An acoustic transmission enhanced metal-based FO-cable for better DAS measurements.

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ABSTRACT

NBG, in collaboration with OFS, have developed SonoSens, a Fiber-In-Metal Tube (FIMT) for vibration sensing in mechanically and environmentally challenging applications. SonoSens is a product that offers as much as 40 % better acoustic performance compared to similar solutions on the market. The combination of polymer protection, advanced fiber coupling, and perforations in the metal tube make SonoSens an incredibly accurate sensor without compromising the overall mechanical strength of the product. The cable houses 3 optical fibers one of which is OFS' AcoustiSens®[i] – an optical fiber specifically developed for vibration detection. The AcoustiSens design dramatically increases Rayleigh backscatter over that naturally occurring in telecom-grade optical fibers by 10 to 15 dB through proprietary, axially positioned refractive index perturbations within the core of the fiber.

INTRODUCTION

Distributed Fiber Optic Sensing (DFOS) has become popular in applications where sensing long distances with tight spatial resolution is important. DFOS promises immediate, pinpoint detection of environmental effects on critical assets, having the ability to monitor long distances (~50 km) in real-time and in harsh environments. As a result, Distributed Acoustic Sensing (DAS) applications, a subset of DFOS, are more prevalent than ever. The equipment provides excellent monitoring for applications like third-party intrusion, pipeline leak detection, seismic sensing, monitoring trains (rail), and in-well monitoring.

The key components of a DAS monitoring system are the Interrogator Unit (IU) and Fiber Optic Cable (FOC), where the optical fiber within the cable is the 'SENSOR.' For a system to detect and locate events accurately, the FOC must be designed to withstand in the installed environment while providing maximum coupling of the acoustic energy source, i.e., transfer as much vibration energy as possible from the event source to the sensor fiber. Because of these unique mechanical and optical requirements, NBG's R&D team designed the SonoSens cable to boost acoustic signal coupling while protecting the fiber in a unique FIMT design, thus closing a gap in commercial sensing cable design offerings.

Figure 1

Figure 2

The SonoSens cable was tested and compared to a standard FIMT design and showed approximately a 40 % optical performance improvement. Both cables were similarly constructed to provide as direct a performance comparison as possible while demonstrating the advantages of the SonoSens cable design. Both cables had identical dimensions and components; however, the FIMT materials and outer coatings differed. SonoSens used alloy 825, a highly corrosion resistant, fully austenitic Nickel-Iron-Chromium, and a polyvinyl chloride (PVC) coating. In contrast, the reference cable used a standard FIMT with stainless steel (SS) 304 and a PA6 (polyamide) coating.

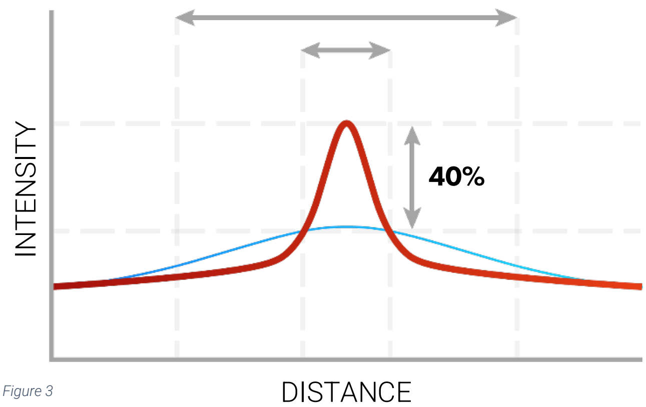

Figure 3

DEVELOPMENT MEMBERS AND EXPERTISE

To address needs in the emerging DAS markets, NBG and OFS collaborate in this paper to combine excellence in FIMT mechanical design with expertise in optical fiber technology, providing an industry first: SonoSens with AcoustiSens inside. Designed for mechanically complex installations, acoustically engineered, perforated metallic tubing protects the fibers while increasing vibrational coupling to those enhanced Rayleigh-backscatter optical fibers within.

NBG

NBG Group's primary focus is Fiber in Metal Tubes (FIMT), integrated Fiber Optic Sensing (FOS) applications, and a range of consulting services for Fiber to the Home (FTTH). NBG's Tube division manufactures fiber optic cables for Downhole, Subsea, and Pipeline sensing applications using Distributed Temperature Sensing (DTS) / Distributed Acoustic Sensing (DAS) / Distributed Strain Sensing (DSS) DTS/DAS/DSS and FBG technologies. Founded in 1996, NBG has over 250 employees in 4 countries. Manufacturing, designing, and engineering are done at the company headquarters in Gmünd, Austria, with a US sales office in Houston, TX. NBG's field of operations ranges from industries including Oil & Gas, Telecommunications, Security, Structural Health, Rails, Roads, Dams, FTTx, and many more. NBG is the leader in manufacturing customized high-quality FIMTs that meet clients' most demanding requirements. NBG continuously refines its manufacturing processes and invests in R&D work in FIMT technology.

OFS

OFS is a world-leading designer, manufacturer, and provider of optical fiber, fiber optic cable, connectivity, Fiber to the-Subscriber (FTTx), and specialty photonics products. They provide reliable, cost-effective solutions for various applications, including Telecommunications, Medicine, Industrial Automation, Sensing, Government, Aerospace, and Defense. These products help customers meet the needs of consumers and businesses, both today and into the future. Headquartered in Norcross (near Atlanta), Georgia, U.S.A., OFS (OFS Fitel, LLC) is a global provider with facilities in China, Denmark, Germany, Morocco, Russia, and the United States. OFS is a wholly owned subsidiary of Furukawa Electric Co., Ltd., a multi-billion-dollar leader in optical communications.

TARGET MARKETS AND APPLICATIONS

DAS Systems are used in many applications where the fiber is the sensor and acts like a series of microphones distributed along an asset being monitored. DAS systems detect vibration signatures that alert the operator to events like pipeline leaks and third-party intrusion. The key to effective/efficient DAS monitoring applications is to install the FOC within coupling range of vibrational events. By increasing sensitivity, SonoSens with AcoustiSens promises to increase this offset significantly, thereby simplifying installation and elevating safety when compared to alternatives that are not optimized for vibrational coupling

- # DESIGN CONCEPT

Acoustic signals (environmental vibrations) transfer best when minimizing the damping characteristics of the materials between the sensor (fiber) and the asset being monitored. Fiber optic cables are designed to protect the fiber from environmental degradation while allowing detectable acoustic energy transfer through to the fiber. The protective layers of the FIMT (outer jacket, stainless steel tube, etc.) attenuate the acoustic energy. NBG's SonoSens improved cable design enhances vibrational coupling. This is accomplished by using advanced manufacturing processes, selection of materials to promote coupling, a unique FIMT design combined with enhanced Rayleigh backscatter AcoustiSens fiber to significantly improve vibrational coupling enabling improved DAS system signal-to-noise ratio (SNR) performance.

MECHANICAL

For acoustic measurements, the best optical solution would be to use a bare, unprotected fiber. However, this is impractical for DAS monitoring applications (Pipeline, In-well, Rail, Perimeter, Subsea, Highway, and Smart City applications) as the surrounding environment – mostly strain, bending, crush, and torsion – are impacts that would damage a bare fiber. The fiber needs to be protected by a cable design made with components that can withstand these influences, protecting the fiber to provide long-term reliability and enhanced sensitivity. The SonoSens cable's primary protection is provided by a metal tube made of Alloy 825 with an outer diameter of 2.30 mm (0.09") and a wall thickness of 0.20 mm (0.008"). Alloy 825 has a low-tension hysteresis while providing high tensile strength. The key to maximizing the acoustic energy transfer onto the fiber is the modified FIMT construction. NBG's R&D team designed the FIMT with elliptical holes at specific intervals to provide the best mechanical strength and acoustic coupling combination. To enhance the acoustic energy transfer from the surrounding environment, NBG's SonoSens cable introduces the optical sensing fiber(s) helically within the FIMT, ensuring longitudinal surface contact throughout the length of the SonoSens cable as an added measure to improve vibrational coupling. The FIMT is encapsulated with a polymer layer, providing improved workability, reduced sliding friction, and enhanced handling performance. The outer diameter is 4.00 mm and is made of PVC, selected for its superior performance of sound energy transmitting through polymers.

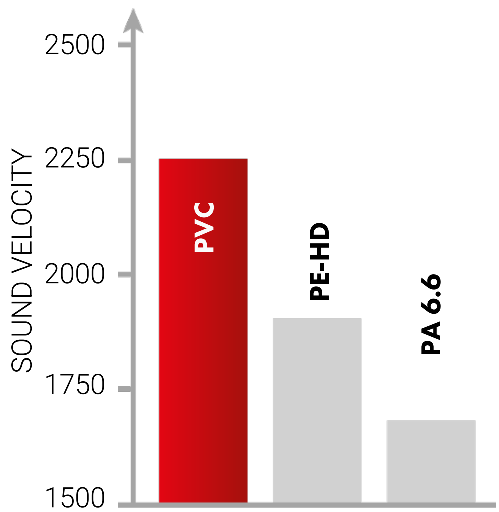

Figure 4

OPTICAL

A significant driver for optical fiber sensor development is the possibility of providing continuous or near-continuous sensing over prolonged lengths in applications that include Structural Health Monitoring, Oil & Gas in-well and Pipeline Monitoring, Seismic Sensing, and Third-Party Intrusion (TPI) applications. DAS depends on elastic Rayleigh backscattering within the optical fiber to detect events along its length. An advanced, OFS-patented process inscribes a continuous array of scattering sites within the core of the optical fiber, thus increasing elastic scattering well above that which naturally occurs. The effect of this is an increase in Signal to Noise Ratio (SNR) for the DAS interrogation system, heightened acoustic sensitivity, and an ability to increase offset of the sensor from the asset it is intended to monitor. AcoustiSens fiber has enhanced backscattering (>10dB above naturally occurring Rayleigh backscatter), low attenuation (<0.7dB/km) and is available in many lengths. In addition, the fiber is interoperable and fusion splice-compatible with G.657 and G.652 optical fibers making DAS system integration with commonly available telecommunications-grade cables easy.

PRODUCT PERFORMANCE

NBG and OFS combined efforts to evaluate the effects and benefits of SonoSens against standard FIMT products. Additionally, the experimentation included direct comparisons between SonoSens containing telecom-grade single-mode fibers and enhanced Rayleigh backscatter AcoustiSens sensor fibers. The SonoSens cable was tested against a standard FIMT cable design, where optical performance and mechanical information were tested and quantified.

Property	Reference	SonoSens
Fibers used	2x G.657.A1 1x G.657.A1-like AcoustiSens	2x G.657.A1 1x G.657.A1-like AcoustiSens
Material FIMT	Stainless Steel 304	Alloy 825
Material Outer Coating	PA6	PVC + Additives
Diameter FIMT	2.30 mm	2.30 mm
Outer Diameter	4.00 mm	4.00 mm

MECHANICAL TEST (NBG)

NBG performed the mechanical testing and analysis of the FIMT at its in-house laboratory. NBG executed the crush resistance test, kink test, and evaluation of the force-displacement diagram according to IEC 60794-1-21:2015. The operational limits for; ultimate tensile strength and maximum operational tensile force are based on a tensile force evaluation. Figure 5 shows the force-displacement test results. A 41 mm/min feed rate and a probe length of 200 mm are defined for the test. Based on safety factors and uncertainties, the ultimate tensile strength is evaluated by 560 N and the maximum operational tensile force by 220 N.

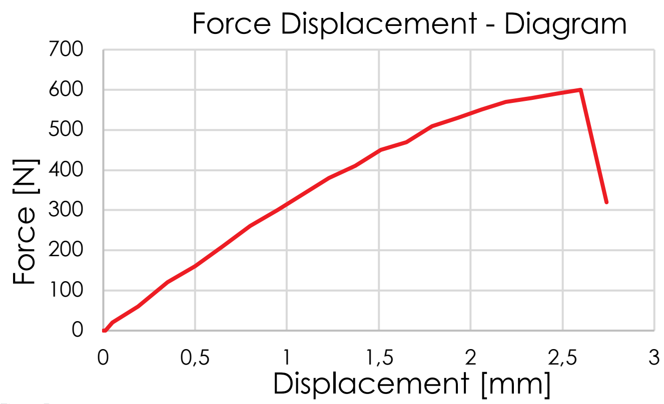

Figure 5

Test Specifications		Result	
Feed rate:	41mm/min	Ultimate tensile strength:	> 560N
Test length	200 mm	Max. operational tensile force:	220N

The crush resistance of the SonoSens cable was tested to IEC 60794-1-21:2015 standard, method E3. The feed rate was set to 10 mm/min, and the test length was 100 mm. Regarding the mechanical evaluation, no holding times are included. Figure 6 shows the test results where the clamping force for the 3 fibers is higher than 8 kN.

The minimum bending radius is an important factor in installing and winding the SonoSens cable and is evaluated with the kink test according to the latest standard. Based on the conducted analysis, the minimum bending radius is recommended to be > 160 mm. The negative deviation of the minimum bending radius compared to the reference cable's 100 mm radius is based on the perforation of the metal tube.

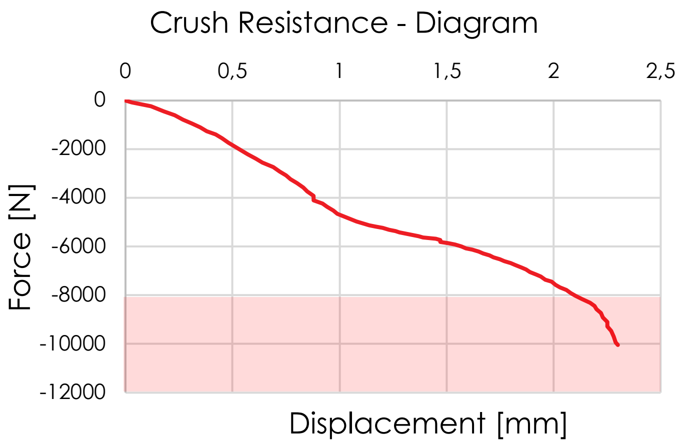

Figure 6

Test Specifications		Result	
Feed rate:	10 mm/min	Clamping Force:	> 8000 N
Test length	100 mm		

DAS CHARACTERISTICS

As shown in Figure 7, a 2 km length of AcoustiSens fiber is fusion-spliced to the distal end of a 44 km lead-in length of telecommunications grade optical fiber. This apparatus is then characterized using a commercially available DAS interrogator, and Rayleigh backscatter intensity is charted. From the trace, the effects of the AcoustiSens fiber are apparent. Over the length of the 44 km lead-In telecommunications-grade optical fiber, DAS intensity deteriorates with distance. The AcoustiSens fiber that comprises the 2 km distal end of the apparatus demonstrates a restoration of backscatter intensity compared to the untreated fiber, improving Rayleigh backscatter Intensity to levels greater than at the DAS interrogator laser pulse injection point. This backscatter intensity plot demonstrates the improvement enabled by the enhanced Rayleigh backscatter fiber technology of AcoustiSens fiber.

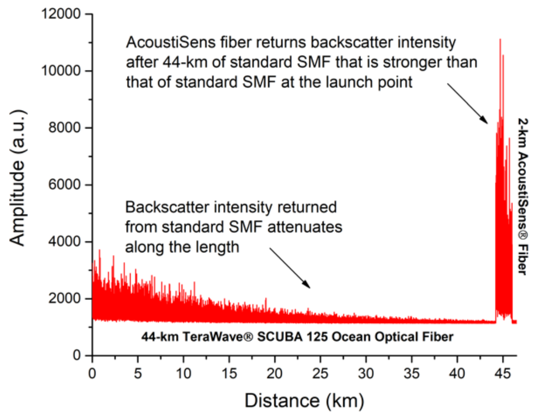

Figure 7

EXPERIMENTAL SET-UP:

Note: Results are representative but will vary depending on cable construction, fiber design, Installation conditions and DAS Interrogator model.

OFS and NBG combined efforts to assess all combinations of FIMT and optical fiber.

1. What is the Signal-to-Noise Ratio (SNR) of typical FIMT with telecom-grade single-mode optical fiber?
2. What is the SNR of typical FIMT with AcoustiSens enhanced Rayleigh backscatter fiber?
3. What is the SNR of SonoSens FIMT with telecom-grade single-mode optical fiber?
4. What is the SNR of SonoSens with AcoustiSens fiber?

To create meaningful data, the team determined a need to expose all Devices Under Test (DUTs) to:

A. Invoke identical vibrational stimuli.
B. Expose and record effects simultaneously from each DUT.
C. Strive for isolation of the DUT's from external vibrations.
D. Explore several vibrational frequencies in a band of interest from 100 to 1,000 Hz.

To these ends, an isolation case was created whereby all DUTs (in this case, zones of interest along the sensory fibers) were enclosed. A speaker was affixed to the isolation case, functioning as the vibration source. The speaker was then driven by a frequency generator, sweeping from 100 to 1,000 Hz at 100 Hz intervals. This design aspect helped isolate the DUTs from undesirable noise and enabled simultaneous exposure to stimuli.

The optical configuration for the experiment included a Fotech Helios®[ii] 3HSI DAS interrogator to generate DAS laser pulses, gather and analyze backscattered energy, a lead-in, telecom-grade G.657.A1 optical fiber of 983 meters.

Zone 1 - Typical FIMT - The lead-in fiber was fusion spliced to an AcoustiSens Wideband (G.657.A1 like waveguide) from meter mark 983 to 989.

Zone 2 - Typical FIMT - the AcoustiSens Wideband was spliced to a length of telecom-grade G.657.A1 fiber from meter mark 989 to 995.

Zone 3 - SonoSens - the telecom-grade fiber was spliced into a segment of AcoustiSens Wideband from meter mark 995 to 1,000.

Zone - 4 - SonoSens - the AcoustiSens Wideband was spliced to a length of telecom-grade G.657.A1 fiber from meter mark 1,000 to 1,005 to form the final zone.

The distal end of the final zone was then covered with index matching light absorption gel to eliminate the strong Fresnel reflection that would occur and could hamper test results. The image below depicts the test setup.

Frequency sweeps were conducted, exposing each combination of sensor fiber and FIMT to 100, 200, 300, 400, 500, 600, 700, 800, 900, and 1,000 Hz stimuli. As a function of the experimental design, each DUT was exposed to the stimuli and data recorded simultaneously. Doing so allowed for a more direct comparison of the DAS SNR response for each DUT. The following charts describe the observations: Chart A: DAS SNR telecom-grade single-mode sensor fibers in typical FIMT (solid, SS304, PA6 coating) and SonoSens (perforated, Alloy 825, PVC coating)

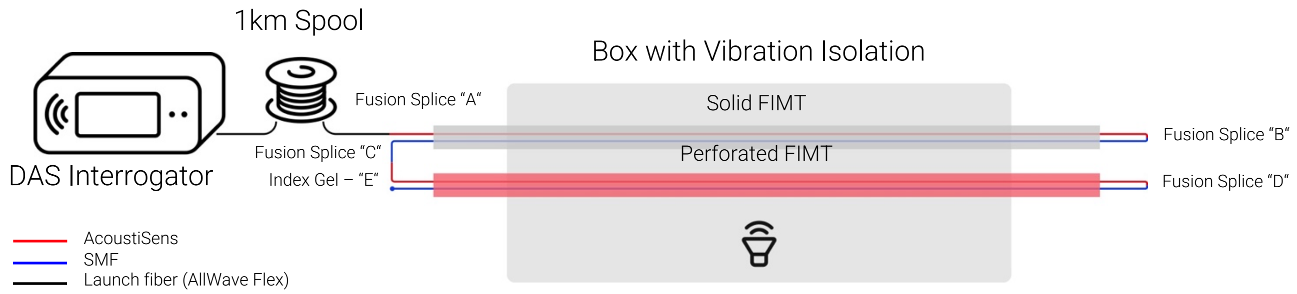

Figure 8

Telecom-grade fiber sensing: After applying a standardized SNR scale (Y-axis), when utilizing telecom-grade single-mode fibers for sensing, the SonoSens showed measurable SNR Improvement at all studied frequencies except for 400 Hz. This observation suggests a resonant frequency for the FIMT near 400 Hz.

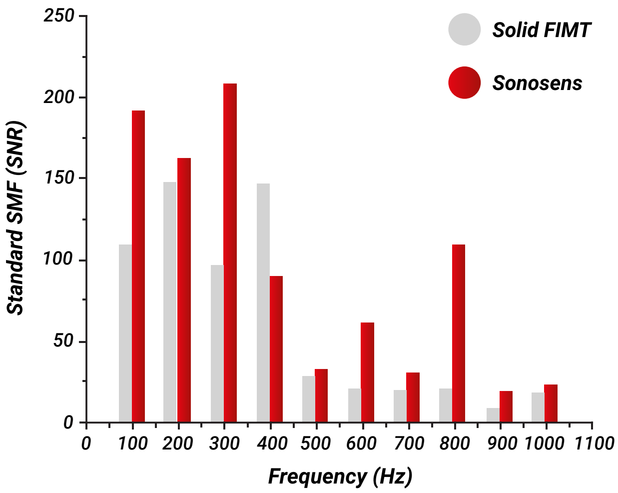

Figure 9

AcoustiSens fiber sensing: Again, using the same standardized SNR scale (Y-axis), when utilizing AcoustiSens enhanced Rayleigh backscatter fibers for sensing, in all measurements, the AcoustiSens shows significant SNR improvement. When combined with SonoSens, the SNR improvements exhibit additional SNR improvement at most tested frequencies. Notably, the response at 400 Hz favors typical solid FIMT construction. As with the telecom-grade comparison, this suggests a FIMT resonant frequency near 400 Hz.

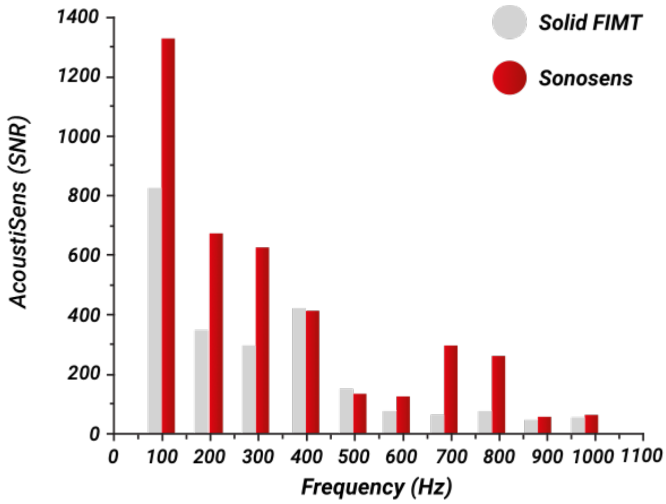

Figure 10

CONSIDERATION

The SonoSens FIMT in this paper is tested and evaluated in its first development stage and has shown significant improvement for acoustic transmission and is protected with a metallic fiber combination. The cable design will be further developed to provide a much higher mechanical resistance as well as the known acoustic performance from the first version. For this reason, additional cable components will be used, which will be aligned in a square and embedded in the outer polymer layer. Additional versions and publications of the SonoSens product will be published in subsequent papers.

EXECUTIVE SUMMARY

This paper covers two advanced DAS-enabling technologies: SonoSens and AcoustiSens. Its purpose is to examine and compare the performance of traditional FIMT with the SonoSens cable, each encapsulating telecom-grade single-mode telecommunications fiber and the AcoustiSens optical sensor fiber.

1. The NBG-developed SonoSens cable is designed for Distributed Acoustic Sensing (DAS) applications in mechanically and environmentally challenging installations; the precise engineering improves coupling by as much as 40% when compared to traditional FIMT cables.
2. OFS, a global leader in advanced optical fiber technologies, introduced AcoustiSens, a patented single-mode sensing product with a design that increases Rayleigh backscatter 10 to 15 dB.

The SonoSens cable's primary protection is provided by a metal tube made of Alloy 825 with an outer diameter of 2.30 mm (0.09") and a wall thickness of 0.20 mm (0.008"). Alloy 825 has a low-tension hysteresis while providing high tensile strength. The key to maximizing the acoustic energy transfer onto the fiber is the modified FIMT construction. NBG's R&D team designed the FIMT with elliptical holes at specific intervals to provide the best combination of mechanical strength and acoustic coupling. The data within this paper was created using the following Devices Under Test (DUTs) to:

A. Invoke identical vibrational stimuli.
B. Expose and record effects simultaneously from each DUT.
C. Strive for isolation of the DUTs from external vibrations.
D. Explore several vibrational frequencies in a band of interest from 100 to 1,000 Hz.

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[i] AcoustiSens® is a registered trademark of OFS
[ii] Helios® is a registered trademark of Fotech Technologies, a Launchpad company from BP