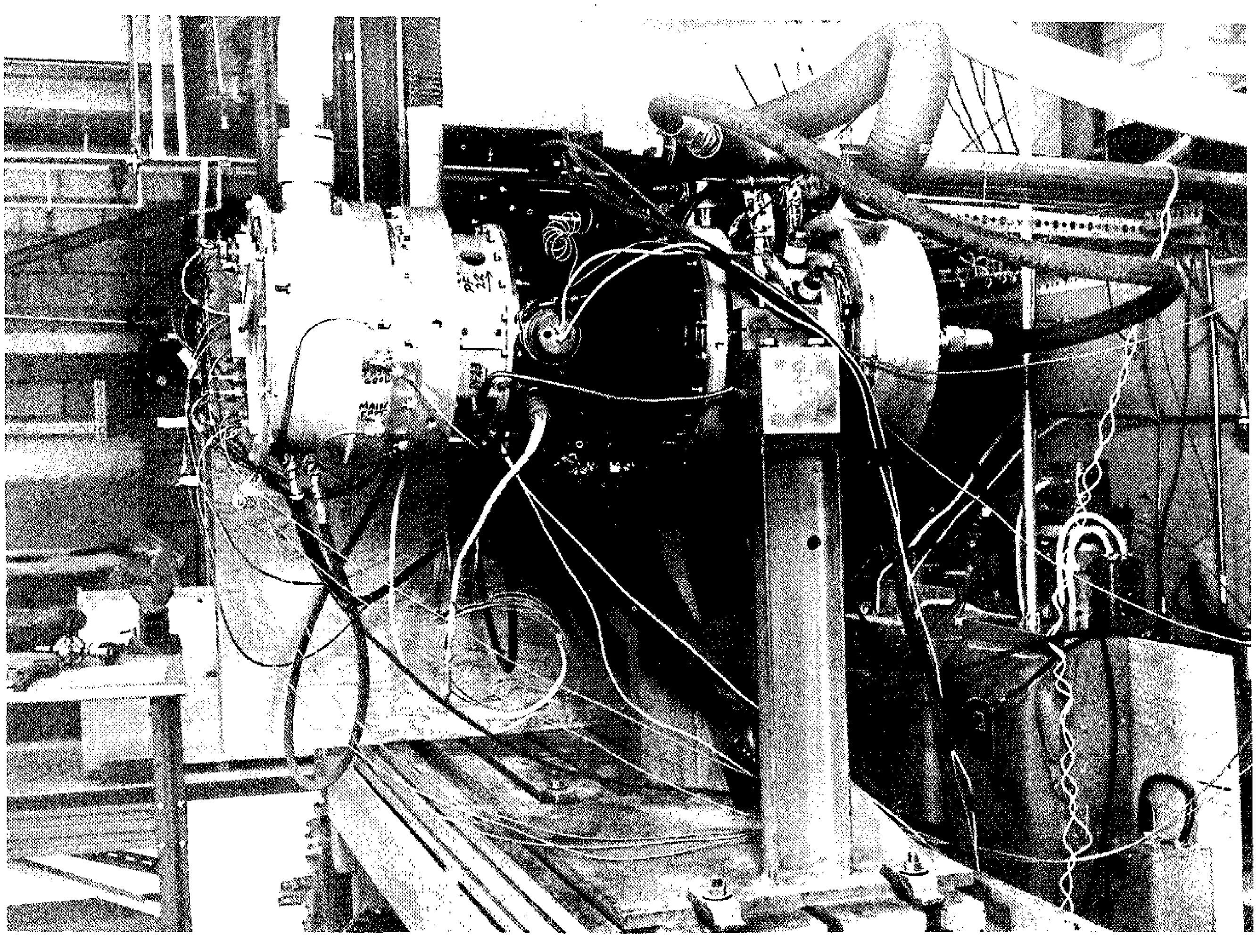
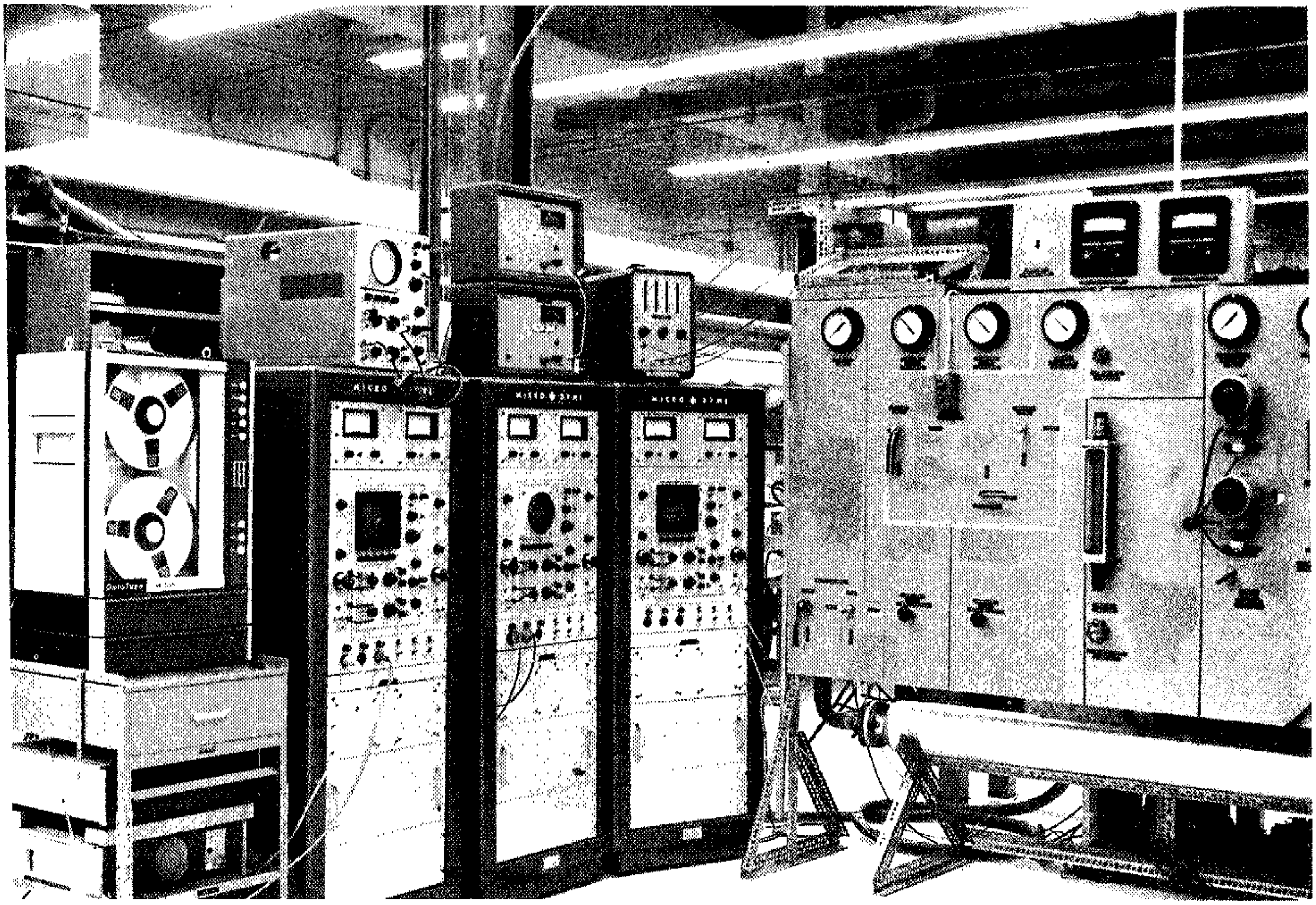
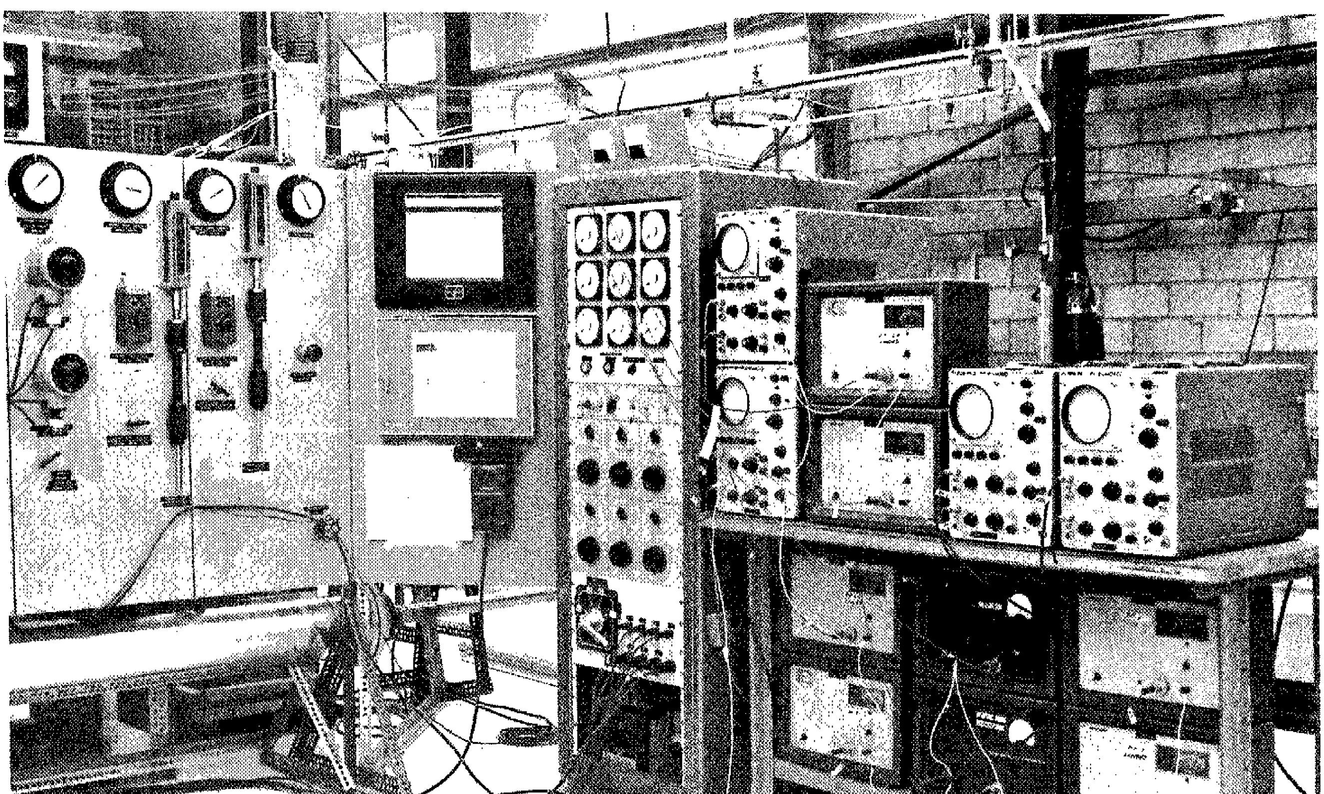


Figure 9. Instrumented turbomachine in a test cell.





Figures 10 and 11. Readout instrumention used in test shown in Figure 9.

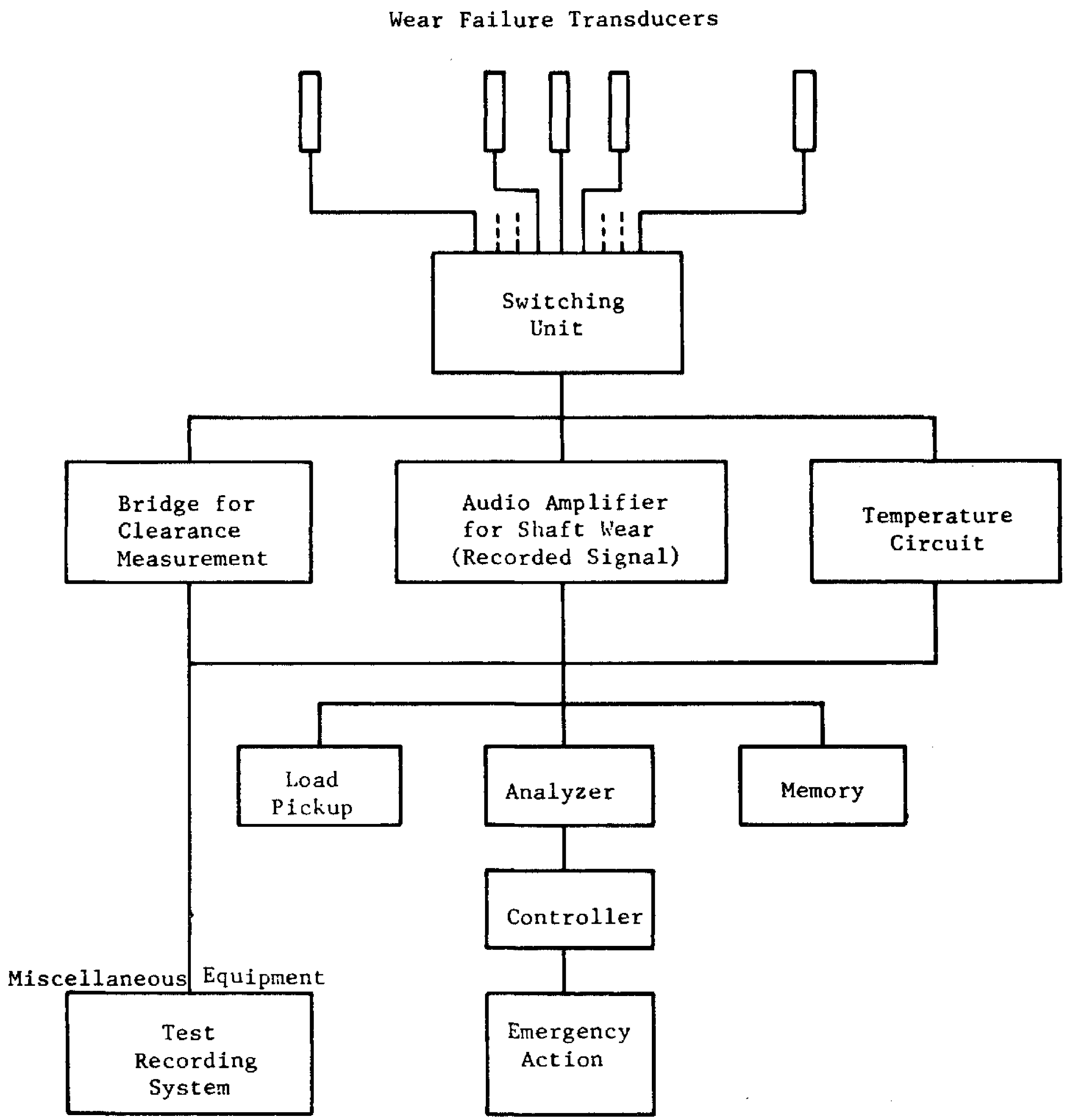


Figure 12. Diagram of approach used to measure specified variables.

tem offers many advantages for the monitoring of clearance, temperature, bearing wear, shaft wear, metal transfer and surface changes such as pitting or galling. These systems will operate reliably in the presence of oil, grime, grit, water, cavitating fluids, etc., over a wide temperature range.

The magnetic inductive pickup is similar to a miniaturized tape recording or erase head, is sensitive to temperature, distance, magnetic fields on the observed surface, the presence of metallic smears, vibration or chatter between the surfaces, surface cracks, etc. This allows one type of pickup to measure all these variables if they can be separated with reasonable ease with the proper electronics. Modern instrumentation techniques have advanced to the point where it is practical to use this type pickup, and using the reasonably simple approach shown on the block diagram in Figure 12 to measure directly or indirectly a specified number of the desired variable.

In operation, the pickup is mounted in the stationary member of the bearing, seal, etc., so that slip rings are not required, and thermal expansion does not interfere with the signal. It is spaced back from the surface by a distance greater than the normal wear. A carrier frequency inductance or eddy current distance measurement from the pickup to the moving surface is made by the use of associated electronics. As shown in Figure 12, one type of inductive pickup can be used with different circuitry to measure one temperature, shaft wear and clearance. See Figure 13.

New transducer instruments

Recently, a resistance method of detecting material wear has been developed. This method employs a transducer consisting

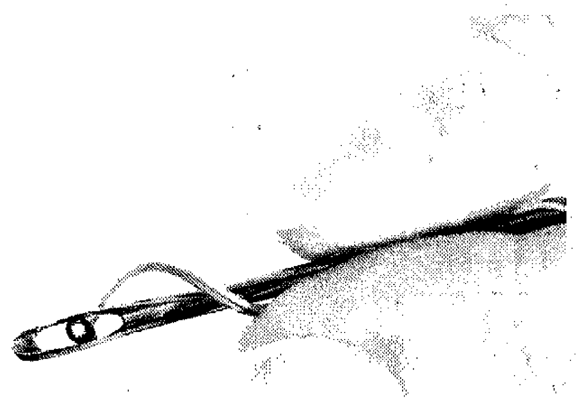


Figure 13. Inductive pickup used to measure wear, temperature, and clearance.

of an electrical resistive element inserted into the wearing surface. As wear progresses, the resistive element is worn away at the same rate as the wearing surface in which it is embedded. The change in resistance is thereby a measure of wear.

This transducer, a simple and reliable device, also has the advantage of not being influenced by thermal expansions and distortions since it is embedded in the wearing material or adjacent to it. Temperature compensation is obtained through careful selection of resistance materials and the use of a compensating resistive element built into the transducer.

The type of readout system depends upon the demands of the application with respect to convenience and accuracy. A quite suitable and very economic readout may be obtained with an ordinary ohmeter.

Thin laminated pressure transducers have recently been developed which permit pressure measurements to be made under conditions that preclude the use of any other type of transducer presently available. This transuducer is particularly well-suited to pressure measurements on turbine vanes or in locations within a turbine or compressor casing where conventional pressure monitoring devices could not be used. Both static and dynamic pressure can be measured with a single transducer. Figure 14 shows details and features of the device.

A new family of non-contacting instrumentation employing Fiber Optics is beginning to find application for the continuous dynamic measurement of shaft vibration, blade tip clearance, displacement, bending under load, and machine vibration monitoring. These devices, which measure linear distance, displacement or motion, by means of light rays are characterized by microinch sensitivity permitting motion or displacement measurement in millionths of an inch. Frequency response is from DC to two megacycles more than one hundred times better than other available equipment. Probe size can be as small as 30 mils in diameter. See Figure 15.

Preventative maintenance

Generally, periodic monitoring of system vibration, oil temperatures, bearing temperatures as well as periodic changes of oil in accordance with recommended practice, is normally done and in most cases, quite carefully. One of the major difficulties contributing to failures is the fact that the desire to keep equipment operating often precludes the decision of tearing down at some point to definitely diagnose a suspected problem and to permanently correct it.

In all fairness, part of the reason for this is that very often that the measurements made are not sufficiently conclusive in defining impending difficulties, thus the use of specifically designed instrumentation as previously described becomes invaluable.

Under operating conditions which are trouble-free, the first real opportunity for comprehensive preventative maintenance occurs at the time of the turn-around. At this point the equipment should be completely dismantled and all critical areas carefully inspected and measured. This should be stressed since a thorough knowledge of critical dimensions is mandatory. For example, in the previous discussion on dynamics, it has been shown that the bearing can exert a considerable influence on the region of operation as well as a response to unbalance.

As a consequence, it is important to know absolute journal and bearing dimensions so as to accurately establish bearing operating clearance. Checks during assembly can be made by lifting the rotor through the clearance gap and measuring the clearance.

A knowledge of initial clearance and the subsequent check by means of moving the rotor through the clearance gap can give insight in terms of the line-up of an assembly. Users are encouraged to make measurement fixtures for their particular equipment. Items such as machined arbors to accurately check tilting pad journal bearing assemblies are highly recommended.

Again it is emphasized that attention to details of this type can mean the difference between high and low vibration, abnormal and normal bearing operating temperatures, as well as an understanding of why certain changes have taken place during operation.

It is well, during the turn-around period or at the time of some unscheduled stoppage, to check the physical rotor for potential defects. The degree that this can be accomplished, of course, will be highly dependent upon the type of facilities either available in the particular plant or readily accessible. Figures 16 and 17 show a type of optical borescope ideally suited for in-place inspection of machine internals.

Other inspection techniques

It would be well to utilize some of the standard crack detection equipment to look at critical areas of the impellers. Another valuable check would be on the balance of the rotor itself. Although very often it might logically be reasoned that little could have occurred to change the basic balance of the unit, experience has shown that significant changes of balance can and do occur with running time.

Some of the above checks may later be verified after the proper instrumentation has been installed. For example, displacement measurement within the machine can give a general indication of balance by virtue of the shaft or rotor orbits at operating speed.

Many other types of inspection can be accomplished in various different ways. Depending upon the process gas, it might be well to periodically sample the lubricating oil for signs of deterioration and loss of effectiveness.

The acidity or neutralization number of the oil, in conjunction with spectrographic oil tests, can be very revealing. In internal combustion engines, for example, the makeup of elements in the oil can give very strong clues to the future health or deterioration of the system. A sample of metallic debris from reservoirs and filters can very often provide strong insights into bearing health and impending deterioration.

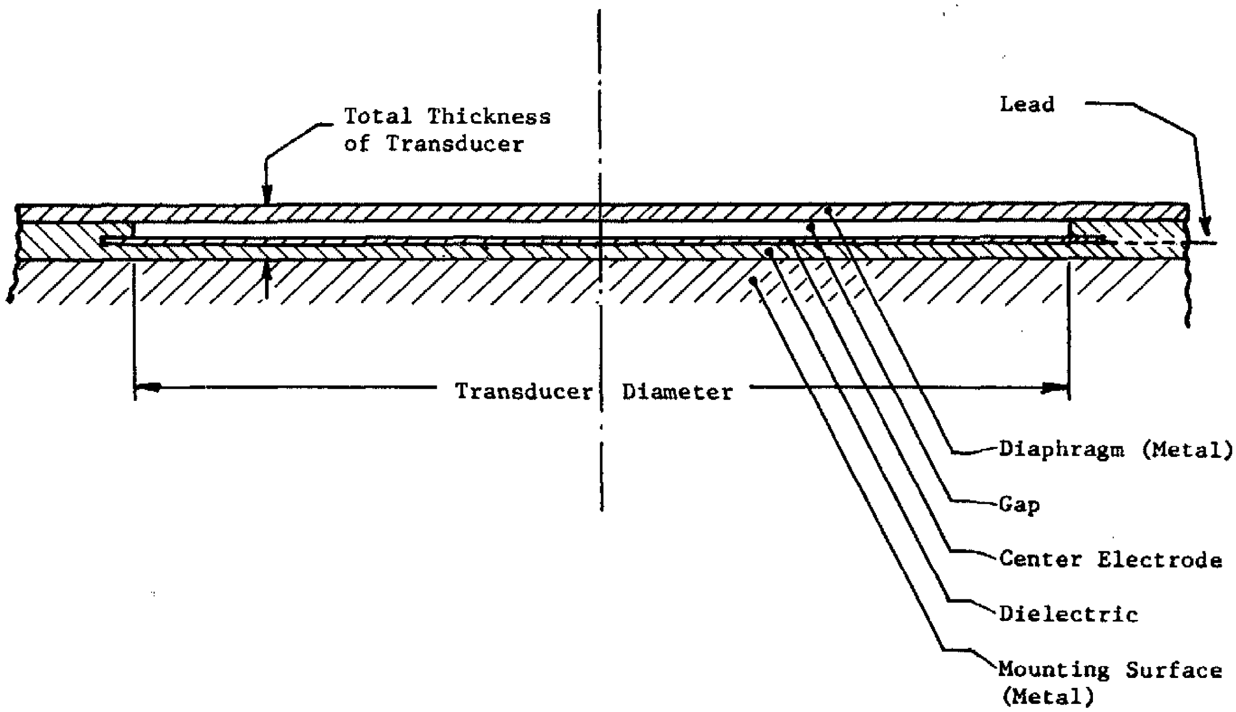
It cannot be emphasized too strongly that the plant maintenance man has at his disposal probably one of the more important tools; that of being able to observe the machine over a long period of time under varying conditions of operation. In essence then, he is in an excellent position to obtain a signature which will be of tremendous importance in assessing the health of the equipment.

Economic implications

There can be no question as to machinery and, therefore, plant reliability being enhanced as a consequence of adapting any or all of the recommendations herein discussed which, in total, are described as a failure prevention program.

The enhancement of plant reliability results in immediate and obvious financial advantages insofar as reduced unscheduled shut-downs, reduced maintenance costs, and ultimately reduced

THIN LAMINATED CAPACITANCE PRESSURE TRANSDUCER*



SECTION THROUGH TRANSDUCER

Typical Cell Data:

Cell Thickness	.007 - .020 inch
Cell Diameter	.080 - .500 inch
Resolution (Dynámic)	.005 - .5 psi
Resonant Frequency	10 - 200 KHz
Pressure Range	0 - 10 to 0 - 1000 psi
Temperature Range	40 - 300°F

L. Hoogenboom
17 February, 1967
Mechanical Technology Incorporated
968 Albany-Shaker Road
Latham, N.Y. 12110

*Patent applied for

Figure 14. Thin laminated capitance pressure transducer.

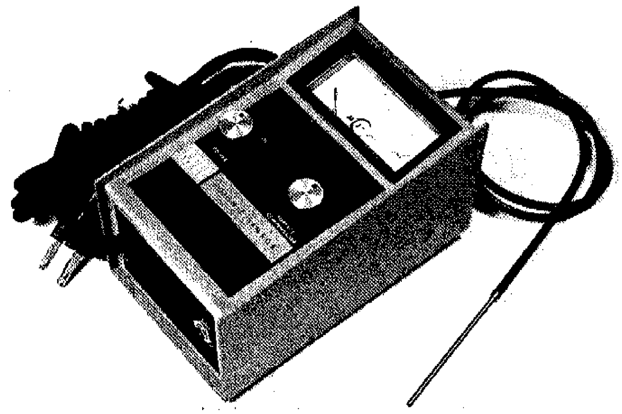


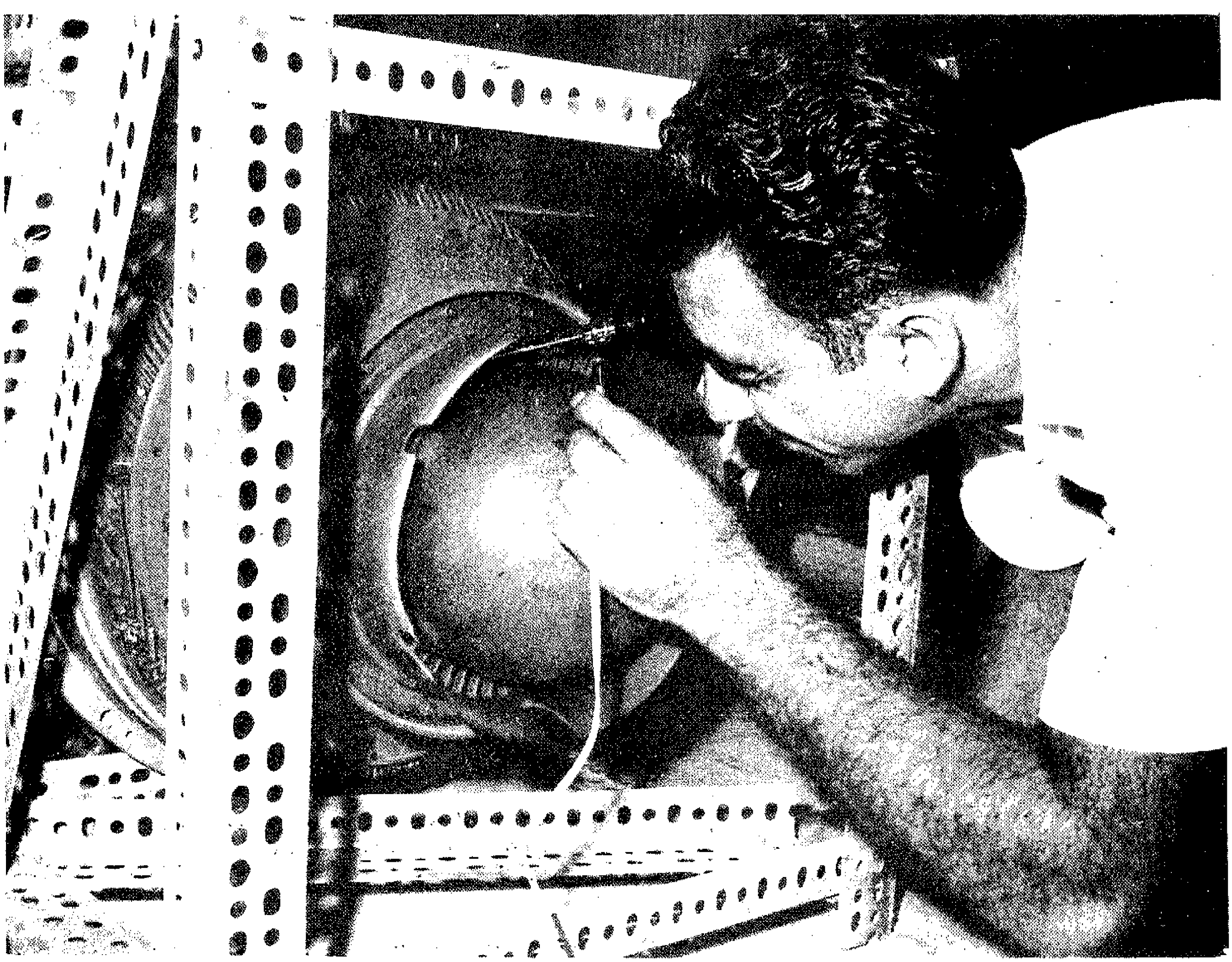
Figure 15. Non-contacting probe used to measure vibration.

Table 2. Component life assessment and costs

	Design Life, hr.	Achieved Life, hr.	Current Cost, $	Cost/ Design Life/hr.	Cost/ Achieved Life/hr.
Compressor stators	20,000	12,000	20,000	1.00	1.67
Blades	20,000	10,000	40,000	2.00	4.00
Discs	20,000	12,000	36,000	1.80	3.00
Combustion cans	15,000	10,000	10,000	0.67	1.00
Turbine vanes	20,000	12,000	20,000	1.00	1.67
Blades	20,000	12,000	32,000	1.60	2.67
Discs	20,000	12,000	12,000	0.60	1.00
Bearings	20,000	10,000	6,000	0.30	0.60
Shafts	30,000	18,000	6,000	0.20	0.33
Casings	30,000	20,000	20,000	0.67	1.00
85% of Total			202,000	9.84	16.94
Total			238,000	11.58	20.00

$$\text{Life extraction} = \frac{11.58}{20.00} = 58\%$$

$$\text{Life wastage} = \frac{1\text{-}11.58}{20.00} = 42\%$$



Figures 16 and 17. Optical borescope being used for in-place inspection of machine internals.

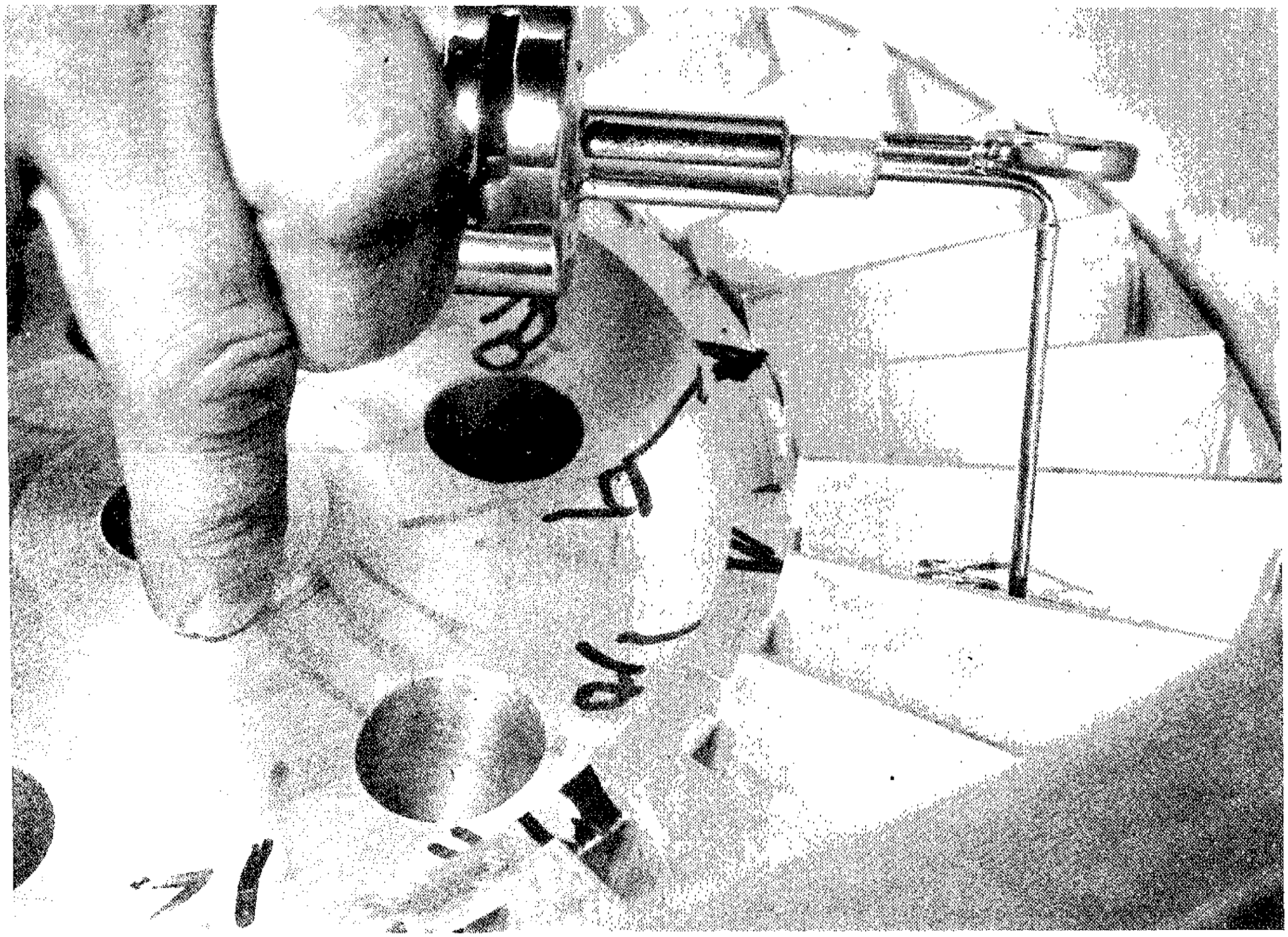


Figure 17,

insurance costs. Experience has shown that the cause of implementing an integrated failure prevention program will be returned many times over again in savings accrued thereby. This is borne out in Table 2.

Conclusions

1. Machinery purchase specifications are not sufficiently detailed to insure the equipment purchased will reliably meet the operating requirements of the service intended.
2. An audit of the design of equipment selected for purchase by other than the manufacturer is a prudent precaution to further insure adequacy of design.
3. Analytical tools are available today for accurately determining critical speeds, threshold of instability, and rotor response to unbalance.
   Bearings, pedestals, seals, couplings, etc. play a major role in dynamic response of turbomachinery and therefore must be included in any analysis.
   Rigorous dynamic analysis provides direct insight into machinery reliability, acceptance testing, and instrumentation.
   Machinery which is well balanced in the factory can get out of balance with time in the field as a result of design and environmental conditions; for example, corrosion, erosion, material deposits, etc.
4. Testing under load of a coupled string of machinery is the best final precaution to insure satisfactory operation in the field.
5. Preventative maintenance programs can be enhanced by the use of improved monitoring instrumentation and on-site test fixtures.
6. Non-contacting monitoring instrumentation is available which will enable installation of markedly improved diagnostic and fail-safe monitoring systems.
7. The formulation and implementation of an integrated failure prevention program employing all of the means discussed will result in significant financial savings to plant operators through fewer unscheduled shutdowns, lower maintenance costs, and lower insurance costs. Additionally, resulting superior equipment reliability will relieve the manufacturers of the risk of liable suits, inasmuch as recent court interpretations indicate that a plaintiff must only show that a product was faulty in order to claim damages.

Recommendations

1. Where reliability and long life operation is required, contractors and plant operators should impose both mechanical and aerodynamic performance specifications on the machinery builders.
2. A rigorous dynamic analysis of individual machines and particularly, machines in coupled systems, should be performed in order to insure adequacy of design and system reliability.
3. Individual machines and complete coupled systems should be tested under load prior to acceptance at the job site by the buyer.
4. Adequate rugged instrumentation located in the proper places should be used for monitoring machinery performance in the field. It is preferable for the builder to install this instrumentation during machinery construction. In this way it can be used in acceptance testing and will be directly correlated with field experience.

5. Maintenance specifications and provision for in-the-field balancing should be factored into equipment design. Adequate damping must be designed into rotating machinery to insure toleration of vibration resulting from an unbalanced rotor.
6. Engineering contractors and plant operators should consult with insurance underwriters regarding the affect implementation of a failure prevention program will have on deductible and premium amounts.

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Discussion

J.P. DZUBACK: Clark Bros. Co.: I want to take complete issue with the foregoing presentation. I want to compliment the contractors and users in this room for the complete detailed specifications that they give us upon which to quote. I also want to compliment them on the complete engineering analysis that they make on this equipment. I've known instances where they have visited installations and spent several weeks or months at the engineering departments reviewing specifications and design criteria. I also want to compliment these contractors for providing the inspection procedures that they follow for witnessing mechanical performance tests, for cooperating and commenting on the lateral and torsional criticals studies that we make. I also want to compliment them on certifying to the integrity of the equipment and backing it up with guarantees and warranties. I don't know of one single failure or incident in an ammonia plant that was due to the mechanical failure of a syngas compressor caused by a basic design mistake.

L. ATWOOD, Worthington Corp.: I think that J. Zimmerman's comments were an excellent treatise on how to design a piece of machinery. But I wonder who's going to pay for the double-design of each machine. Secondly, the U.S. Government purchases pretty much along the way he indicated, very detailed specifications and extensive audit of materials. I do not believe that the government purchases more intelligently than the chemical industry. And I don't believe you can substitute specifications and paper for human judgment and integrity.