An Historical View of Mechanical Failure Prevention Technology

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In April 1967, 42 engineers and scientists concerned with the troublesome and costly problems of mechanical failures met at the Office of Naval Research to form the Mechanical Failures Prevention Group (MFPG). The participants, who represented several government agencies and industries, met to develop a forum to exchange information and innovative ideas on methods to avoid or predict mechanical failures in a wide variety of vehicles, equipment and structures. This meeting was the genesis of a broad interdisciplinary society that has become and serves today as a powerful resource in the field of machinery failure prevention, analysis, diagnostics and prognostics. This article, an updated revision of a paper published in the proceedings of MFPT 50, describes the developments and progress in mechanical failure prevention technology, primarily over the last four decades. The principal sources for this overview are the proceedings of the 49 conferences of the MFPG, which has become the Society for Machinery Failure Prevention Technology (MFPT) and is an operating division of the Vibration Institute.

> *Mechanical failures are a pervasive fact of life in our society. Ranging from the failure of small items that all of us have experienced and that many of us take for granted, to the failure of a large complex structure that often becomes front page news, they have undesirable consequences for our society. The large ones many times cause loss of life or cause serious injury to many people. The minor ones sometimes also cause loss of life or injury, and they always cause frustration and anger on the part of the one to whom they occur. Always they cause loss of valuable material, and have undesirable social and economic consequences.*
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> — Elio Passaglia, executive secretary, MFPG, 1976

The above quote is taken from the introduction to the proceedings of the 20th meeting of the Mechanical Failures Prevention Group (MFPG). Elio Passaglia, who was then chief of the metallurgy division of the National Bureau of Standards (NBS), assumed the responsibilities of MFPG executive secretary after the merger of the MFPG with the NBS Failure Avoidance Program in the early 1970s.

MFPG 20 was a milestone event. Sponsored by seven government agencies and the ASME in May 1974, the meeting was designed to explore the various aspects of mechanical failures, with the purpose of "defining the problem." The symposium organizers chose to examine the topic from the aspect of failure modes, failure consequences and the implication of failure with respect to the emerging technology available in the community. The conference program was planned accordingly; the result was a collection of informative and thought-provoking papers and some new direction for the diagnostic technology development community.

Failure of machinery, equipment or structures has even greater implication today than it did 40 years ago. As our society becomes more and more mechanized, as demands on performance become more exacting, and as our technology becomes increasingly complex, each mechanical failure reaches greater significance. In terms of the economy of the country and our competitiveness in the world markets, mechanical failures represent a cost of billions of dollars every year to industry, the government and the general public. Improved public safety, an area of paramount concern, can be achieved by a higher level of understanding of the mechanical failure process coupled with innovative techniques for failure avoidance, especially when using new or emerging materials in the design of structures and equipment.

Avoiding catastrophic failures coupled with improving durability of materials, machines and structures represent challenges of the highest priority, both regionally and nationally. These challenges must be met. Improved in-service inspection and evaluation methods are needed. Reliability of systems must be enhanced, and more accurate life prediction methods are needed. There are many other requirements, including better communication and information links for the exchange of technical information.

Failure prevention technology is complex and clearly involves a wide range of technical disciplines. Any in-depth history of failure prevention would result in numerous books, each covering one or more of the technologies that relate to failure and its prevention (e.g. materials science, tribology, vibration analysis, etc.). One can only examine advances in failure prevention from a broad perspective, and that is our purpose here. Progress in selected areas of mechanical failure prevention is assessed, particularly over the last four decades. The references cited are primarily from the proceedings of the MFPG conferences held since its inception in 1967 through its name change to the Society for Machinery Failure Prevention Technology (MFPT) in mid 1994 and all subsequent MFPT proceedings through its 40th anniversary in 2007.

Although it is not reasonable to identify all sources of failure prevention technology, it *is* appropriate to acknowledge the fine work of the ASME Committee on Reliability, Stress Analysis and Failure Prevention (RSAFP). This committee was organized in 1969 under the leadership of Dr. Jack A. Collins. He is author of the outstanding text on *Failure of Materials in Mechanical Design: Analysis, Prediction, Prevention.*[1] His book provides definitive guidance to assist engineers in understanding potential failure modes and in designing for failure avoidance. When the RSAFP committee was first formed, the principal forum for their technical papers was the ASME Winter Annual Meeting. The committee grew and Collins chaired the first RSAFP conference in 1975 as a part of the biennial design technical conferences.

The RSAFP committee and MFPG have been following parallel courses and have many interests in common. The differences appear to be with respect to emphasis, with the ASME effort primarily concerned with design to avoid failure. While the MFPG meetings have covered a wide variety of topics that bear on failure prevention, the areas treated most frequently related to condition monitoring and fault evaluation for machinery and structures. These topics relate to maintenance more than design and are usually identified as diagnostics and prognostics. This article places special emphasis on these aspects of failure prevention and their relationship to the larger picture.

Failure Prevention in Perspective

The need to prevent failures has been with us since man began inventing functional gadgets. There has always been an unwritten rule that each gadget should operate as long as possible without breaking or malfunctioning. Taken as a whole, failure prevention is considered by many to be a technology. The definition of technology is the application of science. Therefore, mechanical failure technology could be defined as the application of science to mechanical failure processes. Understanding the failure process may require a study of what is failing, the nature of a practical failure and the sequence of events that leads to failure. One must then describe the failure process in terms of design or material variables.

Early in its history, MFPG recognized this as a complex process and that there are many ways to prevent mechanical failures in service. These actions include but are not limited to:

- Developing better design techniques
- Improving reliability predictions
- Providing more complete materials information.
- Better understanding of the failure process
- Improved quality control
- Effective maintenance
- Improved diagnostics
- Cleanliness
- Lubrication/wear reduction
- Improved failure analyses
- Feedback of analysis results

By its sixth meeting, held in conjunction with the 1968 ASME Winter Annual Meeting, MFPG's steering committee recognized that increasingly large numbers of interested persons were attending two-day symposia. Papers were given and discussions heard covering almost all identifiable aspects of mechanical failures. Although these meetings provided the best forum for information dissemination, they did not foster structured pursuit of specific mechanical failure prevention tasks. To meet this need technical committees were organized on detection, diagnosis and prognosis, mechanisms of failure, design (including testing), and state of the art and applications. With the objectives of MFPG remaining essentially the same, its committee structure was modified slightly over the years in response to changing emphasis. The 1995 committee designations were:

- Diagnostics and prognostics
- Failure analysis
- Life extension and durability
- Sensor technology

For convenience, these titles are used as topic areas for the material presented here. To avoid confusion in the update of the original paper, the original format, discussion and order will be continued through 1995. Following the section on sensors, a discussion on developments since 1995 will be included.

Diagnostics and Prognostics

Diagnosis is the art or act of identifying a condition from its signs or symptoms. *Prognosis* is the art or act of predicting a future condition on the basis of present signs and symptoms. Any method used for identifying incipient failures and/or predicting ultimate failure of materials, structures or systems would fall within the scope of the Diagnostics and Prognostics Committee. Note that there are overlapping areas of interest among all technical committees. For example, predictive maintenance, a subset of condition-based maintenance, involves diagnosis and prognosis. At the same time, effective application of maintenance philosophy is a proven technique for extending the life of machinery. In this section, the most commonly used techniques for diagnostics are discussed. The issue of prognostics is addressed, and an attempt is made to place our current capabilities for failure prediction in perspective.

Diagnostic Methods. Vibration signal analysis and oil analysis are treated separately as techniques for diagnosing condition and fault mechanisms in machinery and structures. Other selected nondestructive testing and evaluation methods that are applicable to materials, structures or machinery are then described. Note that discussion of detection techniques using various sensors, an essential element of accurate diagnostics, is included in the section on sensor technology.

Vibration Analysis. It is not known when vibration signature analysis was first used as a diagnostic tool. It is clear that by the time MFPG was organized in 1967, machinery health monitoring techniques using vibration signatures had already been in use for a number of years. The minutes of the first MFPG meeting indicate that the technical presentations all related in some way to diagnostics involving vibration. The theme of the sixth meeting was *Detection, Diagnosis and Prognosis* (DD&P) as well as that of a number of meetings that followed. With a few exceptions, DD&P was a part of the program at all MFPG meetings, and vibration was always very much in evidence as a diagnostic tool.

The 10th MFPG meeting was organized with specific emphasis on the utility of vibration analysis methods in mechanical failure prevention. A presentation on time-series analysis techniques clearly showed the usefulness of analytical techniques for comparing differences in vibration waveforms. The discussion that followed showed lack of agreement on how these techniques could be applied to machinery condition monitoring. Five papers were devoted to the use or trial of automated vibration monitoring and diagnostic systems for aircraft gas turbine engines, ships' machinery, helicopters, commercial jet aircraft and internal combustion engines. Advantages and limitations of the various systems were discussed. At that time, there were some limitations with respect to available instrumentation as well as in the capability to identify the faults in and condition of machinery so that effective maintenance planning could be achieved.

By the time of MFPG 44, some 15 years later, it was evident that instrumentation capability had increased dramatically but that techniques for fault diagnosis had evolved more slowly. Since the tools were still more advanced than the techniques, it is useful to examine three technical areas that must be addressed for effective fault diagnosis using vibration:[2]

- Condition and fault mechanisms
- Modification of signal transmission paths
- Signal analysis

Condition and fault mechanisms are important technical areas because the faults of a machine cannot be diagnosed and its condition cannot be evaluated unless the mechanisms that result in vibration are quantified. In other words, the mechanical condition of a specific machine component must be matched to the signal from the analyzer. For example, in the case of a large rolling element bearing with a defect on the outer race, the corresponding time signal and frequency spectrum can be used to identify the defect. The pulses in the time signal are caused by the elements as they roll over the defect at a frequency equal to the ball pass frequency of the outer race. The frequency spectrum shows the ball pass frequency of the outer race and its orders at various magnitudes. The pattern of vibration magnitudes at different frequencies provides information about the condition of the bearing.

Condition evaluation requires quantification of the magnitudes of vibration and its frequencies in both the spectral and time domains. This process, called pattern recognition, had not yet been formalized in 1990, although it was first considered more than 15 years earlier. A so-called calibration requires that vibration information be compared to a known defect. The time-domain signal must be considered in this process, because the spectrum is not unique. Since phase is not considered when the spectrum is evaluated, it could represent two totally different mechanical conditions.

Modification of the signal transmission path is another technical area that must be addressed. During the time required for a vibration signal generated by a defect to progress from its origin to a sensor, the signal can be modified by joints and mass-elastic-damping properties of the machine. Theoretically a transfer function between the source and the sensor location can be measured with a dual-channel FFT analyzer, but it is not practical to do so for operational machinery. Nonlinear joint and structural mechanisms complicate the process of formalizing the problem.

Signals clipped by passage through a machine joint cause more problems in fault diagnosis than linear mass-elastic-damping modifications. The most functional solution to the problem would be to mathematically model the transmission path since, by so doing, the machine would not have to be shut down for experimental calibration. Before such procedures are possible, better physical simulation will be required. The limiting factor is the lack of joint stiffness models and damping data for mechanical systems.

Signal analysis is the third technical area that must be addressed in diagnosing faults and evaluating machinery condition. Of primary importance is the measurement parameter. The most directly measurable parameter is always used for fault analysis – relative shaft vibration when flexible bearings are used and absolute casing vibration when stiff bearings are used. The flexibility and damping of a machine support are affected not only by the bearings but also by the parameters of adjacent machine components, such as shafts, pedestals, housings and foundations. Although microphones or some other non-contacting remote sensor might be convenient, the problem of the transmission path negates their practical application. The analysis techniques used are based on identification of frequencies; these techniques have been used for years but have never been formalized. Measured frequencies are matched to the operating speeds of a machine and their orders and/or to sidebands. Sum and difference frequency modulation and pulsation of the signal are often evaluated.

The operating speed of a machine is generally considered to be the reference frequency for analysis in the frequency identification process. In the case of mass unbalance, a high-magnitude vibration occurs at the operating frequency of the machine. Pulsation in a blower may be identified by the vibration occurring at the machine speed. A long sequence of difference frequencies at the running speed of an impacting printing press is a pattern typical of impacts occurring in a machine. Frequencies at shaft speed and two times shaft speed are present in cases typical of misalignment. The component at two times shaft speed is larger. A gear-mesh frequency at the pinion frequency is typical of a faulty gear mesh. Techniques for processing and analyzing signals require time and spectral domains, orbits, start-up and coast-down data, as well as cascade diagrams. These techniques are currently being used with varying degrees of success. Expert systems for machine fault diagnosis are evolving, but developers are limited by current knowledge of mechanisms and signal path transmission. Indeed, there is also a need to develop advanced data processing techniques and information identification techniques. When the reasoning and experience associated with current knowledge of machine mechanisms, identification of transmission paths, and data processing are finally formalized, expert systems will become more effective.

The 1994 proceedings at MFPG 48 contain several papers that reflect significant progress in applying vibration analysis to diagnostics. Advances were reported on helicopter transmission fault detection and classification, alarm threshold settings for vibration monitoring of rotating machinery and pattern classification of vibration signatures using neural networks. Some preliminary ideas on the application of smart structures in conjunction with vibration signature analysis for on-line machinery health monitoring were presented. It will be interesting to see how the use of this technology evolves.

Oil Analysis. All machinery requires lubrication to minimize wear. This includes various engines (internal combustion, diesel, turbojet, etc.) and their components (transmissions, gear boxes). Everyone knows that the oil must be changed in automobiles at regular intervals to extend the life of the engine. This routine maintenance action is necessary because the oil gets dirty. Dirty, worn out oil not only does not lubricate well, it actually increases engine wear. Why? What is this dirt in the oil? How can information about it be used to ensure that engines operate safely and to identify engine components that will fail with potentially catastrophic results unless corrective action is taken? The process is called oil analysis, a proven diagnostic tool for mechanical failure prevention.

At the second MFPG meeting in June 1967, Ward described a Navy spectrometric oil analysis program initiated in 1955.[3] The goal was to find out whether the concept employed by the railroads for determining the condition of diesel engines by analyzing used oil samples could be applied to aircraft engines. The Bureau of Aeronautics felt that if these techniques could be applied, in-flight failures could be minimized, extension of engine operating intervals could be justified and reductions in engine overhaul costs could be achieved. This was not a new idea, but the concept had been restrained for some time by concern over the many factors that could work against developing successful techniques. Consider that the wide variety of engines in service, the many sources of wear metal contamination, the many sources of lubricating oil base stock, the necessity for developing metallic contamination threshold limits, the time and cost involved in sample analysis and the sample handling and data communication problems must all be dealt with to achieve success.

They were able to handle these and other problems successfully, and in 1958 two positive results accelerated the program. They found an oil sample from an R-1340-AN engine that appeared abnormally high in iron, copper and aluminum to lab personnel. Tear-down of the engine revealed the front impeller shaft bearing had completely failed. A few months later, they discovered a failed cam drive gear in an R-985 engine. By 1967, the Navy was working jointly with the Army and Air Force. The results were very impressive – 217 units corrected by field maintenance as a direct result of laboratory warning and 54 removals confirmed by disassembly inspection reports or, as the other services call them, tear-down reports. Although they thought of the oil analysis program as primarily a technique concerned with engine condition, these figures included six helicopter gear boxes, an aft transmission and three constant-speed drives. As time went on, they monitored more transmissions and gear boxes and determined that these were relatively easy equipments on which to predict condition.

As stated earlier, the Navy program was motivated by the pioneering work of the railroad industry on diesel engines. The use of oil analysis to detect malfunctioning diesel engine parts and thereby schedule maintenance operations is practically as old as the diesel engine itself. It was long recognized that certain malfunctioning parts would manifest themselves as changes in oil properties in the same way that human diseases show up in blood analysis.

For many years, conventional analyses for oil properties were the only tests conducted. Properties assessed included viscosity, acid number, insolubles, resins and water content. By interpreting changes in these properties, malfunctions like leaking fuel injectors, plugged oil coolers, blowing pistons rings and water leaks could be determined. While these indications were helpful, many malfunctions could not be detected by this technique.

About 30 years ago, the railroad industry pioneered in what is now called spectrographic oil analysis. They reasoned that every wearing, oil-wetted component would impart minute quantities of metals to the lubricating oil. Each engine would establish equilibrium quantities of the wear metals in the oil under normal operating conditions. Any increase in the values would indicate abnormal wear conditions that, if undetected, could lead to catastrophic failures. Since the wear metals were in the low parts per million range (100 ppm = 0.01%), the spectrograph was considered the most suitable means of measurement.

To apply spectrographic analysis to an engine, criterion elements for wear have to be selected. For a typical engine with aluminum pistons, tri-metal bearings and chromium-plated cylinder liners, the significant presence of certain elements in the oil can be tied to specific sources. Lead is related to bearings, silicon to airborne dirt, iron to piston rings and gears, chromium to liner and water leaks, aluminum to pistons and copper to bearings and bushings. An increase of the criterion elements over normal values can be used to accurately predict incipient bearing distress, poor air filtration, piston distress, ring and liner wear, gear wear, etc. Scheduling maintenance on the basis of the analyses makes it possible to take corrective action or replace parts before failure occurs.

The use of oil analysis, as reported at the MFPG conferences, has been an invaluable diagnostic tool over the years. Application of the technique to internal combustion engines was discussed at MFPG 12 and to commercial aircraft at the 14th and 16th meetings. Oil analysis was the theme of MFPG 16, and advancements in both techniques and analysis equipment have been faithfully reported in the proceedings since then. At MFPG 48, the Naval Research Laboratory[4] reported on a real-time, on-line, optical oil-debris monitor that is expected to provide a cumulative record of the health of engines and gear boxes as well as advanced warning of catastrophic failure.

The monitor is based on illumination of the oil lubrication column with a diode laser, followed by imaging in the transmission of suspended particles and identification of the particles by analysis of their shape and size using an on-board computerized particle classifier. The optical monitor is capable of recognizing metallic and ferrous particles, such as ingested sand and debris from ceramic or composite bearings. Another advancement reported was an automated oil monitor designed for condition monitoring of large utility transformers.[5] Development of this system was initiated to provide on-line diagnostics for transformer oil gaseous content to evaluate transformer material condition and predict the onset of transformer failure. The device is designed to operate continuously and provide real-time or near-real-time analysis of transformer condition. This automated monitor is intended to replace the current laboratory analysis of manually removed oil samples by extracting gases from the transformer oil and determining the concentrations (PPM) of seven different gases of interest. These concentrations can be trended or compared against alarm criteria.

Nondestructive Testing and Evaluation (NDE). Although vibration and oil analysis are both nondestructive diagnostic techniques, they have been considered separately because they are among the most commonly used methods of condition monitoring. NDE in general is the technology of measurement, analysis and prediction of the state of material systems for safety, reliability and assurance of maximum lifetime performance. It is an old technology (more accurately a set of technologies), yet it is only in recent years that engineers and managers have awakened to the true importance and great potential of NDE. NDE test technologies that can be effectively applied to diagnostics include acoustics, microscopy, optics, thermography, electromagnetics and radiography. The capabilities of these NDE methods as diagnostic tools for equipment and structures have increased significantly with the rapid development of advanced hardware and software. Although a detailed discussion of progress in each of these areas is not covered here, it is useful to describe how some of these methods are used for fault diagnosis.

Acoustic Methods. Vibration analysis is generally included among the several special acoustic nondestructive testing methods. In this section, limited descriptions of some of the other acoustic NDE methods are given. *Tap testing* is probably the simplest, most common and inexpensive form of acoustic inspection. The inspector taps the surface of the test structure and evaluates the sound that is generated. He either listens directly to the sound or uses a specially designed receiver to analyze the sound and compare the response with one from a discontinuity-free part. The technique is useful for detecting near surface delaminations in composite laminates. A lack of bond is readily apparent by the difference in the tone or frequency of sound when tapped with a coin or rod over a delamination as compared to the sound for a bonded area.

The *acoustic emission* (AE) technique is a method where sound waves emitted from a growing crack or flaw in a structure are detected. These signals are then evaluated to determine the nature of the damage. The advantages of AE are that it offers global monitoring capability and real-time information as to the state of damage. The problems with the technique arise from the complexity of sound propagation in solid structures, which makes interpretation of the AE in terms of structural damage difficult. Research in AE tends to focus on the propagation of sound in plates and shells, since many practical structures of interest such as aircraft skins and pressure vessels are of these geometries. A better understanding of the multiple modes of sound that propagate with different velocities in plates has led to an improved capability to locate the emission source in metals and composites. Information as to the nature and orientation of the AE source has also been determined from the evaluation of these plate modes. Additionally, modeling of the propagation of AE in plates has been carried out with good agreement between theoretical predictions and experimental measurements observed.

The *acoustoultrasonic* (AU) technique was devised to assess diffuse discontinuity populations of the mechanical properties of composites and composite-like materials. This NDE method, also known as the *stress wave factor* technique, has been used to evaluate fiber-reinforced composites, adhesive bonds, lumber, paper and wood products, cable, rope and human bone. The AU technique has been demonstrated to be sensitive to interlaminar and adhesive bond strength variations and has been shown to be useful in assessing microporosity and microcracking produced by fatigue cycling.

The AU method belongs to a class of techniques that includes tap testing, dynamic resonance and structural damping measurements. These are in addition to more directly related techniques like acoustic emission and pulse echo methods. Sonic tap testing can be considered a primitive version of AU testing, except that AU *tapping* is usually done with a piezoelectric transducer and *listening* is done with a second piezoelectric transducer and appropriate electronic instrumentation. An acoustic emission system in its elementary form constitutes half of an AU testing system: passive listening but no active interrogation. The combination of an AE sensor with an active pulser forms the basis for an AU system.

Acoustography is a process of forming ultrasonic images in a manner similar to X-ray fluoroscopy using a detector screen that converts ultrasonic energy directly into a visible image. A full-field imaging method, acoustography may be used to rapidly screen parts for discontinuities. Once located, the anomalous regions can be inspected using conventional point-by-point ultrasonic scanning to make accept/reject decisions. Consequently, inspection throughput can be enhanced significantly by limiting point-by-point ultrasonic scanning to anomalous regions only. In this method, a sound source is used to illuminate the test object with a field of ultrasound. As the sound waves pass through the test object, they are absorbed, reflected, refracted and scattered by the anomalies. The projection image created by the ultrasound, as it exits the test object, is converted into a corresponding visual image by a detector screen containing a sound-sensitive liquid crystal layer that is viewed under polarized light.

Acoustic holography is yet another useful NDE method that was first discussed by MFPG participants at the 9th meeting. The interaction of sound with solids and liquids is different from the interaction of electromagnetic radiation. Sound can travel a considerable distance through dense, opaque homogeneous matter and lose little energy, yet it loses significant energy when it passes through an interface. The opposite is true for electromagnetic radiation. Acoustic holography can therefore be very effective in nondestructive diagnostics, because it is the discontinuities or flaws that are of interest. Acoustic holography involves only the recording of a hologram and its image reconstruction. Unlike optical holography, the additional interferometry step (after stressing the material) is unnecessary to produce an image depicting internal anomalies. The reconstructed images from acoustic holograms do not possess the high-resolution image quality of the shorter wavelength optical holograms.

As indicated at the beginning of this section, vibration analysis is considered to be an acoustic method. This is partly because sound produced by machinery can be used in the same way as vibration for machinery diagnostics. After all, the sound radiated from machinery is produced by the vibration of the machine. There have been technical discussions at MFPG and other conferences about whether vibration or acoustic signal analysis is most useful. Either can be used effectively. In the simplest way for using an acoustic signal, an experienced machine operator will know that something is wrong when his machine sounds different than it normally does.

Infrared Analysis. Infrared or thermographic analysis provides a high-resolution, noncontact means of monitoring the condition of electrical and electromechanical equipment, roofing and wall insulation and oven refractories. Infrared scanners, similar in appearance to video cameras, detect differences in surface temperatures and highlight those differences in black and white or color images that are displayed on a television screen. These images can be photographed with conventional film or recorded on videotape, and the images, called thermograms, are used to analyze patterns of heat gain or loss.

Infrared analysis is an effective predictive maintenance tool, because mechanical or electrical breakdowns are often preceded or accompanied by changes in operating temperatures. This information can be particularly important in electrical machinery where circuits and connections may show no visible signs of deterioration until moments before a complete failure. Thermographic analysis can also detect cracks or deterioration in roof or wall insulation and oven refractories, which can increase heat loss or reduce production efficiency.

Infrared scanning is nondestructive and can be performed at a distance for machinery that is difficult or awkward to reach. Since surveys are best done while the equipment is in operation, there is no need for machine downtime and lost production. In addition to helping avoid costly or even catastrophic equipment failures, infrared analysis can be used to prioritize repairs prior to planned maintenance, to evaluate completed repair work and to check new installations prior to startup.

Motor-Current Signature Analysis. Motor Current Signature Analysis (MCSA) provides a nonintrusive method for detecting mechanical and electrical problems in motor-driven rotating equipment. The system was developed by Oak Ridge National Laboratory as part of a study on the effects of aging and service degradation of nuclear power plant components. The basis for MCSA is the recognition that an electric motor driving a mechanical load acts as an efficient, continuously available transducer (the motor can be either AC or DC). The motor senses mechanical load variations and converts them into electric current variations that are transmitted along the motor power cables. These current variations, though very small in relation to the average current drawn by the motor, can be monitored and recorded at a convenient location away from the operating equipment. Analysis of these variations can provide an indication of machine condition, which can be trended over time to provide an early warning of machine deterioration or process alteration.

Smith, *et al.*,[6] from Oak Ridge National Laboratory discuss MCSA and the application of advanced linear demodulation techniques to the analysis of several motor-driven systems. The use of high-quality amplitude- and angle-demodulation circuitry has permitted remote status monitoring of several types of medium- and high-power gas compressors driven by three-phase induction motors rated from 100 to 3500 hp with and without intervening speed increasers. Flow characteristics of the compressors, including various forms of abnormal behavior such as surging and rotating stall, produce at the output of the specialized detectors specific time and frequency signatures that can be easily identified for monitoring, control, and fault-prevention purposes. Resulting data are similar in form to information obtained via standard vibration sensing techniques and can be analyzed using essentially identical methods. In addition, other machinery such as refrigeration compressors, brine pumps, vacuum pumps, fans and electric motors have been characterized via the specialized detectors to identify numerous types of mechanical and electrical faults.

Other NDE Diagnostic Methods. Ultrasonic scanning techniques are widely used for detecting and identifying defects in materials and structures. Increasingly, ultrasonic devices are used for scanning and detecting leaks and certain other defects such as bearing wear on steam, pneumatic, hydraulic and vacuum systems while in operation. The advantage is that while most audible sounds of a pressure leak, for example, may be masked by ambient noise, the ultrasound will still be detectable with a scanning device.

Sophisticated devices are available that can be used in conjunction with nondestructive measurement techniques to permit a more detailed analysis of defects or changes in engineering properties during the service life of materials, structures and machinery. Four major analytical devices are scanning-electron microscopy (SEM), scanning-electron acoustic microscopy (SEAM), scanning acoustic microscopy and X-ray diffraction.

Prognostics. The words *prediction* or *prognosis* appear in a number of titles of papers in MFPG proceedings. The *prediction* papers usually deal with mathematical models for fatigue life estimation, stochastic models for cumulative damage or trending algorithms. Usually these papers report useful work that is consistent with the definition of *prediction as a way to establish beforehand the expected value of some parameter at a definite future time*. However, these methods have not yet been effectively applied by the predictive maintenance community for on-line prognostics.

Some ideas have shown promise. Dunegan[7] suggested that the combination of acoustic emission and linear fracture mechanics can provide quantitative information regarding structural failure. His paper shows that for certain situations, acoustic emission techniques can be used to accurately estimate the stress intensity factor K at a growing crack, and therefore provide predictive information regarding structural failure. Wicks[8] proposes that experimental modal analysis techniques can be used as a tool in predictive maintenance programs. Modal models of a given machine provide a baseline from which trends may be monitored and evaluated. At MFPG 47, this same idea was examined with respect to structures.[9] The author believes that existing modal testing technology can be used to develop a structural monitoring system that measures the vibration of a structure, identifies changes in its modal parameters and predicts occurrences of structural faults.

Salter[10] stated in 1978 that on-vehicle computing instrumentation technology offers new capabilities to improve life-cycle reliability through prognostic maintenance management (PMM). Prognosis enables the selection of the best time for maintenance while reducing inspection requirements, vehicle breakdowns and secondary failures. A PMM program enables an improved user confidence while maximizing the productivity of scarce maintenance resources.

The program requires a micro-data system that can automate condition trend analysis using a technique that Salter calls *geriometry* – or the measurement of the causes of vehicle degradation (all other maintenance techniques measure effects). Geriometry could provide prognostic criteria for vehicle subsystems with unpredictable degradation trend patterns, wear fatigue failure mechanisms, and inspection difficulties, as represented by a requirement for significant disassembly with a risk of maintenance-induced failures. It is unclear whether these idea were made to work, but the premise was good. Effective prognosis can be important to maintenance management. Some technique is necessary to choose the time for maintenance that will minimize maintenance costs while achieving a desired reliability and availability. The technique must be quantified in terms of measurable parameters. The precision and variance with which these parameters describe the subsystem life must yield decision criteria within close confidence limits. The rationale for prognosis as an effective technique for maintenance is somewhat subjective, since data to prove the contention do not yet exist. Many people in maintenance anticipate that a number of benefits will accrue through implementing reliable prognosis methods.

In terms of the economy of the country and our competitiveness in the world markets, mechanical failures represent a cost of billions of dollars every year to industry, the government and the general public.

For the most part, the MFPG papers with *prognosis* in the title are lacking information on effective prognostic techniques. Prognosis is there because it relates to diagnosis or because of differing opinions on what is meant by prognosis and how well failure can be predicted. Eshleman[2] provided an assessment of prognostic capabilities that is largely still valid:

> *Procedures for prognosis of failures (life estimation) have been established only for turbine blading. Life estimation has usually been based on limited experience with failures of specific machine components. The remaining life of a machine or component must be based on wear, the environment, and the history of stress cycles in the machine. These factors must also be considered when establishing its current condition. Only after the current condition of a machine is known can meaningful life estimates be made. Information about current condition can also be used to evaluate effects of changes in components and wear to assess whether or not machine life can be extended. The techniques of prognosis involve diagnosis, condition models and failure models.*
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> *Data from measurements are applied to a modal model to obtain the internal forces in a component or machine. These forces are used in a condition model along with measured data and the operational history of the machine to determine stresses, state of wear, and defects in the machine or its components. The current condition of the machine is then extrapolated from this information to predict time to failure using a failure model. The available failure models – Miner's Law for example – are expressed in terms of number of cycles to failure.*
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> *Although some data exists for failure models, they are rarely*

applied. The reasons are the complexity of the process and a lack of information about the history of machine operation. Development of techniques for estimating the life of a machine and its components is a major challenge in the field of predictive maintenance. Whether analytical methods will be developed or a purely empirical approach will be followed remains to be seen. The empirical method requires gathering and processing a large quantity of data in a consistent way and then relating the data statistically to different types of component failures. It is possible that a combination of analytical and empirical methods will be necessary. Factors that affect machine life include steady and dynamic stresses of structural members, hardness and strength of materials, wear, life history of components, and cumulative damage. Development of models based on these factors, which determine the condition of a machine or a component when it responds to known forces or motions, is a challenge in predictive maintenance.

Failure models that predict time or cycles to failure have been available for materials and simple structures for years. But no failure models have been developed for factors other than stress and strength. Theoretically, structural failure models that are broken down into small elements can be applied to complex components and machines for the purpose of life prediction. Good results are now being obtained with computer models that have been experimentally verified and calibrated. However, the development of failure models and the data to implement them will be a challenge for engineers.

There are research programs in place to develop prediction capabilities to implement condition-based maintenance. A Penn State effort[11] has as a primary research focus of developing a prognosis capability; i.e., the ability to accurately and reliably predict the remaining useful life of machinery in service. They have developed an hypothesis about mechanical system failure that they believe may enable them to achieve this objective. The hypothesis is that failures in mechanical systems follow a particular *failure trajectory* that may be predictable within a multi-dimensional state-space sufficiently far into the future to be useful to the operator as well as the maintainer. This hypothesis forms the basis of belief in the ability to reliably and accurately predict *remaining useful life* of equipment in service. Achieving this goal will require a fundamental and integrated understanding of failure mechanisms in all types of equipment and structures, with a similar understanding of how to monitor and predict the evolution of these failure mechanisms. The intent is to formulate and execute a multidisciplinary research program including material properties, failure mechanisms and symptoms, sensing, signal processing, dynamic systems prediction, and system-level decision support methodologies. These capabilities are the foundation of condition-based maintenance.

Predictive maintenance is an intensely competitive technology, and there are a few systems on the market that are proposed by the developers as solutions to effective condition monitoring and performance assessment. How well do such systems meet the need? Obviously, each new system must be evaluated on its own merits.

Failure Analysis

As stated earlier, the first name for the MFPG Failure Analysis Committee was Mechanisms of Failure. The original broad objective of the committee was to coordinate all aspects relating to the modes and mechanisms of failure as they pertained to the overall goal of mechanical failure prevention. Among other things, the pursuit of this objective involved standardizing terminology and establishing interrelationships among causes, modes and results of failure. The scope of the current committee not only covers mechanisms but also methods of failure analysis and the application of *lessons learned* from failure analysis results.

Collins[1] defines mechanical failure as "any change in the size, shape or material properties of a structure, machine or machine part that renders it incapable of performing its intended function." He defines a failure mode as "the physical process or processes that take place or combine their effects to produce failure." In Chapter 2, Collins lists and defines 23 failure modes, five of which have several sub-categories. He also presents a suggested systematic classification system for failure modes based on defining the type of failure, the cause of failure and the failure location. The more important modes of failure, such as fatigue, creep, fretting, impact buckling and corrosion are detailed in other chapters of the book.

Failure mechanisms were not neglected at the MFPG meetings. Beginning with the early conferences, failure modes were very much the topics of discussion. The important modes of fatigue, wear and corrosion were extensively covered at several meetings. The 11th meeting was devoted exclusively to examining *mechanical fatigue* as a critical failure mechanism. Basic fatigue mechanisms, the fracture mechanics approach to the explanation of fatigue, environmental effects on fatigue and fatigue design criteria were all covered at this conference. In addition, some practical problems and solutions were presented, and the role of nondestructive testing in fatigue studies was examined. From these 1970 proceedings, it may be inferred that it was easier at that time to explain why a fatigue failure occurred than to design to prevent the failure in the first place. Significant progress has been made since then, but there is justification for assuming that this notion is still valid today.

Of the MFPG papers relating to wear, the majority deal with minimizing wear by design of surface finish or by the use of lubricants and coatings. A number of papers in the proceedings concern wear problems and solutions for specific critical components such as bearings. This is at least in part due to the extreme complexity of the wear failure mode detailed by Collins.[1] At least nine subcategories of wear have been defined, and more than 20 variables are involved in the wear process. Progress in wear reduction is better demonstrated by reporting on specific solutions to the problem. For example, MFPG 13 was concerned with standardizing surfaces to minimize wear (or fatigue) failure. The 16th and 30th meetings were devoted to lubricants and lubrication. All of the 23rd and part of the 37th meetings dealt with coatings to improve wear resistance, and these are tribological solutions. *Tribology* is the science of the mechanisms of friction, lubrication and wear of interacting surfaces that are in relative motion. Tribology was pioneered in the United Kingdom and has proved to be a very useful technological approach to the wear problem.

Corrosion is another important complex failure mode. As with wear, many variables are involved in the corrosion process that relate to environmental, electrochemical and metallurgical aspects. There are 11 recognized direct subcategories for corrosion; in addition, f*retting corrosion, stress corrosion, corrosion wear* and *corrosion fatigue* may be regarded as special synergistic failure modes. Corrosion was a topic for discussion at several MFPG meetings. The 15th and 17th meetings were concerned in great part to various aspects of this process. The objective of MFPG 15 was to examine the state-of-the-art in the study of various corrosion mechanisms. The papers at MFPG 17 addressed environment-sensitive failure modes such as *stress corrosion cracking* and lubrication failure, which can, among other things, lead to corrosion.

Cavitation as a damage mechanism was the topic for discussion at MFPG 19, with more than a dozen excellent papers covering various aspects of the problem. Peterson provides a detailed discussion on how this complex, imperfectly understood phenomenon can lead to mechanical failure.[12] Some of the types of damage associated with the presence of cavitation are surface material removal (erosion), delamination and structural-vibration-induced failures. When cavitation erosion occurs and surface particles are removed, a fresh unprotected surface may be exposed to a corrosive medium and *cavitation corrosion* can occur. In a way, *fretting corrosion* is a similar phenomenon, only in this case, the protective surface is removed when two contacting surfaces are subjected to small-amplitude, cyclic, relative motion with respect to each other.

Peterson points out that the literature has been somewhat confusing concerning the phenomenon of fretting. For purposes of clarification, he presented the following four definitions:[13]

- Wear – attrition or damage of the surface of a material as a result of mechanical action.
- Fretting – wear and material disruption caused by oscillatory

small amplitude slip between two surfaces.

- Wear corrosion – corrosion resulting from wear.
- Fretting corrosion – corrosion resulting from fretting.

From these terms, it is clear that wear can be different from fretting, and the corrosion may or may not accompany either process.

The theme of MFPG 35 was "Time-Dependent Failure Mechanisms and Assessment Methodologies." The principal failure modes covered were fatigue, stress corrosion cracking and creep for both metals and nonmetals. It is of interest that the papers dealt with these mechanisms in connection with a variety of applications, including gas transport cylinders, concrete and wood structures and ceramics. This is consistent with the MFPG objective to examine problems related to failure of structures and machinery and to develop realistic approaches to their solution.

With knowledge of the life-cycle environments for his equipment and a reasonable understanding of the failure modes that are likely to occur, a designer is well equipped to develop a more reliable product. Even so, there will be failures and, in many cases, an analysis to determine the cause of failure is justified. The most vivid examples are failures that cause catastrophic accidents resulting in loss of life, such as air or rail crashes. The National Transportation Safety Board (NTSB) investigates all such accidents as a matter of routine,[14] with the goal of avoiding similar failures in the future. Such cases are extraordinary, but it is always useful to determine the root cause of failure when it is economically feasible to do so.

The general topic of the 8th MFPG meeting was critical failure problem areas in the aircraft gas turbine engine. The papers at this conference were not formal failure analyses, but they reported on causes of failure as determined during required engine repair or routine overhaul and maintenance. This information was used to justify research efforts on improved materials for design and/or diagnostic techniques and to develop better design capabilities. Failures in internal combustion engines were treated in a similar way at MFPG 12. The conference objectives were to identify critical failure modes in these machines, the current procedures for obtaining data on service failures, and to determine ways of minimizing such failures.

Bennett presented an excellent paper at MFPG 20 on the importance of analyzing service failures.[15] What can be learned from the analyses, and how can we use the information that is obtained? Although his paper was concerned primarily with fracture as the failure mode, his closing statement is presented as being equally valid for broader-based failure analyses:

> *A great deal can be learned about failure prevention from the analysis of service failures and from related research in fatigue, fracture, stress corrosion, wear, and nondestructive evaluation. One of the most important tasks we face in the future is the more effective utilization of information obtained from these activities.*

The 21st MFPG meeting could be considered a response to Bennett's call for action. The theme was "Success by Design: Progress through Failure Analysis." The collection of papers clearly demonstrate the value of the feedback of information gleaned from service failures into the design process.

Three papers enhance the idea that failure analysis is important to failure prevention. A quote from Rieger, *et al.*,[16] applies:

> *Rotating equipment failures cause millions of dollars of unrecovered costs in lost energy production, plus additional millions of dollars in replacement equipment costs paid by casualty insurers. During a loss event, efforts are usually focused on restoring the unit to service as quickly as possible. It is important that a comparable effort is made to understand the failure root cause and to apply the information gained by the failure experience. Experience has conclusively shown that where failed rotating members are simply replaced with identical components, the original problem is likely to be re-installed, and the failure scenario may be reinitiated.*

Pond[17] describes an approach by the nuclear power industry for using failure analysis results to provide a method for failure prevention. He discussed how failure analysis results can be analyzed and packaged to extend the value of analysis beyond cause and blame assessment.

Finally, Natishan[18] summarizes the issue very clearly:

> *For as long as there have been engineered structures, systems and components, there have been failures of those structures, systems and components. In most cases, failure of machinery or structural components is inconvenient. In some cases, it creates a safety hazard. In some cases, failure has a strong economic impact. But in all cases, understanding what caused the failure provides insight to improving the design and how we use or maintain the system. Unfortunately we tend to learn more through failure than through success. When something fails, we learn quickly the limitations of the design. Success tells us little of the limitations! Success only makes us see possibilities for stretching that design success further and results in decreased conservatism. It is only in failure that design limitations are defined, and it is typically because of failure that the approach to design is altered. We can learn much from probing failures to their root cause, and we can and should implement the knowledge gained to improve designs, increase safety and reliability and decrease manufacturing and operating costs of our technologies.*

Life Extension and Durability

The immediate predecessors of the *Life Extension and Durability Committee* were committees on *Materials Durability* and *Machinery Durability*. The committee's organizational meeting was held in April 1994 at MFPG 48, while its scope and mission were still evolving. However, it was clear at that point that the interests of the committee would include study and development of ways to extend the life of structures and machinery through:

- Design
- Life extension of machinery facilities and equipment using condition-based maintenance
- Combination of active control and on-line monitoring for machinery life extension
- Integration of on-line diagnostics and manufacturing process control
- NDE techniques for fracture safety assessment and life extension
- Systems engineering and life extension
- Failure analysis and its contribution to life extension and durability
- Life estimation methodology

The terms *durability* and *life extension* need some clarification. Ideally, a design engineer establishes some achievable goal for the expected service life of the system he is designing and then proceeds to design the system to meet that goal. The durability of the system is some measure of how well the system survives without failures throughout its expected service life, while functioning effectively with little or no loss in efficiency. If because of a special design effort, the system is capable of functioning beyond its normal expected service life, the designer will have achieved life extension by design. Life extension can also be achieved through the use of on-line condition monitoring systems capable of detecting imminent failure in time to avoid failure through effective maintenance procedures. Properly implemented, the condition-based maintenance approach can ensure that machinery will operate at peak efficiency, not only through its normal expected service life but well beyond.

Although there are several accepted cumulative-damage theories used to estimate fatigue life, the application of these theories in practice is not straightforward. In fact, order-of-magnitude errors in life estimates are not unusual. In recent years, a lot of work has been done on life prediction based on local stress-strain and fracture mechanics concepts, but the process is not simple. Rieger discusses in detail the various factors involved in the development of life estimates for turbomachinery blades.[19] An illustration in his paper shows the inter-relationship of these factors and illustrates the complexity of the problem. In a later unpublished lecture on "Technology for High-Durability Blading," Rieger described a procedure for estimating advanced blade life; his closing comments discuss its limitations:

> *While the above procedure includes all major parameters and is adequate for the prediction of life trends, it is not certain that this method can be used with confidence within a factor of 2 to 3 for precise estimates of component life. This is due to inaccuracies associated with the material strength properties in the environment, lack of knowledge on how the crack develops from the pit site, and on the dynamic loading that typically varies in magnitude during the operating life of a blade.*

Based on the difficulties involved, it is reasonable to assume that designers are not able to estimate the service life of their system with any degree of accuracy. Instead, it is suggested that engineering designers will develop an environmental life cycle profile for the system they are designing and use their knowledge of materials and failure modes to develop the most durable and reliable system that they can.

At MFPG 27, durability and life extension was examined from a different perspective. The central theme of the conference pertained to the durability of consumer products. The collection of papers in the proceedings provides a practical look at a broad range of issues related to product durability. In the case of consumer products, durability involves both technical and economic considerations. So the major problem of design is to increase durability within the constraints of economics. Lund and Denney offered keen insight on the issues involved in extending the life of consumer products.[20] Other papers dealt with product life testing methods and reasons for being concerned about improved product performance, such as materials conservation, waste reduction and product safety. The 27th meeting also included a panel discussion on the topic "Can and Should Product Life Be Extended?" From the published introductory remarks by the panelists, it appears that the debate was lively with respect to both aspects of this question.

Active service life extension programs are ongoing in the nuclear power, aircraft and petrochemical industries, as well as for bridges and highways. Manufacturers recognize the wisdom of extending the life of their machinery. A few papers at MFPT 49 dealt with life extension, through both design and maintenance procedures. It is expected that presentations on these topics will be much in evidence at future MFPT conferences.

Sensor Technology

Sensors are key elements of data acquisition systems and, since measurement has always been an important part of mechanical failure prevention efforts, sensor technology has been of prime interest to the MFPG since its inception. Whether the problem is fault detection and diagnosis, structural inspection for defects or experimental life estimation procedures, use of sensors is usually required. For this reason, it is the role of the experts on the *Sensors Technology Committee* to provide technical guidance for other MFPT committees on linking failure modes to appropriate sensing technologies.

In 1968, Janowiak suggested that sensors used for the diagnosis of mechanical failures must be adapted to physical effects resulting from known failure modes in mechanical systems.[21] He pointed out that a vast sensor technology exists that is applicable to diagnostics and that a comprehensive search for sensors to bridge the interface between the mechanical and diagnostic systems was required. It is not certain whether such a search was conducted in an organized way, but the examples that follow illustrate the wide variety of sensor applications that have been reported at various MFPG meetings:

- Accelerometers versus microphones for vibration/acoustic signature analysis (MFPG 6)
- Inductive and capacitive sensors as wear particle detectors for oil analysis (MFPG 6)
- Accelerometers for monitoring shock pulses for bearing condition monitoring (MFPG 14)
- Fiber optic sensors for detecting particulate debris for oil analysis (MFPG 16)
- Noncontact displacement probes, velocity and acceleration sensors for bearings (MFPG 18)
- Piezoelectric polymers to measure dynamic stress, strain, acceleration, sound, vibration or shock for a broad range of diagnostic applications (MFPG 25)
- Laser scanning to detect exoelectron emission to measure fatigue deformation (MFPG 25)
- Transducer arrays to detect acoustic emissions in complex structures (MFPG 25)
- Chip detectors to detect ferrous debris in helicopter transmissions (MFPG 26 and 32)
- Use of pulse-echo ultrasonics to measure tire casing fatigue (MFPG 26)
- Inductive proximity probes for condition monitoring at high temperatures (MFPG 26)
- Piezoelectric transducers used as a part of an acoustic valve leak detector for ultrasonic emissions characteristic of internal valve leakage (MFPG 28)
- Fiber optic sensors for bearing performance monitoring (MFPG 28)
- Polymer sensors for monitoring bearing condition (MFPG 28)
- Gamma ray detectors for radioactive measurement method to detect engine wear (MFPG 32)
- Oxygen sensors to monitor exhaust emissions and provide feedback control to prevent failure in catalytic converters (MFPG 32)
- Fibroscopes for gas turbine engine health monitoring (MFPG 32)
- Contaminant monitors for fluid power and lubrication systems; determines level of contamination by measuring silting torque to indicate changes in friction (MFPG 36)
- Infrared sensors to measure automobile emissions (MFPG 36)
- Digital sensors for diagnostic and control systems for computer interfaces (MFPG 36)

The preceding description of applications is evidence that innovative engineers can develop sensors to measure almost any failure-related parameter that may emerge. There are other examples in later proceedings. Floyd discussed four types of sensors with respect to their impact on condition monitoring.[22] One type was an advanced-warning ice detector for the inlet stages of gas turbine engines, a very critical problem. Redden described a program to develop an intriguing smart integrated micro-sensor system capable of real-time fatigue analysis of strain data.[23] The use of embedded fiber optic probes to measure temperature through the thickness of composites was described by Whitesel and Sorathia.[24] Some interesting comparisons were made on the use of laser vibrometers, parabolic microphones and accelerometers for rolling-element bearing diagnostics.[25] Several other new or unique sensor developments were reported in MFPG 48 and MFPT 49.[26-32] It is reasonable to conclude that the greatest advances in the mechanical failure technology arena over the past 40 years have been in sensor development.

Developments Over the Last 10 Years

The 61st MFPT meeting was held on the 40th anniversary of the society. Since the first version of this history was written more than a decade ago, the MFPT technical committee structure has changed. The Diagnostics and Prognostics and Prognostics Committees have changed to Diagnostics and Signal Analysis and a separate Prognostics Committee. The Failure Analysis and Sensors Technology Committees are still very active. The Life Extension and Durability Committee was eliminated and new committees on Distributed System Architecture, Tribology and Structural Health Management were formed. The mission of the society remains the same, but new developments are rapidly advancing our technology. A number of outstanding papers have been published over the last decade, but none of these will be referenced or discussed here. Instead, four areas that have most contributed to technological advancement are described briefly:

- Significant new developments in computer software and hardware have greatly enhanced our computational capabilities.
- Capabilities in data acquisition, data handling and signal analysis have increased greatly. Data processing at the transducer and rapid transmission of digital data to the computer for further analysis is not uncommon.
- The number of highly qualified engineers in MFPT technologies,

especially diagnostics and prognostics, has increased several fold. This growth has resulted from increased training and certification. Ten years ago, the authors felt that they knew all the experts in the field. This is no longer true.
- Ten years ago vendors had to 'push' their predictive maintenance products to convince customers of the value of this technology. Presently there is a 'pull' market. More and more organizations, both public and private, have predictive maintenance programs. They are seeking consultants and equipment to ensure that their programs are effective.

Summary

A limited evaluation of mechanical failure prevention technology as reported in the proceedings of the MFPG/MFPT meetings since 1967 has been attempted. Nearly 2000 papers have been published in these proceedings, in whole or in part, over the 40-year period. Some of the earlier proceedings provided only abstracts or synopses for several of the papers. These proceedings represent a significant body of work in a number of different technical areas all tied together by the common thread of failure prevention.

Diagnostics *and* prognostics received somewhat more emphasis than the other topics in this article, in part because they are of high priority to the MFPT Society and in part to share this maintenance-oriented information with other organizations having similar interests. In addition, this is a "hot topic" in both the public and the private sector, because successful condition-based maintenance (CBM) programs using D&P technology can have a very high payoff, both technically and economically. The majority of U.S. industrial firms view effective maintenance as a fundamental prerequisite to economic success and are currently using some type of predictive maintenance (PdM), a major component of CBM. It is useful to consider why this is happening, keeping in mind that the technical result of successful PdM efforts is failure prevention and life extension.

The MFPG/MFPT proceedings clearly indicate significant improvement in condition monitoring and diagnostics capabilities over the past 40 years. Improved techniques developed by creative engineers, coupled with marked advancements in diagnostics hardware and software, have resulted in more successful PdM efforts. In many cases, faults can be detected early, the location of the fault can be identified and appropriate maintenance can be scheduled in time to avoid catastrophic failure. More and more PdM systems are automated, and many employ a combination of diagnostic techniques. In many cases, time to failure can be predicted with reasonable accuracy. However, prediction of time to failure should not be confused with prediction of remaining service life. Although some progress has been made in prognostics, much work remains to be done on the development of life estimation methods. The difficulty of predicting service life increases with the complexity of the system and the number of potential failure modes.

Procedures for conducting failure analyses are well established but are usually relatively expensive for systems with any degree of complexity. Natishan points out that there are many situations where component failure has little or no impact on safety, reliability or economics.[18] Therefore, the cost of doing a failure analysis must be weighed against the benefits to decide whether or not an analysis is justified. As a general rule, in all cases where failure has a major impact on safety or operations, it is essential that the cause of failure be determined.

Once a failure analysis has been completed and the root cause of failure determined, it is imperative that the results be fed back into the design or maintenance process. Otherwise, the effort will have been wasted. There are a number of applications for lessons learned from failure. Among the more important are developing new design methods, redesign to improve safety or reliability, improving maintenance procedures and extending service life.

This article began with a quotation from the proceedings of MFPG 20. It is appropriate to close by citing six papers from the same proceedings[33-38] that address the broad implications of mechanical failures for the divergent segments of our society that are concerned with failure prevention. These papers provide useful perspectives on mechanical failure that, taken together, define the national scope of the failure prevention problem:

- In describing the implications for science, Hirth first discusses the current status of several fundamental aspects of the failure problem.[33] He then provides a very good shopping list of needed theoretical and experimental research, primarily related to modes of failure.
- Paxton covers the current status of selected problems on designing to avoid failure from the engineering viewpoint.[34] He then offers some good advice to engineers on more informed design approaches and better control over material selection for new designs.
- As director of the Ford Scientific Research Laboratory, Compton discusses mechanical failure with respect to the engineering, manufacturing and design aspects of the automotive industry.[35] He presents an informative description of the design process for automobiles and closes with a plea to the research community for its continuing help in developing the proper models for mechanical behavior of materials.
- Ryan provides useful insight on mechanical failures from the perspective of a manufacturer of industrial and consumer durables.[36] He calls for a partnership between industry and government to develop regulations on safety and reliability of products based on what is to be achieved rather than how it is to be achieved.
- Kushner discusses mechanical failure from the viewpoint of the then four-year-old Consumer Product Safety Commission.[37] Kushner's paper was followed by a lively discussion that was transcribed for the proceedings. It should not be surprising that it includes a provocative interchange between him and Ryan on regulatory issues.
- Roberts of the NBS describes the implications of mechanical failure for public policy.[38] He strongly suggests that the nation needs a coherent public policy relating to materials and mechanical failure and that the concerned citizens and technical specialists of MFPG can and should contribute to formulating that policy.

These last six referenced papers clearly show that the impact of mechanical failures on our society is very broad and that almost all segments of the public and private sectors are concerned in one way or another with their prevention. Beyond that, these papers strongly suggest that solutions will be found more quickly through cooperation, better communication links and effective mechanisms for interchanging technical information on mechanical failure prevention technology.

The relevance and technology insights that have characterized the growth of MFPT continue into the 21st century. The focus in the early years was sensing, diagnostic techniques, failure mechanisms and preventative technology. With the great strides that have occurred in these areas, MFPT's mission has focused on the future technology needs of the user community. Prognostics development and the integration of fault detection and prevention technology into the products of the future are some of the new MFPT challenges in the coming years. With the past as guidance, the society in partnership with the Vibration Institute, looks to the future with confidence.

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