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BY

J. REINTJES, J. E. TUCKER, P. L. HOWARD, A. SCHULTZ
C. LU, T. SEBOK, C. HOLLOWAY, L. L. TANKERSLEY, AND T. MCCLELLAND

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J. Reintjes(1), J. E. Tucker(2), P. L. Howard(3), A. Schultz(4), C. Lu(5), T. Sebok(6), C. Holloway (6), L. L. Tankersley(7) , and T. McClelland (2

(1) Code 5604.1, Naval Research Laboratory, Washington, DC
(2) Code 5614, Naval Research Laboratory, Washington, DC
(3) P. L. Howard Enterprises Inc., Newmarket, NH
(4) Code 5360.1, Naval Research Laboratory, Washington, DC
(5) Department of Computer Sciences, Towson University, Towson, MD
(6) Lockheed-Martin Tactical Defense Systems, Akron, OH
(7) Department of Physics, US Naval Academy, Annapolis, MD

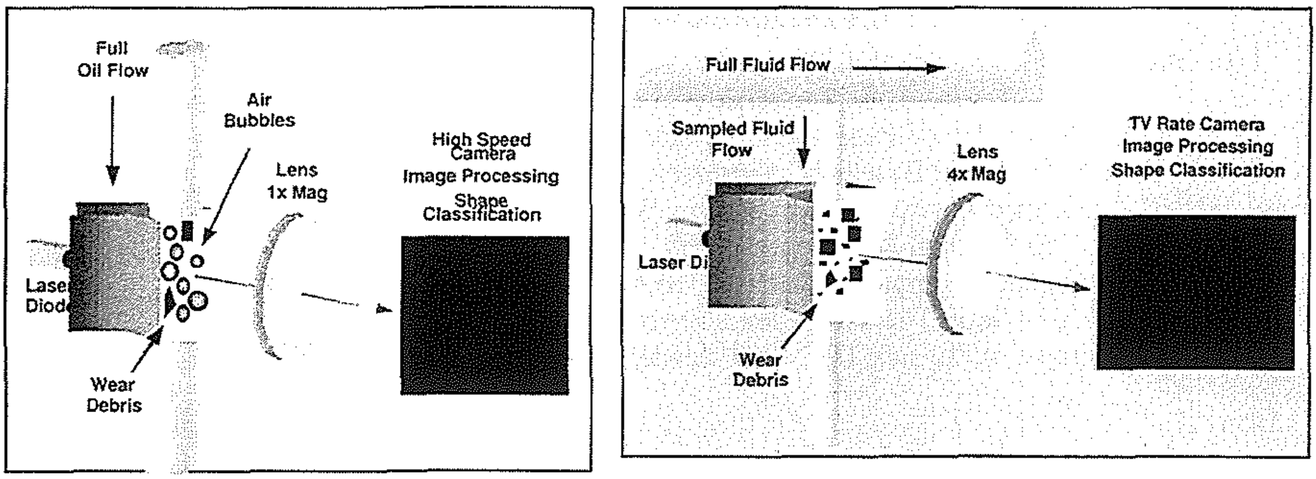
1. INTRODUCTION. LASERNET machinery monitoring technology is intended to provide on site and on-line determination of type, severity and rate of progression of faults in oil-wetted mechanical systems through measurement of size, shape characteristics and rate of production of debris particles. [1-3] The LASERNET technology family consists of the LASERNET and the LASERNET FINES oil debris monitors. The LASERNET oil debris monitor is a real time on line full flow device that detects the relatively large particles, (50-100 micrometers and larger), associated with failure related faults in engines, drive trains and gearboxes. It provides early detection of failure related faults allowing avoidance of catastrophic failures in operation. The LASERNET FINES monitor detects particles at sizes greater than 5 micrometers and provides wear classification based on shape information for particles larger than 20 micrometers. This is also the size range in which particulate contamination of hydraulic and fuel is important. LASERNET FINES thus can provide information on cleanliness of hydraulic and fuel systems.

LASERNET FINES can be configured in several ways – as an off-line batch processor, as an on-line temporary monitor, or as an on-line full-time monitor. The off-line batch processor is suitable for monitoring multiple pieces of equipment such as in a laboratory, onboard a ship or for fleets. It is also useable for equipment such as splash-lubricated gearboxes that do not have flowing lubrication systems. The temporary on-line system is appropriate for fleet monitoring using short-term attachment and is useful when rapid turn-around is important. The on-line monitor provides continuous autonomous monitoring of equipment. It provides a continuous monitoring that can detect transient debris production and can function as part of an advanced CBM system for reduced manpower installations.

The LASERNET monitors provide fault specific detection of debris related faults, allowing optimal decisions for maintenance actions or alteration of operating conditions. They combine easily with on line oil condition monitors based in infrared spectral analysis [4] to provide comprehensive oil analysis system that will enable condition based maintenance systems. They also combine with vibration, temperature and other sensors to provide improved early fault identification and reduced false alarms in advanced machinery monitoring systems.

2. TECHNOLOGY DESCRIPTION The basic operation of the LASERNET monitors is shown in Fig. 1a for LASERNET and Fig. 1b for LASERNET FINES. In each case an image of objects in the flowing oil system is formed by illuminating a section of the oil flow with a pulsed laser diode and imaging the transmitted light onto an electronic camera. The objects in the resulting image are analyzed with image processing routines to determine their characteristics. The full-flow LASERNET monitor must examine all of the oil. As a result, high speed imaging must be employed and the pattern recognition system must distinguish debris particles from air bubbles. The LASERNET FINES monitor samples a fraction of the full flow. It can be operated at lower speeds that are compatible with conventional television formats.

It has been shown through extensive laboratory analysis that the wear mechanisms responsible for production of debris particles can be inferred from a combination of their size and



(a) (b)

Figure 1. Schematic of LASERNET (a) and LASERNET FINES (b)

shape characteristics.[5-11] The LASERNET monitors use a neural network trained on a library of labeled debris particles to determine wear class of the particle. The LASERNET monitor sorts particles into fault-related and non-fault related classes. The LASERNET FINES monitor sorts particles into fatigue, sliding, cutting wear classes, and also recognizes oxides, fibers and water bubbles.

3. LASERNET We have designed and constructed a prototype LASERNET system based on parallel/series CCD imaging technology, high speed dedicated image processors and neural net classifiers for fault identification. [5-9] The system has been tested on the T700 engine at the helicopter power train test cell at Naval Air Warfare Center, Trenton, NJ. A schematic of the system is shown in Fig. 2. It consists of a single mode diode laser operating at a wavelength of 830 nm, a flow adapter, a 512x512-pixel CCD imager with a frame rate up to 1000- frames per second, and image processing electronics. The light transmitted through the viewing area of the flow adapter is imaged onto the CCD camera. Because of the speeds involved for framing and image processing, many conventional image processing approaches could not be used, and data reduction schemes had to be employed throughout the system. The uniformity of the laser illumination was optimized, allowing a global threshold to be performed in the camera and one-bit image data to be transferred to the image processor.

A block diagram of the data flow in the processor is shown in Fig. 3. The data stream from the camera is held first in a full frame buffer. Pixels associated with edges of objects are identified in a field programmable gate array (FPGA). The boundary pixels are assembled into individual objects in a DEC-alpha processor, and are then subjected to a series of shape identification tests. The processing strategy adopted was to identify air bubbles according to an ascending series of criteria, and to identify as debris all objects that failed the tests for bubbles. Bubbles were identified by a series of tests of increasing complexity, with objects that satisfied one level of test not being tested in subsequent steps. As a result, increasingly complex tests were applied to fewer objects, minimizing overall processing times. The tests examined objects for circularity (single bubbles), double overlapping bubbles, and multiple bubble patterns. In order to meet the speed, false alarm, and debris detection requirements a dual processor architecture was adopted. Tests for single, double and simple multiple bubble patterns were done in the serial DEC-alpha, contained in the dotted box in Fig. 2. Objects that were not discarded were passed to a second processor, which performed detailed tests based on local curvatures to identify more complex bubble patterns. The tests performed in the DEC-alpha processor reduced the computational load for the secondary processor to a level of about one object per second. The performance of the resultant system was consistent

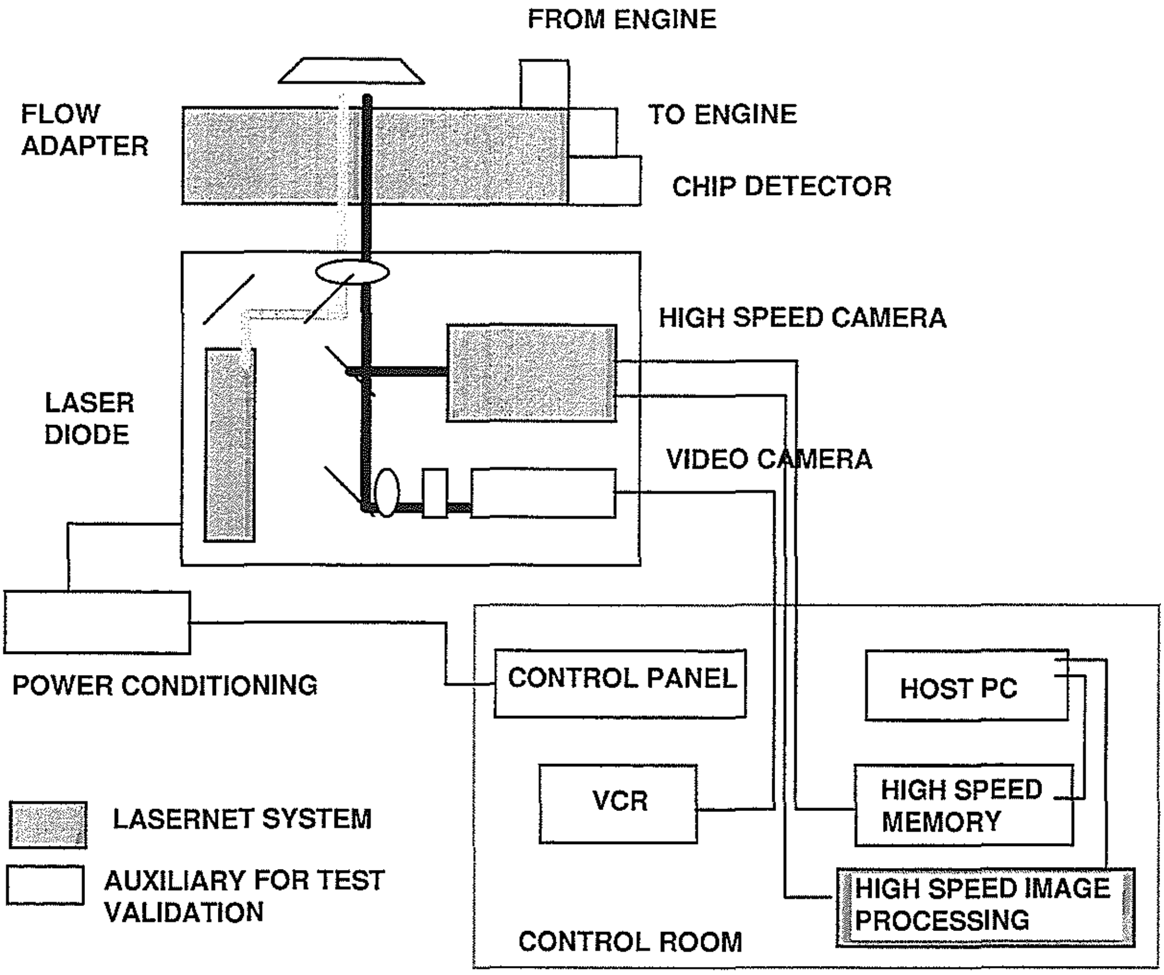


Fig. 2. Schematic diagram of the LASERNET test system for the T700 engine

with a false alarm rate (defined as an incorrect identification of a rejectable gear box) of less than one every 2000 operating hours.

3.1 Engine Tests. The system has been tested on the T700 engine at the helicopter power train test cell at Naval Air Warfare Center, Trenton, NJ under a variety of engine operating conditions. The flow adapter was connected to the engine at the auxiliary gearbox manifold in place of the existing chip detector. The chip detector was replaced in the system immediately after the viewing area of the flow adapter, providing the opportunity for visual comparison of the two detectors. The first set of tests were directed at demonstrating an acceptably low false alarm rate along with the ability to identify failure related debris. The test on the T700 engine was chosen for the low debris generation rate of the engine, providing a platform on which the false alarm rate could be examined under a variety of conditions. The system was operated at different engine conditions including ground and flight idle and a variety of applied torques. In order to train the classifier to distinguish various air bubble patterns from debris, images of bearing debris from a bearing test stand were introduced into images obtained from the high speed imaging system.

The results of these tests are summarized in Figs. 4 and 5. In Fig. 4 the evolution of the false alarm rate, defined as an incorrect identification of a rejectable gear box, is shown over the course of the

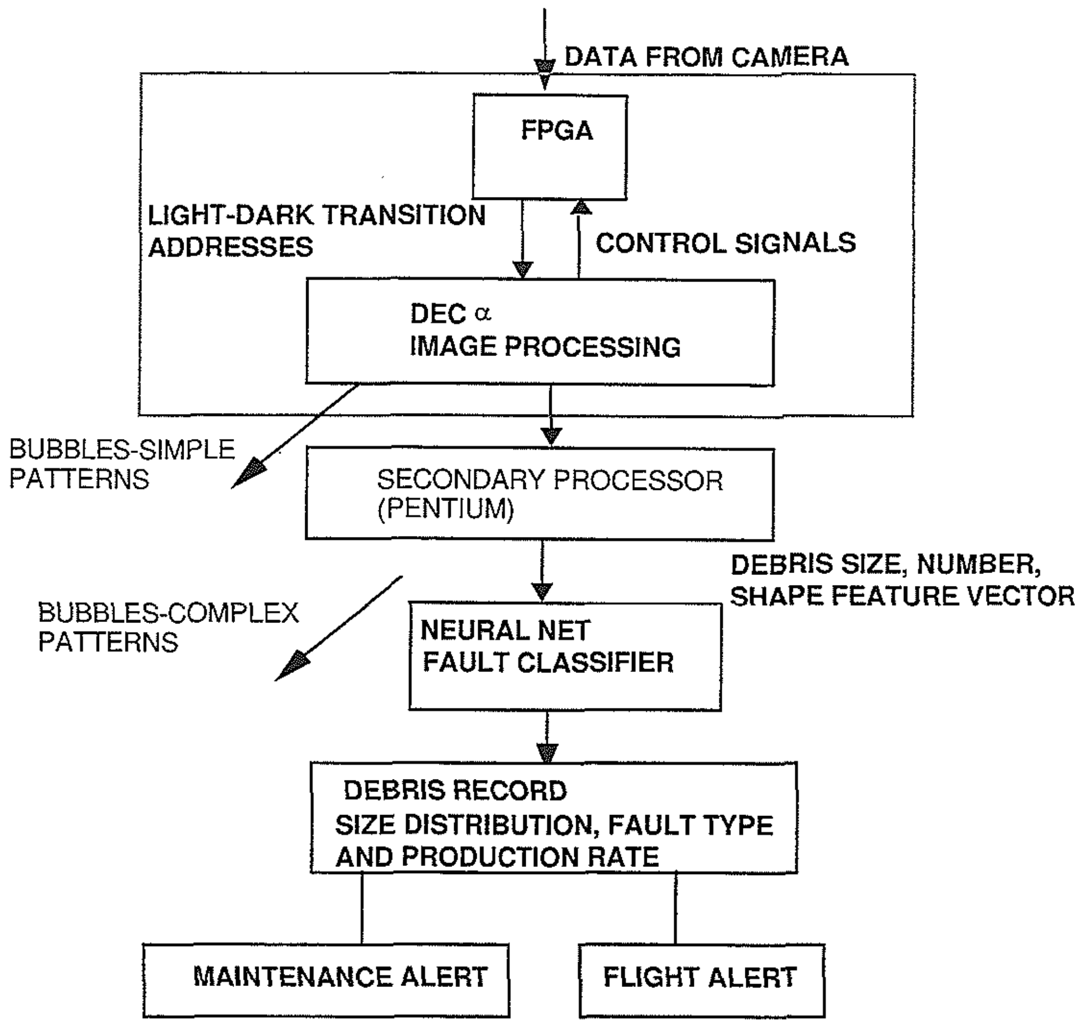


Fig. 3. Block diagram showing data flow in the image processor and fault classifier.

trial. As the trial progressed, additional tests were introduced to handle increasingly complex bubble patterns as described above, and as these tests were introduced, the false alarm rate decreased. At the end of the trial a system showing zero false alarms was operating, with the corresponding false alarm rate shown in the figure.

The corresponding particle detection efficiency is shown in Fig. 5. Here, again the detection rate increased as the processing algorithms were improved. At the end of the tests the system was close to the target for the larger particles, but somewhat below the target for smaller particles. Further improvements can be obtained with the use of higher resolution cameras (1000 x 1000 pixels) that are now available.

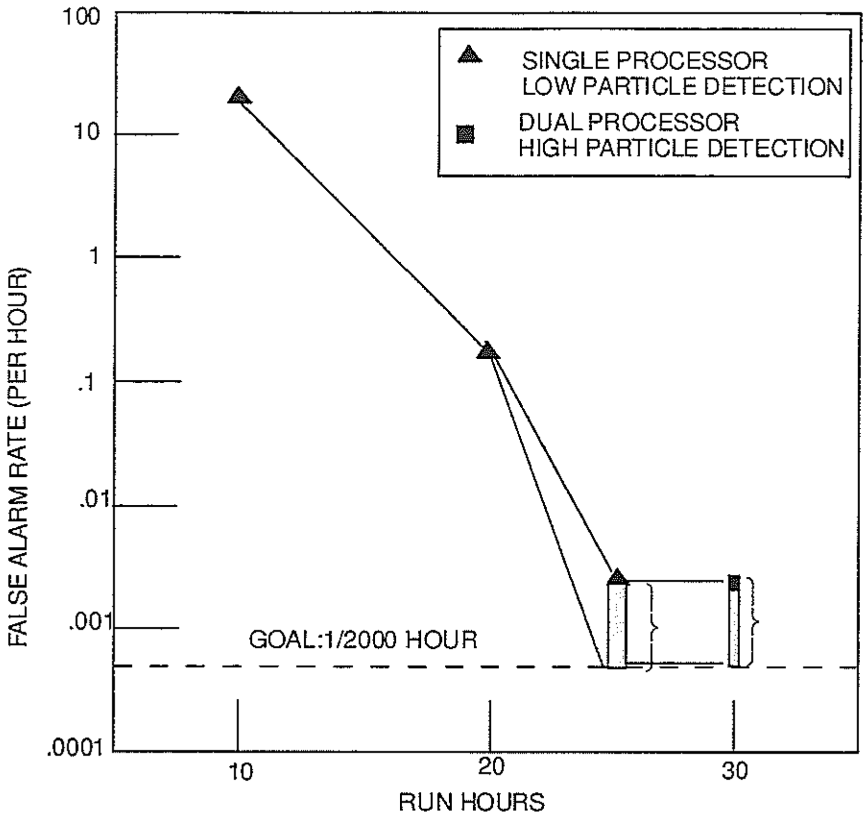


Fig. 4. False alarm rate progression for single and dual processor architecture. The brackets show the range of false alarm levels consistent with the demonstrated performance.

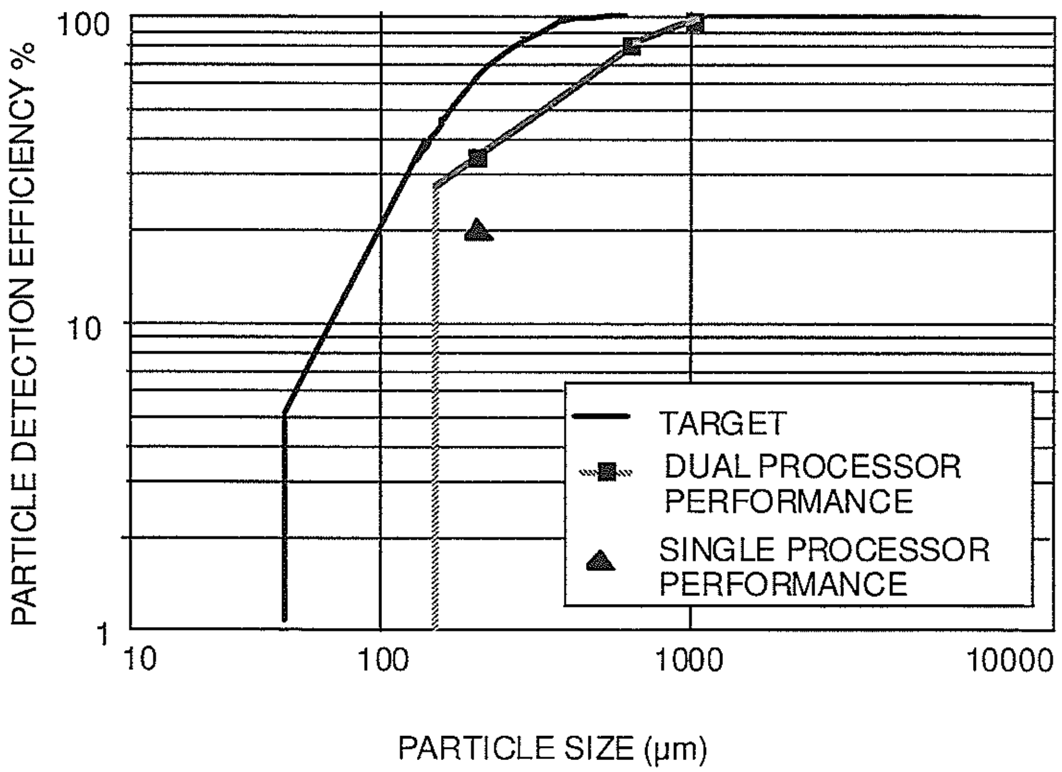


FIG. 5. Particle detection efficiency with single and dual processor architectures

4. LASERNET FINES. An instrument based on the bench-top batch processor configuration of LASERNET FINES has been developed by Lockheed Martin Tactical Defense Systems, Akron OH, under the ONR program on Condition Based Maintenance (CBM). The instrument, shown in Fig. 6, is self contained and menu driven with touch screen input. It has a total sample cycle time of about 8 minutes. It provides classification of particles above 20 μm into fatigue, cutting and sliding wear, and oxides. Fibers are also identified. The instrument is capable of operating with fluids having viscosities up to 350 centi-Stokes at room temperature. It can work with synthetic and mineral based lubricants, hydraulic and gearbox oils, and automatically compensates for fluid darkness.

Data is presented on the screen in tabular and graphical form, and is saved on internal disks for trending. Trending graphs, which serve as the bases for machine condition assessment, are provided for each of the wear debris categories, as well as for total particles, and statistics such as mean particle size, standard deviation and largest particle size are determined. An Ethernet connection is provided for connection to a computer system for transmission of data. The results of the sample analysis are transmitted as text files that can be read by external condition assessment systems for incorporation into larger CBM systems. Examples of display screens for equipment information, main results screen and data trending are shown in Figs. 7-9.

LASERNET FINES is currently being evaluated in several shipboard and shore based environments on a variety of mechanical equipment. Part of this program is directed at baselining operational equipment and developing features of debris production that can be related to the condition of the machinery. Presently, these instruments are collecting wear debris distribution baseline information on equipment such as:

Main Propulsion Diesels
Ship Service and Emergency Diesel Generators
Main Reduction Gears
Electric Drive Gearboxes
Aircraft engines
Helicopter gearboxes

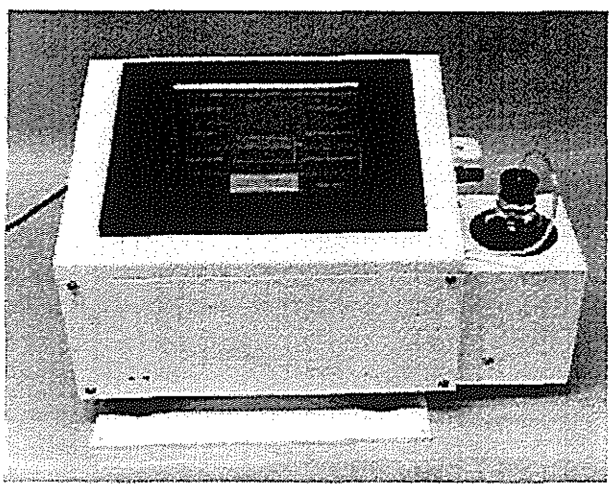


Figure 6. LASERNET FINES instrument built by Lockheed-Martin Tactical Defense Systems under ONR program on CBM.

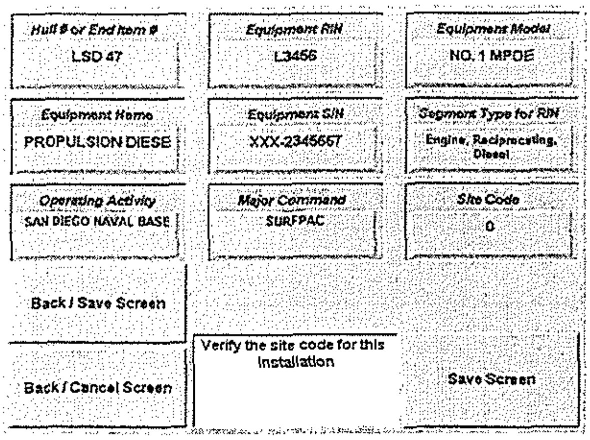


Figure 7. Equipment Information Screen.

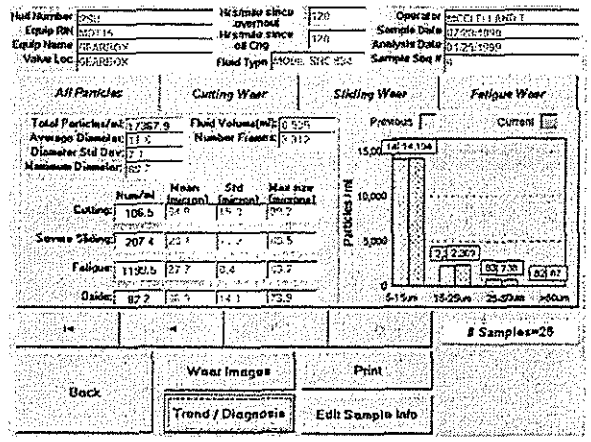


Figure 8. Sample Results Screen.

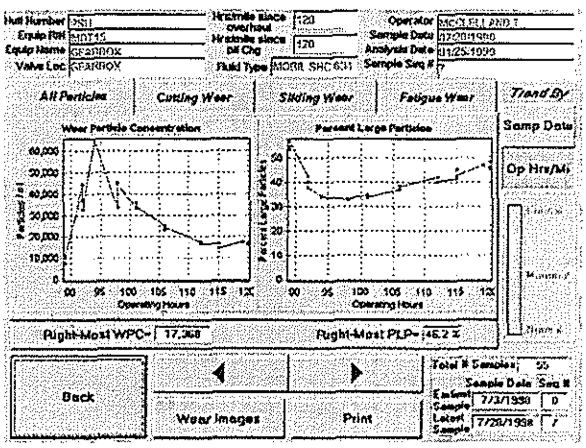


Figure 9. Sample Trend Graph.

5. LASERNET FINES PERFORMANCE. Here we illustrate the performance of LASERNET FINES on hydraulic calibration fluid and on a series of accelerated gearbox failure tests. The results of lasernet fines analysis of hydraulic medium test dust calibration fluid from Fluid Technologies (FTI ISOMTD) is shown in Fig. 10 along with the corresponding particle size distribution provided by the National Institute of Standards and Technology (NIST). The LASERNET FINES results show excellent agreement with the NIST standard over the range in which NIST certifies the material (particle size up to 30 micrometer). There are too few particles above 30 micrometers for a certification to be made. The LASERNET FINES results are done without the need for separate calibration at each particle size.

Results of analysis of oil samples from accelerated gearbox failure tests being conducted at Pennsylvania State University under the ONR CBM program [12] are shown in Figs. 11 and 12. The MDTB accelerated gearbox failure tests are conducted on single-reduction 10 hp gearboxes. The gearboxes are run in for approximately four days at maximum normal load provided by an electric generator on the output shaft. After that, a 3X overtorque is and the system is run to failure. The system is stopped approximately every two to three hours for bore site inspection and oil sampling. LASERNET FINES results from two of these runs are show in Figs. 11 and 12 for MDTB Runs 14 and 15. In Fig. 11a, histograms of the total particle concentration corrected for sampling dilution are

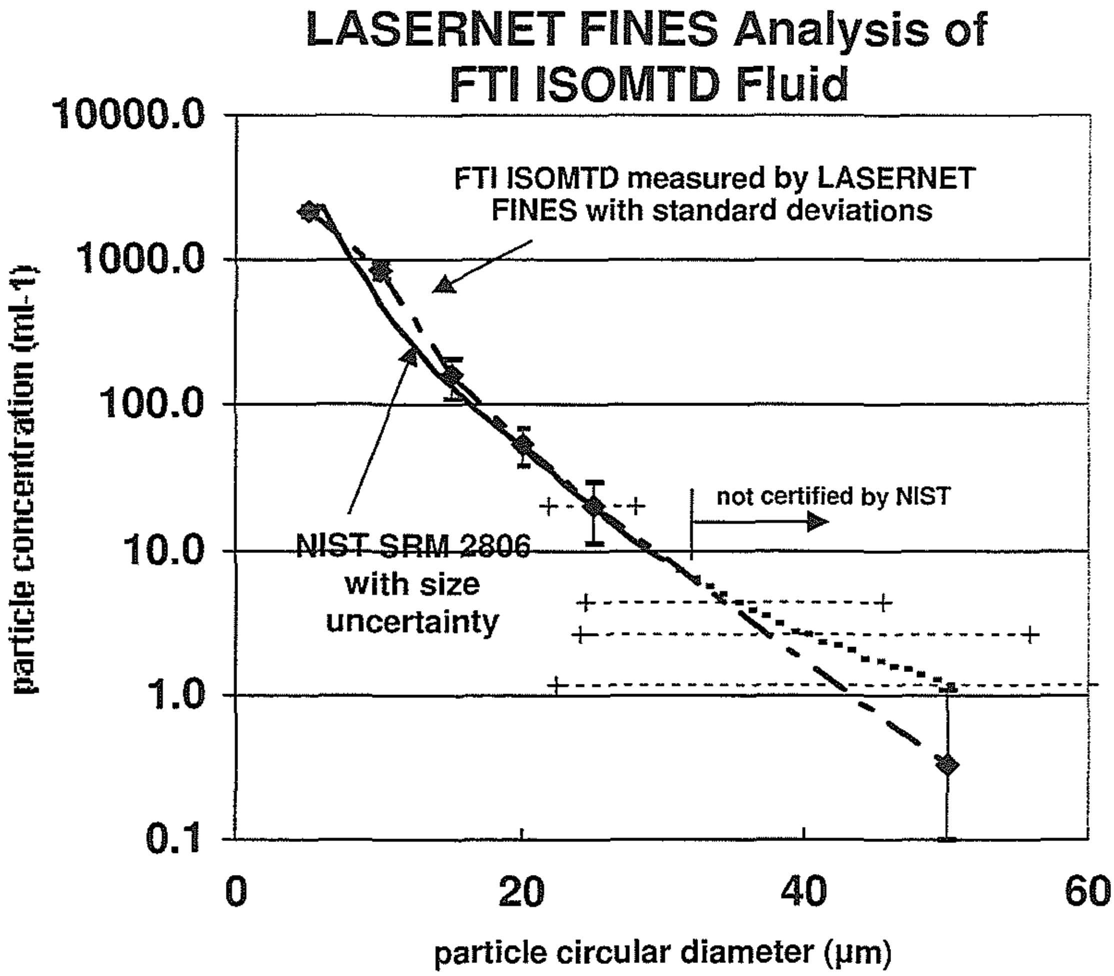


Fig. 10. Comparison of LASERNET FINES analysis with NIST size distribution for hydraulic medium fine test dust calibration fluid.

shown in different particle size ranges. Corresponding bars in the four size ranges are from a single oil sample. Oil samples were drawn at successive times during the test as indicated in the Figures. A similar set of data for the particles classed as fatigue, severe sliding and cutting wear are shown in Figs 11b.,11c., and 11d., respectively.

The first sample in Fig. 11 was taken at the end of the run-in period and subsequent samples were taken at successive times under the loaded conditions. The sample location was changed between the 2 and 4 o'clock samples, which changed the measured debris concentration. Near the end of the test, several teeth on the output gear broke between the 2 am and 5 am samples. In Fig. 11a, the total particle concentration in the 5-15 µm size range shows a general decrease during the run. In Fig. 11b, however, an increasing concentration of particles classed as fatigue are seen in the 25-50 µm size range after the 3X overtorque was applied. This behavior is apparent well in advance of the ultimate failure and may be related to the excess wear conditions responsible for failure. Similar changes in the concentration of particles classed as severe sliding and cutting wear was not seen in any of the particle size ranges (Figs 11c and 11d).

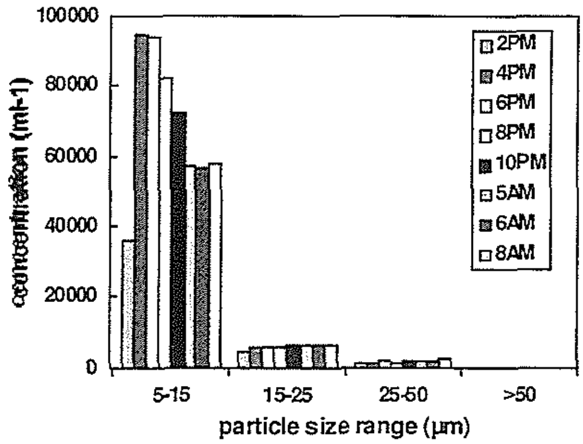


Figure 11a PSU MDTB Run 14 total particle concentration distributions

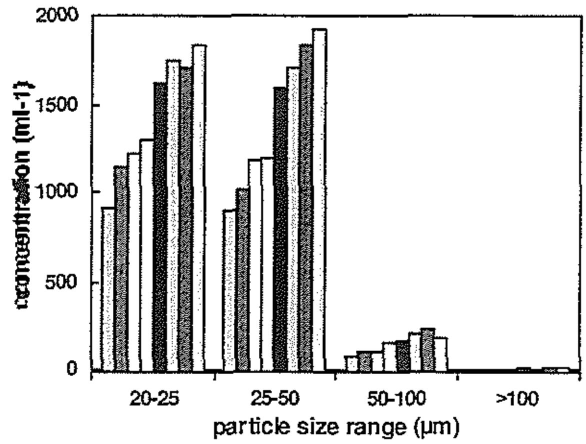


Figure 11b. PSU MDTB Run 14 fatigue particle concentration distribution

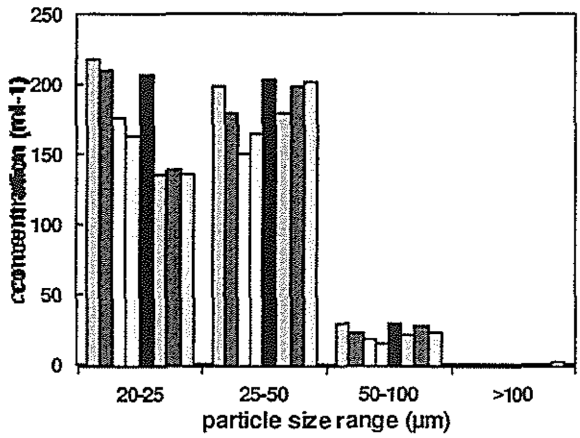


Figure 11c PSU MDTB Run 14 severe sliding wear particle concentration distributions.

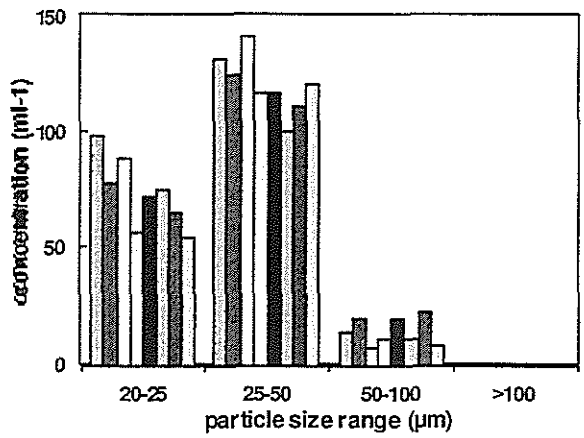


Figure 11d. PSU MDTB Run 14 cutting wear particle concentration distribution

LASERNET FINES results for MDTB Run 15 are shown Figs. 12a and 12b. The loading history of MDTB Run 15 was the same as for MDTB 14, but fluid sampling procedures were altered. For MDTB Run 15, the gearbox had a 4 hour green run which was followed by a cleaning with solvent. The gearbox had an 85 hour break-in period before a 3X overtorque was applied to the output shaft. The gearbox was filled with clean fluid after the green run and smaller volume samples were removed during each measurement in a consistent manner and location. In this test, the input shaft broke at 120 operating hours.

Figure 12a shows the small particle concentration over the entire test. Figure 12b shows the concentration of particles classed as fatigue in different size ranges from the beginning of the break-in period to the ultimate failure. Concentrations of particles in the other wear classes were considerably smaller and are not shown.
The small particle concentration was very high at the end of the green run and rapidly approached a low equilibrium value during the breakin period. It increased immediately when the overtorque was applied and then decreased toward a new equilibrium value. The concentration of particles classed as fatigue increased toward an equilibrium value during the breakin period (Fig 12b). After the overtorque was applied the concentration of the larger particles first increased and then gradually

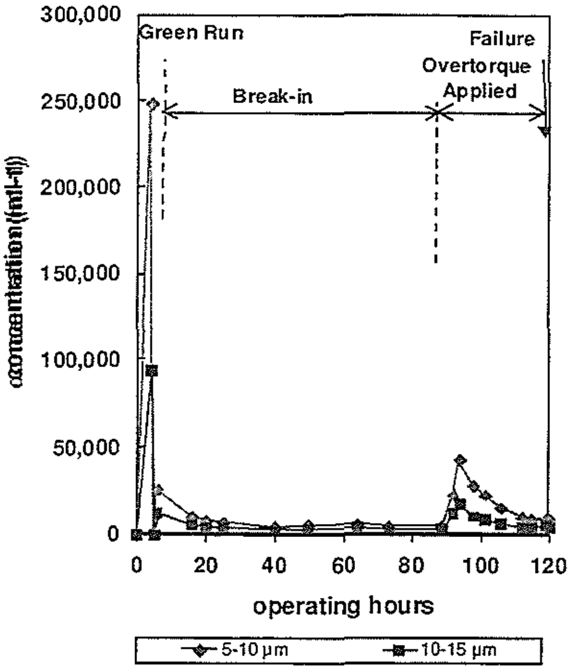


Figure 12a: PSU MDTB Run 15 small particle concentration vs. operating hours.

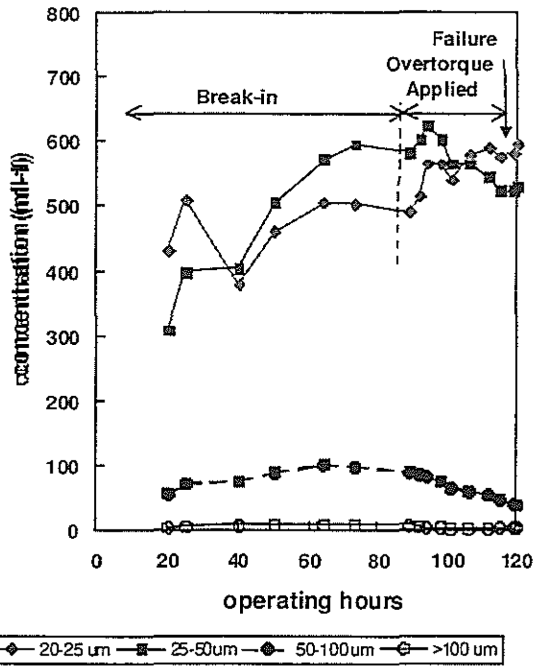


Figure 12b: Concentration of fatigue particles for different size ranges in PSU MDTB 15 vs operating hours

decreased. This behavior is different from that seen in MDTB 14, and the ultimate failure was different as well.

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