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THE ENVIRONMENTAL SCANNING ELECTRON MICROSCOPE (ESEM) - THEORY AND APPLICATIONS

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ABSTRACT

The environmental scanning electron microscope (ESEM) allows direct observation of specimens in their natural state, without the need for elaborate sample preparation techniques. Recent technical developments allow the detection of various signals generated by the specimen, such as secondary and backscattered electrons, cathodoluminescence, and x-rays. Images are formed from these signals, either from individual signals (backscattered electron image) or from combinations of signals (secondary and backscattered electron images). X-ray microanalysis (energy-dispersive and wavelength-dispersive) is possible, but there is a definite loss of spatial resolution, increasing with higher pressures in the specimen chamber due to interactions between the beam, the gas, and the specimen-generated signals.

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MICROSCOPE ELECTRONIQUE A BALAYAGE ENVIRONNEMENTAL THEORIE ET APPLICATIONS

par

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RESUME

Le microscope électronique à balayage environnemental permet l'observation directe d'échantillons à l'état naturel sans préparation complexe. Des développements techniques récents permettent la détection de divers signaux émis par l'échantillon, tels que les électrons secondaires et rétrodiffusés, cathodoluminescence et rayons x. Les images sont formées par ces signaux, soit à partir de signaux individuels (électrons rétrodiffusés) ou à partir de combinaisons de signaux (électrons secondaires et rétrodiffusés). La microanalyse de rayons x (en fonction de l'énergie ou de la longueur d'onde) est possible, mais il y a une nette perte de résolution spatiale augmentant en fonction de la pression, due à des interactions entre le faisceau d'électrons, le gaz et les signaux émis par l'échantillon.

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INTRODUCTION

The environmental scanning electron microscope (ESEM) was developed to fill a need to observe samples in their natural state, without artifacts or modifications introduced by sample preparation; the ESEM allows such direct observation of wet, dry, conductive, or insulator specimens (1). Sample preparation is therefore reduced, but the optimal operating conditions needed to maintain a specimen in its natural state can vary tremendously and therefore affect final interpretations.

New ESEMs allow heating or cooling of the specimen, microinjection of liquids, and specimen manipulation. Real-time video processing is also needed to maintain a useable signal-to-noise ratio of the image (1). Dynamic experiments may be performed and controlled in the ESEM, which is not possible in the traditional scanning electron microscope (SEM). Some of the specifications of the ESEM are listed in Table 1. The ESEM uses a lanthanum hexaboride (LaB_6) electron source, both to reduce the effects of beam scattering and to increase the resolution.

The ESEM evolved from the SEM, modified such that gas may be introduced, and the pressures in separate zones may be controlled by differential pumping (1, 2). The ESEM has two different vacuum regions, the first for the generation and focusing of the electron beam (pressure $<10^{-2}$ Pa), and the second, a region of high pressure (>609 Pa); the regions are separated by small apertures that restrict the flow of gas (3). A minimum of two apertures (Fig. 1, 2) is needed to control the pressure in the electron optics column, and their sizes and positions play a crucial role in ESEM operation. Gas flowing through the first pressure-limiting aperture (PLA1, Fig. 2) is pumped out and only a small

amount of gas leaks through the second pressure-limiting aperture (PLA2, Fig. 2) in the column. The required low vacuum in the column is maintained by the usual pumping means (diffusion and rotary pumps), while the desired pressure in the specimen chamber is maintained by a turbomolecular pump and valves (Fig. 2). Depending on the optics design, PLA2 may coincide with the objective lens aperture.

The specimen chamber of the ESEM is filled with gas, the most commonly used being water vapour, nitrogen, argon, and helium (oxygen, methane, acetone, and xylene may also be used). The role of the gas in the specimen chamber is to maintain a certain level of pressure necessary to retain certain properties of the specimen (e.g., to maintain a liquid phase or to allow a particular reaction). The gas becomes ionized and thus a good electrical conductor, which enables the imaging of insulators without pretreatments. The focused electron beam entering the specimen chamber is rapidly defocused due to collisions with the gas molecules; however, a useable beam survives for some distance. The specimen must be placed within this short distance, and hence the short working distance required by the ESEM. Various detectors may also be positioned in this restricted space to detect the emerging signals (Fig. 3).

Advantages of the ESEM include the basic features of the SEM (resolution, depth of focus, variety of signals, and signal manipulation) plus the advantage that the specimens may be insulators or semiconductive and require no coating, regardless of the accelerating voltage. Observations of gas-liquid-solid systems are also possible, and the ESEM can operate either in the presence or absence of gas.

DEVELOPMENT

Only a short review of the historical developments of the ESEM will be given here, as a complete review is beyond the scope of this paper. The first developments in environmental electron microscopy were mainly related to transmission electron microscopy, but Robinson (4) and Robinson and Robinson (5) suggested the use of an SEM environmental cell, where the presence of residual gas would eliminate charging artifacts. The first attempts to introduce gas in the electron microscope were made by Ardenne and Beisher (6). The first observations of hydrated specimens were reported by Abrams and McBain (7). More comprehensive reviews can be found in (8) and (9). Danilatos and Postle reviewed the more recent developments of the ESEM (10).

Several new developments were needed to make the ESEM possible; both theoretical and practical considerations had to be overcome first, and known detection systems had to be modified. More complete discussions of theoretical considerations and experimental findings may be found in (10) and (3).

THEORY AND DESIGN

The presence of gas filling the ESEM specimen chamber introduces a variety of new concepts and considerations related to pressure and gas flow that will not be addressed here; however, the reader is referred to (3) and (11) for detailed reviews of these mathematical considerations.

INTERACTIONS

Similar interactions occur both in the SEM and ESEM, such as the primary electrons undergoing elastic or inelastic collisions which result in the generation of secondary electrons (SE), backscattered electrons (BSE), and x-rays, leading to specimen changes such as molecular scission or cross-linking, and atom dislocation. However, in the ESEM, there are four interacting entities: electron beam, gas, specimen, and signals. Six types of interactions occur: 1- beam-gas, 2- beam-specimen, 3- specimen-signal, 4- signal-gas, 5- gas-specimen, and 6- beam-signal.

Beam-Gas Interactions

These interactions result in scattering of the beam, signal generation (SE, BSE, x-rays, cathodoluminescence (CL)), and modification of the gas through the creation of positive or negative ions, dissociation products, and excited molecules and atoms. The overall performance of the ESEM depends on the extent of beam scattering, since this determines the limits of contrast and resolution, which, in the ESEM, are affected by the presence of gas. The signals generated by the primary beam in the gas add a constant level of noise to the corresponding signals from the specimen. The degree of alteration of the neutral gas may affect the role of the gas as an environmental conditioning medium (3).

Beam-Specimen Interactions

Beam-specimen interactions result in beam scattering (defining the interaction volume), signal generation, and modification of the nature of the specimen (beam irradiation effects). Theories developed for the SEM can also be applied to the ESEM,

but must account for the added effects of a liquid or gas phase in the chamber.

Specimen-Signal Interactions

These interactions result mainly in signal modification and to a lesser extent in specimen modification. For example, a charging surface may affect the SE signal, and topographic features may influence the BSE signal; the x-rays may affect the specimen itself.

Signal-Gas Interactions

The signal-gas interactions result in mutual modification of both the signal and the gas. The presence of gas creates a whole range of new considerations and possibilities. Danilatos introduced the concept of using the gas as a detection medium (current mode - images are based on current variations measured on collecting electrodes) as well as an environmental conditioning medium (12). The gas modifies the various signals to different degrees, limiting the applicability of conventional detectors, which must either be modified or totally redesigned. The signals modify the gas much like the primary beam, but over much larger areas. The signal-gas and the beam-gas interactions have different energies and spatial distributions, which makes it possible to separate the two effects.

Gas-Specimen Interactions

These include general physicochemical reactions; these may be modified by products from the beam-gas and signal-gas interactions, or new reactions may be created that could affect the overall performance of the ESEM.

Beam-Signal Interactions

The primary beam could indirectly affect the signals through interactions with the

gas (additional background noise); however, it is unknown at this point whether the specimen signals could similarly indirectly modify the beam.

ELECTRON BEAM PROFILE

The electron distribution of the focused beam below PLA1 is modified relative to that in a vacuum by the introduction of gas in the specimen chamber. This new distribution resulting from collisions between the electrons and gas molecules or atoms must be known in order to establish various parameters such as the beam interaction volume in gas (scattering cross section, number of collisions, shape, mean free path, electron loss), the beam diameter at different pressures, and the effects on the gas itself (ionization, energy loss, excitation, deexcitation, etc.), as well as on the specimen. All these parameters may ultimately affect the contrast and resolution, but can also greatly influence the design of new detector systems or the modification of conventional ones. A detailed discussion of the associated mathematical considerations can be found in (3) and (11).

SIGNAL DETECTION

The same signals that occur in the SEM operating in vacuum are encountered in the ESEM: BSE, SE, cathodoluminescence (CL), x-rays, etc. Due to the presence of gas and/or due to geometrical restrictions imposed by the short working distance (specimen distance from PLA1), specific detectors may need special modifications or new designs.

Backscattered Electrons (BSE)

Wide-angle scintillator BSE detectors were first used, until several new geometries

became available. BSE can travel several millimetres through gas without losing much energy; the gas therefore does not seem to limit operation of the BSE detection principle, but the detectors must be designed specifically for the ESEM. The difficulty arises in positioning the detectors close to both PLA1 and the specimen (Fig. 2, 3), without decreasing their efficiency. For example, two symmetrical BSE detectors may be used to allow the addition and subtraction of signals for topographic or atomic number contrast, as in other SEMs. For operation at higher pressures, the specimen must be even closer to PLA1 (<1 mm); above a particular pressure, the detectors should be placed above PLA1 (which makes possible imaging at pressures up to 1 atm) (3). Solid-state detectors can also be used with gas. Detection of BSE was the predominant detection mode until new SE detectors were designed (13).

Secondary Electrons (SE)

Initially, images of wet specimens were obtained by injecting a jet of water vapour on the specimen surface, and simultaneously pumping away the diffusing vapour cloud. A steady-state gas density was maintained immediately above the specimen, the pressure decaying rapidly with distance. Associated problems included a low maximum pressure and the difficulty in achieving and controlling the desired environment. The collected signal was also higher in a gas than in a normal SEM vacuum; this was attributed to extra secondary electrons created by collisions of the primary electrons and the gas. Unknown pressure variations in the gas cloud also led to difficulties in assessing the relative contributions of various signals. In new ESEMs, the environmental conditions are easier to control and modify, but the relative contribution of the various components of the signal

are still not known; however, it appears that SE are a major component (2). Various collecting electrode configurations allow the separate detection of SE and BSE, based on the signal induction principle but the images usually show a combination of both SE and BSE signals (14). The development of an environmental secondary imaging detector (ESD) allowed the acquisition of high-resolution images at ESEM pressures (1). This detector uses gas ionization phenomena to detect signal electrons; the collisions between the secondary electrons and neutral molecules result in a collision cascade, where more electrons are produced, leading to an increase in the secondary electron signal (Fig. 3) (2, 15, 16). The slow-moving positive ions formed in the collision process effectively neutralize any surface charging on the sample. The ESD is insensitive to light; this allows the study of light-emitting samples, which is not possible with a regular SEM SE detector. Laser or UV illumination may also be used while imaging (16).

Cathodoluminescence (CL)

Detection of the cathodoluminescence (CL) signal is possible in the ESEM (17); some BSE detectors can be used for that purpose by removing the plastic scintillator coating, so that the clear acrylic plastic can collect and transmit the CL signal from the specimen (13, 3).

X-rays

X-ray analysis of liquids by scanning electron microprobe was first achieved using window cells (liquid placed in a small cavity on top of a specimen stub, covered by an electron transparent film). X-ray detection is possible in the ESEM, with both energy-dispersive and wavelength-dispersive spectrometers (17). However, several factors will

affect microanalysis in the ESEM. The loss of x-ray spatial resolution caused by electron scattering is the most important (18).

Auger Electrons

The detection of Auger electrons require ultra-high vacuum, which is incompatible with the presence of gas, making the ESEM unsuitable for this purpose.

Multipurpose Gaseous Detector Device

Danilatos suggested that the gas itself may be used as a detection medium for various signals; this is mainly based on signal-gas interactions, where the ionization produced by some signals may be used for the detection of these same signals; the excitation of the gas is then measured (12, 13, 3). The efficiency of this gaseous detector device depends on several variables such as the nature, pressure, and temperature of the gas, electrode bias and configuration, accelerating voltage, intensity of the primary beam current, scanning speed, and nature of the specimen (12). As a general rule, with the proper collecting electrode configuration, this gaseous detector device produces an SE image in the lower pressure range, and a BSE image in the higher pressure range (13, 14). Three types of interactions are of particular interest: ionization, imaging (new variations on images by changing some parameters such as bias, pressure, and position of the collecting electrode), and excitation (fluorescence of the gas).

CONTRAST AND RESOLUTION

The contrast and resolution both depend on the primary beam, the specimen, and the detection system. The limit of resolution (resolving power) of the SEM is about equal to the beam diameter. In the ESEM, under conditions where there are few collisions in

the gas, there is no broadening of the original beam; it weakens and acquires an electron skirt (3, 11). The limit of resolution of the ESEM is therefore similar to that of the SEM, if the gas pressure is not too high, the beam irradiation effects are not too severe, there is sufficient contrast, and the beam-specimen interaction volume is not wider than the beam diameter. Under different conditions, the resolving power of the ESEM is not as good as that of the SEM, but can be restored to the original resolution if the pressure and the specimen distance can be adjusted so the electron skirt coincides with the beam-specimen interaction volume (3, 11). In x-ray microanalysis, the beam-specimen interaction volume determines the resolution.

The resolution should also be considered in conjunction with the contrast; the signal-to-noise ratio (S/N) should be estimated to determine whether a particular feature is visible at all; the mean free path, current, and pressure are used to calculate the increase in current required for different pressures, assuming one mean-free-path distance (3). The loss of resolution with increasing pressure is due to a loss of visibility due to noise; local variations in depth correspond to differences in the S/N.

In an ESEM, the contrast and resolution can be maintained, provided the beam current is increased by a certain amount; the resolution is governed by the spot size corresponding to the increased current; however, this increase may cause undesirable beam irradiation effects which can then affect the contrast and resolution.

BEAM IRRADIATION EFFECTS

The deterioration of the S/N with beam irradiation effects is one of the most serious difficulties in the ESEM. In the case of specimens unaffected by beam radiation, an

appropriate increase in beam current can compensate for the noise, but the resolving power will be affected. Irradiation effects may still be the limiting factor. The lowest current and accelerating voltage possible should thus be used.

Beam irradiation effects include all effects, whether damaging or not; they include charging, heating, contamination, and damage to the specimen (atom dislocation, loss of crystallinity), cross-linking, mass loss, etching, or general chemical reactions. These effects are common in all types of microscopy, but the gas may modify them, or create new ones.

Charging

Charging (local concentration of electrons, shown as image distortion, flickering, or edge brightness) is not a problem in the ESEM; all kinds of specimens may be examined, even uncoated and untreated insulators. Charging in the SEM is lowered or suppressed by using a low accelerating voltage; in the ESEM, the charging artifacts are suppressed because the ions generated in the gas by the electrons migrate to the surface and neutralize surface charges (18). A few tens of Pa pressure is usually sufficient, but the pressure level is variable, dependent on the application. A satisfactory image is achieved by a combination of pressure and accelerating voltage. Various methods have been used to determine the level of surface charging and its suppression in the ESEM during various applications (see 3).

Contamination

Contamination is almost always present, usually from residual hydrocarbon gases in the specimen chamber, or from specimens not properly prepared. Danilatos reported

that contamination was not a problem with most of the applications undertaken, but was when using the lowest possible accelerating voltage and current, at relatively low magnifications (3). He did, however, report that the surface properties of liquids may be affected; for example, a thin crust was occasionally observed to form on the surface of water for reasons unknown. Several other unexpected strange phenomena were observed, but not documented fully.

Damage

Several types of beam damage may be observed on the specimens: cutting, etching, pitting, creasing, bubbling, and mass loss from within (3). Those were observed after long exposure times (10-30 minutes), but may appear in a relatively short period of time, and seem to be dependent on the type of gas. Beam radiation effects can also affect the contrast and resolution adversely, leading to a poorer image quality.

APPLICATIONS

The following section reviews various types of applications to very different fields of interest, concentrating on materials and physical sciences; a brief mention of biological applications is included.

PETROLEUM TECHNOLOGY

The ESEM can be used in petroleum technology to characterize reservoir rocks, to understand the processes that control rock petrophysical properties, and diagenesis. Dry or oil-bearing core samples can be observed, and maintained in a dry, wet, or water-

flooded state. Applications range from in situ water flooding, to matrix acidizing, to smectite hydration, to cement hydration and curing studies (19).

Water-flooding studies are designed to test the presence of residual oil and the migration of clays to block pores under specific flooding conditions; to do preliminary assessments of the effect of swelling clays on rock porosity and permeability; and to obtain information on individual mineral wettability and oil saturation, leading to a better evaluation of laboratory oil-water relative permeability measurements.

Matrix acidizing studies are done to assess formation damage, where pore blocking materials such as rock cements, fines, and clay minerals may have to be dissolved. Rock minerals dissolve preferentially in acids, leading to the gradual removal of specific minerals (e.g., feldspars) and to the creation of porous substructures. A better choice of acid mixtures may lead to a more selective dissolution of the problem materials or minerals.

Smectite hydration studies are done to better define the effects of water on swelling clays in rock, which may lead to improved porosity estimates under wet reservoir conditions.

Cement hydration and curing studies are done to observe microstructural changes in the dry cement particles as water is added, and to better define the reaction products. These studies may lead to the design of new acid-resistant cement blends (19).

CEMENTS

Preliminary studies of the hydration of cement pastes (Portland cement and model

tri-calcium silicate, C_3S) were undertaken by Sujata et al. (20). Their results show that the hydration of cement produces a microstructure that is sensitive to moisture content in both types of cements. The C_3S reacts with water to produce an amorphous compound (nonstoichiometric calcium silicate hydrate, C-S-H) and calcium hydroxide (CH). Shortly after mixing water and C_3S (8 hours), an amorphous coating of C-S-H formed on the surface of the grains, which were not highly interconnected. After 16 hours, the grains were completely covered with the hydration product and connected. Ordinary Portland cement grains were slowly hydrated in the ESEM; a C-S-H layer formed on the surface within the first half hour after mixing, similar to the C_3S case. In both cases, the amorphous layer (C-S-H) was easily observed in the ESEM, but may have been damaged in previous observations in an SEM at high vacuum.

There are further applications in various industries including pulp and paper, ceramic materials, superconductors, semiconductors (topographic contrast and metrological applications (21)), metallurgy (in-situ oxidation studies (22, 23)) forensic science, agriculture, chemistry, and biology (1). Doehne & Stulik reported a wide range of uses for the ESEM in conservation science, from the study of deterioration mechanisms (dynamic study of wetting and drying of adobe samples, semi-dynamic study of lead corrosion as a result of exposure to formaldehyde), material treatments, and ancient materials and technologies (imaging of outgassing samples (parchment), swabs from the Sistine Chapel cleaning, x-ray analysis of gold and garnet jewelry) (16). The ESEM can also be used for studies of insulators such as dynamic in situ fracture studies,

ice, powders, and polymer adhesion (2).

BIOFILMS

An evaluation of the artifacts introduced during SEM preparation of biofilms was reported by Little et al. (24). Biofilms are typically monolayers of bacterial cells found on a large variety of engineering materials placed in biologically active liquids, and have been defined through SEM observations. They are used in several diverse applications, such as removing dissolved and particulate contaminants in fixed-film biological systems (e.g., trickling filters, fluidized bed wastewater treatment plants); they also determine water quality by influencing the dissolved oxygen content, and may serve as a sink for toxic and/or hazardous materials. The microorganisms within biofilms can be used to recover minerals and to remove sulphur from coal. Biofilms can also form undesirable deposits reducing heat transfer, increasing fluid frictional resistance, and causing plugging and corrosion.

Historically, the SEM sample preparation involved extensive manipulation, including fixation, dehydration, air-drying, or critical-point drying in a long series of handling steps. ESEM allows for the examination of wet biofilms, eliminating most of these manipulation steps, except for fixation. Comparing wet biofilms and biofilms that went gradually through the steps for SEM preparation showed that the latter modifies the original biofilm extensively, by removing some of the biological material (e.g., diatoms) and reducing the areal coverage of the biofilm. ESEM also showed that the bacteria are not found in a monolayer, but are distributed in layers throughout the biofilm and corrosion layers. Their numbers were also underestimated by traditional SEM sample preparation techniques.

LIVING MATERIALS

Danilatos reported the observation of seedlings and cross sections of the stems of various plants, in a fresh or living state (25, 3). He showed that live specimens can be observed at various stages of their growth, survive the ESEM operating conditions, and continue growing when returned to their natural environment. Beam irradiation effects depend on the age and portion of the sample observed. Embryos were sensitive; leaf cells seemed more resistant than stem or root cells. However, beam irradiation effects increase rapidly with increasing beam current or imaging time.

LIMITATIONS

The most serious limitation of the ESEM resides in microanalysis. Several problems are created when the electron beam enters the specimen chamber and interacts with the gas: degradation of x-ray spatial resolution due to scattered electrons, changes in beam current with pressure and working distance, low-energy noise caused by cathodoluminescence from the gas (13), low-energy x-ray absorption through ice deposits on the detector, and occasional degradation of window and seal materials by the gas environment (18). Beam scattering increases very fast with increasing pressure; for example, at 3 torr (0.40 kPa; water pressure, 30 kV, 15 mm working distance), 45% of the beam may be scattered beyond 25 μm, and 66% at 5 torr (0.67 kPa). Bolon suggested a background spectrum subtraction procedure to address this problem (18).

Several parameters contribute to the image quality and optimization, such as the gas, the gas pressure, the accelerating voltage, and the working distance. The relation

between gas pressure and working distance is very important for image optimization: the higher the pressure, the closer to the PLA the sample must be, thereby requiring a high accuracy in positioning the sample (16). Image optimization may require extensive experimentation with the type of gas or gas combinations, the pressure, the accelerating voltage, and the beam current.

Beam irradiation effects are still present in the ESEM and may affect the resolution. Some of the effects may effectively be suppressed by the presence of gas (charging), or be reduced by using low beam currents and accelerating voltages (contamination and specimen beam damage), but the gas may create new effects which must be recognized and accounted for.

Secondary electron emission in the ESEM is a function of the target material, the topography, the components absorbed on the target surface, and the environmental conditions in the specimen chamber. To avoid a decrease of the spatial resolution from electron beam scattering (on gas molecules), the working distance is limited at ~8-10 mm at 250 Pa, and is even more restricted at higher pressures. This also limits imaging of samples with a large depth of focus. Because of the short working distance and the diameter of the PLAs, the minimum magnification is ~100-200X.

CONCLUSIONS

The environmental scanning electron microscope (ESEM) allows the direct observation of a variety of specimens (liquids or dry, conductive or insulator samples) at relatively high pressures, in their natural state, without artifacts or modifications introduced

by sample preparation techniques. The ESEM may be used in a wide range of application fields, such as the petroleum industry, the superconductor industry, forensic science, and biology (including live specimens).

Recent developments now allow the detection of the same signals as are commonly used in traditional scanning electron microscopy (SEM): secondary electrons, backscattered electrons, and x-rays. The x-ray spatial resolution is affected by the presence of gas, thereby limiting microanalysis; this effect increases with higher pressures.

Image quality depends mainly on the pressure, the accelerating voltage, and the working distance. New potential beam irradiation effects due to the presence of and interactions with the gas must be recognized and accounted for. Careful experimentation is needed to realize the full potential of this new instrument.

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Table 1 - Operating conditions and performance - Comparison of SEM and ESEM (16)

Operating conditions	Conventional SEM	Environmental SEM
Imaging modes:	Secondary Electrons (ET) Backscattered Electrons	Secondary Electrons (ESD) Backscattered Electrons
Working Distance:	6-40 mm	6-15 mm, resolution limited by beam scattering in gas
Accelerating voltage:	1-30 kV, normally 20 kV	1-30 kV, normally 20 kV
Vacuum Conditions:	10^{-5} to 10^{-3} Pa High vacuum	10^{-4} to 0.9 kPa Normally 10-250 Pa. Atmospheric pressure is 100 kPa. The imaging gas is usually water vapor, but air, helium, oxygen and nitrogen can also be used.
Magnification:	10 to 100,000 times	70 to 100,000 times
Resolution:	1.8 to 6.0 nm, usually 4.5 nm	7 or 5 nm
Sample Requirement:	Compatible with high vacuum Dry and conductive samples only	Any sample type (including liquids, solids, powders, and insulators) plus dynamic reactions.
Sample exchange time:	3-5 minutes	30-60 seconds
Approximate Cost:	$65,000-250,000*	$179,000-250,000*

*Depending on resolution and configuration

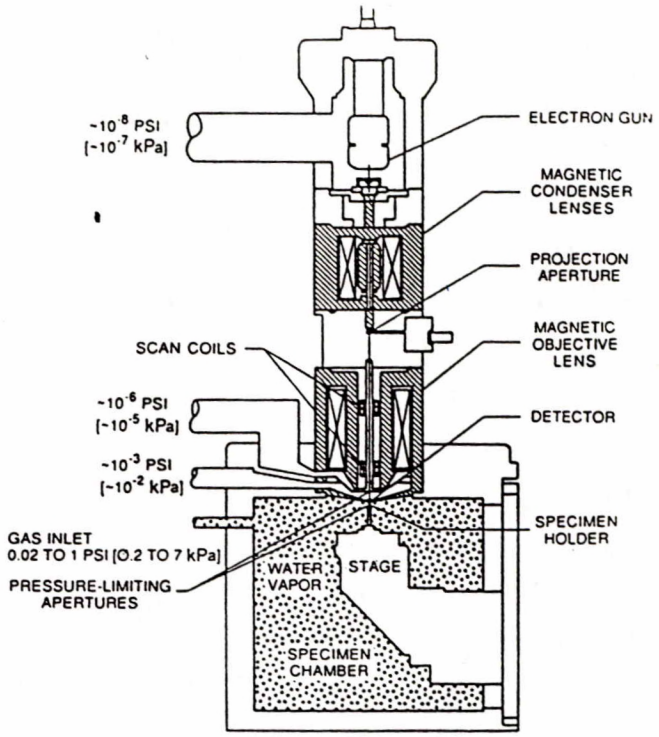

Fig. 1 - Diagram of an environmental scanning electron microscope (ESEM) showing the various pressure zones and the pressure limiting apertures (19)

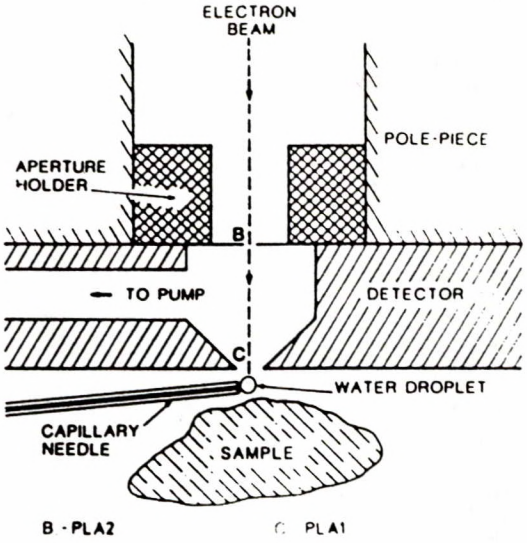

Fig. 2 - Diagram of the area containing the pressure-limiting apertures (PLA1, 2) and their positions relative to the specimen and the detector (3). A microinjector for liquids is also shown (capillary needle).

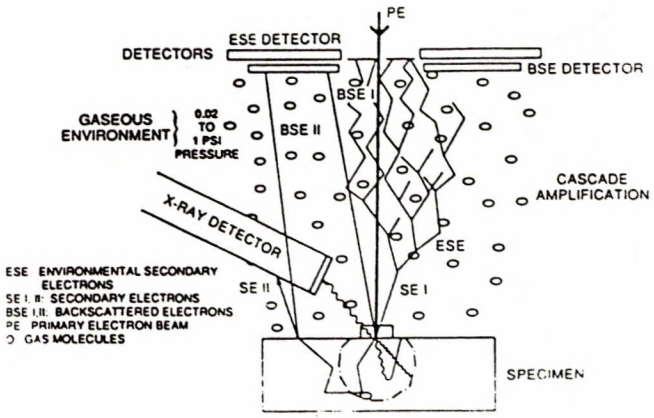

Fig. 3 - Schematic diagram of signal generation and detection in the ESEM ((19), not to scale).