PORTABLE NUCLEONICS INSTRUMENT DESIGN — THE PORTACAT EXAMPLE

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Abstract

Portable nucleonic gauges prototypes are designed and manufactured in New Zealand for niche applications. Considerable development in hardware and software provide new opportunity in design of relatively low cost portable nucleonic gauges. In this paper are illustrated principles, and specific factors to be consider when designing portable nucleonic instrumentation, using an example called PortaCAT, which is a portable computed tomography scanner designed for imaging wooden power poles.

1. INTRODUCTION

The penetrating properties of radiation present unique opportunities for measurement applications in industry. However, in addition to the high costs associated with the sources and radiation detectors, there is general public concern with safety issues. While much of this concern is irrational, there are three principles by which potential radiation applications should be judged: justification, optimisation, and limitation. Clearly, if alternative techniques are available, then the continued use of radiation must be justified by the unique benefits it delivers. Safety must be assured. Given that justification, the particular form of radiation to be used must be selected to enhance measurement of the required property. For instance, with a density measurement using attenuation of gamma or X rays, this means choosing the energy which gives the necessary penetration, but which also has sufficient loss to be sensitive to density changes. The third principle is to limit the amount of radiation necessary to make the measurement. Obviously, the last two principles are not necessarily independent.

The high costs of nucleonic instrumentation also partly arise from safety considerations. For instance, radioisotopic sources should be in *special form*, and encapsulated in appropriate safety enclosures. Design and use are subject to regulatory authority approval. Considerable development has occurred in radiation detectors, providing new opportunities in applications. However, these are not consumer items, and the combination of development and production costs means that they are relatively expensive.

In general, the principles underpinning nucleonic gauge applications have been long-established. It is the new detectors coupled with modern electronics and computers that continue to make new applications feasible. Although feasibility may be assured, unless industrial end-users are prepared to pay for the final product, there is little point in investing further development costs. It is increasingly important that the relevance of the research is established from the outset, and a way of showing this is through market analysis, and demonstration of the potential cost-benefits that would evolve through adoption of the new instrumentation.

2. THE POLE INDUSTRY

2.1. Cost benefits

Many countries have extensive overhead power distribution, and the supporting poles represent a large capital investment made by an electrical supply authority. In New Zealand, total replacement costs currently average about $US750 per pole. Throughout Australia, there are about eight million wooden poles in service. The expected lifetime of each is about 30 years. There are considerable savings to be made by lifetime extension. If, through better techniques, pole replacement can be delayed, and average lifetime extended by 5 years, there are potential annual savings of $US29 million in Australia. The other aspect is sudden pole failure. This can be as a result of various means, particularly fungal or termite attack in the critical zone (about ground level). Although infrequent, consequences can be dire, and linesmen have been fatally injured carrying out maintenance on defective poles. The collapse of a pole can also lead to unexpected power outages.

2.2 Required performance for an NDE pole technique

A pole must withstand the forces applied to it by the power lines it supports. A successful technique for pole NDE needs to provide an accurate estimation of the available bending moment of the pole about the critical zone. This depends on the type of timber, and its distribution within the cross section of the pole. Defects, such as rot or cracks, may not necessarily detract from the strength of pole provided that they remain central or limited. Clearly, cross sectional imaging is to be preferred over spot measurements obtained by drilling. However, the imaging device would have to be quick, cost-effective and reliable in pole assessment; it should be non-destructive; be able to be used safely on public streets, as well as cross country; require only one person to operate; and not need a graduate engineer to use, and interpret the results.

3. COMPUTED TOMOGRAPHY

3.1. Principles

Computed tomography (CT) is a standard technique developed in the 1970s for body imaging in the medical field. It is a combination of numerous radiation (normally X ray) transmission measurements from which a cross sectional image can be reconstructed. If the object to be scanned is fixed, then the source and detector must translate and revolve around the object. The geometry applicable to first generation CT scanners is illustrated in fig. 2 which shows parallel line integrals of X ray attenuation ("ray sums") at three different angular steps ("projections"). Standard methods are available for image reconstruction from this data [9,11,12,13,14].

A variety of applications of CT to industrial inspections have been reported, but these have mostly been done on borrowed medical scanners, or laboratory set-ups, as demonstrations [1-7]. The inverse procedure, meaning that the scanner visits the "patient" at an industrial site, has proved difficult to implement. The very few exceptions to this have generally required a vehicle to transport the scanner and ancillary equipment, and cannot be regarded as truly portable. An understanding of the difficulties in applying industrial CT scanning can be gained by consideration of the CT triangle (Fig. 1). CT is governed by three interdependent factors: spatial resolution, contrast or density discrimination, and scanning time. Any gain in one or two of the factors results in a loss in the others. Hence a performance trade-off always applies. Medical CT scanners maintain good image resolutions and short scan times by using multiple detectors and high X ray fluxes. They are large, fixed instruments. To achieve similar performance with a transportable instrument would grossly limit its utility and cost-effectiveness. Furthermore, plant engineers ever conscious of costs, and can generally fall back on traditional "maintenance by replacement" practices.

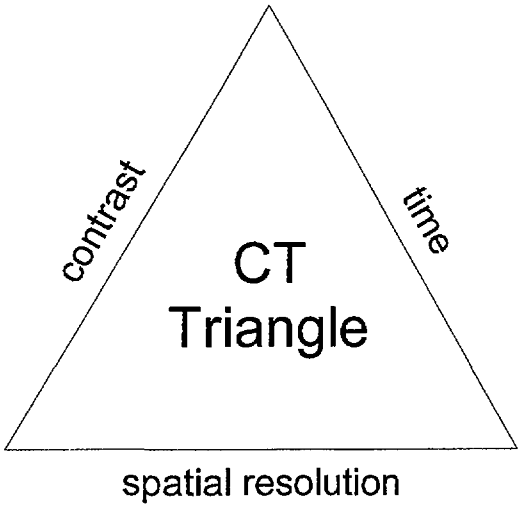


Figure 1: The CT triangle.

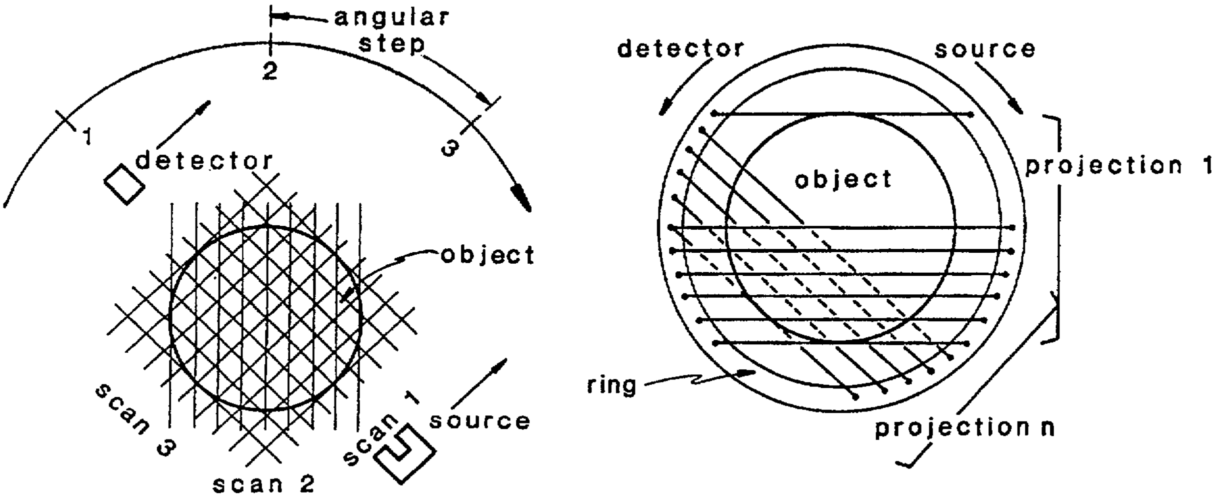


FIGURE 2: Conventional, first generation CT scanning (left) and portaCAT scanning (right).

3.2. PortaCAT CT

A prototype portable CT scanner for poles was first reported by Miller [8], and PortaCAT is a development from this. To minimise the space required around the pole, a circular scanning motion is used. While similar to the fan-beam geometry used by medical scanners, it differs in that the source and detector rotate about the centre of the object, rather than the detector moving at a constant radius about the source.

In practical terms, an X ray tube and power supplies are too bulky to satisfy the requirement for a truly portable scanner. Therefore, a radioisotopic source of X rays is indicated. Although the 60 keV is somewhat lower energy that optimum [10], the ^{241}Am emission has sufficient penetration through 300mm dry wood to be suitable. Because the source output is greatly inferior to a tube, the resolution was compromised to maintain a reasonable data acquisition time. A minimum image pixel size of 10mm for 300mm pole diameter (15mm for 450mm) was decided upon. The number of ray sums required for each projection is n = 31. As the image region is circular, a total of $pn^2/4$ or 755 non-zero density values are required. This implies 755 independent measurements, so that the number of projections necessary is m = pn/4 or 25. The projections must cover 180°, giving a separation of 7.2°. Clearly, automated data acquisition was essential for acceptable performance.

4. PORTACAT DESIGN

Portability places additional demands on nucleonic equipment design. Radiation shielding must be adequate for the environment in which the instrument is expected to work. Intrinsic safety features must be adopted if working in hazardous areas. If equipment is exposed to marine or other corrosive environments, fabrication materials should be selected for compatible electrochemical properties. Battery operation of electronics demands low power consumption. Both internal and external electronics plugs/sockets should be minimised for reliable field operation. Ergonomics should be incorporated in equipment design — ease of use aids efficiency and eliminates potential human errors. And with routine operations, data processing and presentation should be sufficiently advanced to allow ordinary inspection staff to make correct judgements on site. Most of these factors have been incorporated in the design of PortaCAT. It is packaged as two handheld units, scanner and electronics, powered by a 12 V, 7 Ah battery. A schematic of its components is shown in Figure 3.

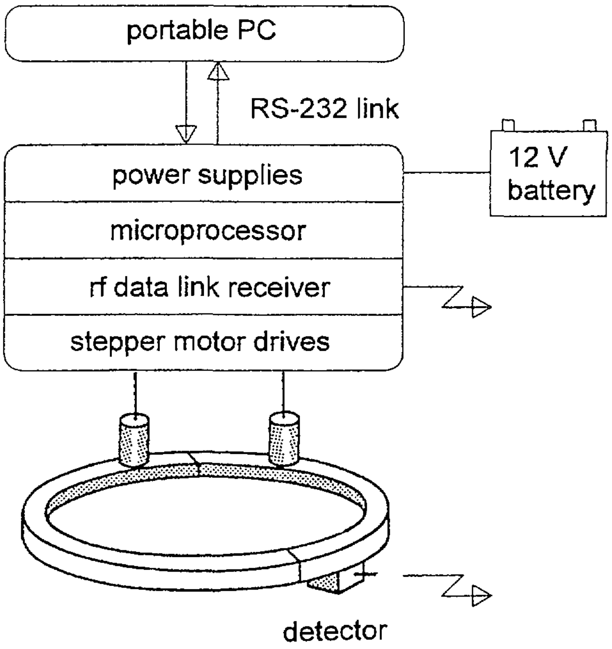


Figure 3: Schematic of the PortaCAT components.

4.1. Mechanical design of the scanner

Concern for the ease of operator action in using the instrument pervades the design of the scanner component parts. Source and detector are mounted on separate split rings, individually driven by sprocket wheels meshing onto gear chains. Movement of the rings is obtained by step motors, geared to give a positioning accuracy of 0.1°. The ends of the rings engage through ball-socket joints, and the outer surfaces are automatically thrust against idler bushings. Precision fabrication is required for reliable operation. Minimising the moving masses of source and detector is important for speed, and well as power consumption. Up to half of the time scanning is spent simply repositioning to take the next measurement. The aluminium housing containing the rings is split and hinged to allow the scanner to be quickly wrapped around the pole. Source and detector rings have physical home positions enabling accurate repositioning. A scanner for 300mm diameter objects needs an external clearance of 440 mm; 450 mm diameter needs 680mm clear. Neglecting motors and clamps, the thickness of the scanner is about 100mm

A key time saving factor is in the attachment of the scanner to a pole (Fig. 4). The split housing is held together by one clasp, and the housing is automatically centred on the pole using pairs of geared arms. These are held to the centre of the scanner by spring-tensioned 50mm fabric belts, and are spread as the housing envelops the pole. A ratchet engages when the housing is closed up, and the belts are then tensioned by hand to stop the scanner slipping down the pole. The result of this design is that PortaCAT can be attached to a pole by one person, and be ready to start in seconds. The alignment of the image in relation to scanning is marked on the housing. This is important for correlating line load with later calculation of bending moments.

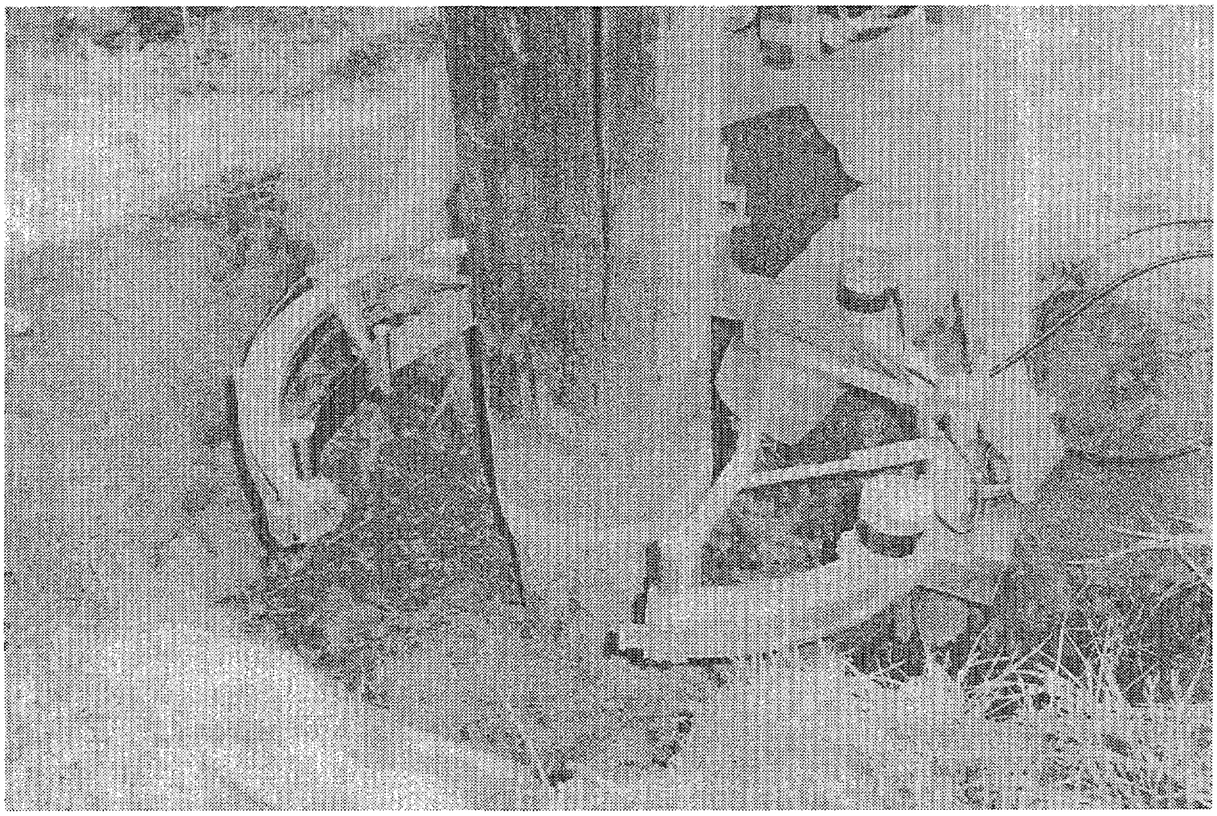


Figure 4: PortaCAT scanner being attached to a pole.

4.2. Source Enclosure

The source used is 11.1 GBq (300 mCi) ^{241}Am; Amersham AMC17, type X92/0, IAEA special form GB/39/S. The adherence to *special form* sources is important for transport of the instrument.

The source has an active area of 12mm diameter, and is contained in a stainless steel enclosure, with a shutter which springs open when it is moved from its home position on the scanner. This protects the operator when attaching the scanner to a pole. A manual override can be used to lock the shutter in the closed position. Because the source and detector are rarely diametrically opposite each other when taking data, the radiation beam is deliberately wide angle. The varying distance between the pair compensates for the changes in solid angle through each projection. Figure 4 shows the dose rates adjacent to the 410mm diameter housing (300mm object size). With nothing in the scanner, a 25 μSv/hr boundary would be a circle of 1.5m diameter centred on the scanner. However, when wrapped around a pole, this 25 μSv/hr boundary is reduced to a circle of 0.8 m diameter. Based on this, the scanner can be judged as safe for use in public areas.

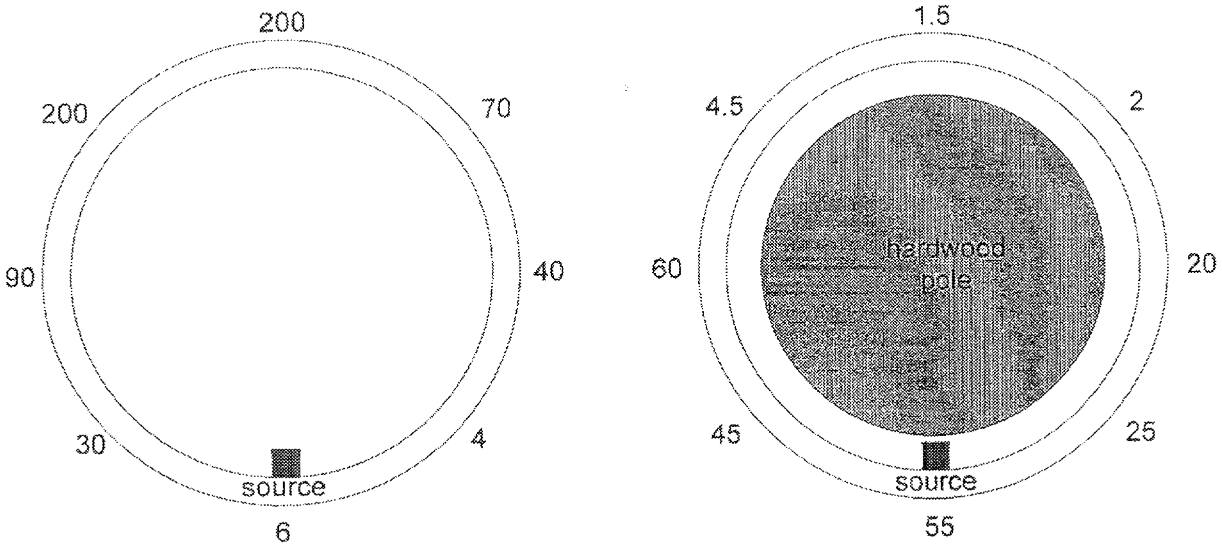


Figure 5: Ambient radiation (μSv/hr) around PortaCAT scanner.

4.3. Detector

As with the source, a physically small detector was indicated. Two CdTe semiconductor counters, 2 mm thick, were mounted in a sealed enclosure butted together to give a sensitive area of 10 x 20 mm. The two counters are simply paralleled, feeding into a hybrid charge sensitive preamp. This is followed by a two stage amplifier-shaper, using low power opamps, and output fed into a low level discriminator set just above the noise level to produce logic pulses. Initially, the detector was connected by cable to the microprocessor electronics. Tracking inconvenience arising from rotation of this cable was later overcome by replacing it with a digital VHF radio link. To achieve this, the detector electronics had to be extended to include onboard counting, an rf transmitter and a self-contained power supply. The counting is done by a low power I^2C counter which is controlled by a programmable interface controller (PIC16C71). Counting is done in intervals of 100 msec, after which the counter is read by the PIC, and the value is encoded into a data packet suitable for direct on/off-keying of the transmitter hybrid. The rf frequency used is 303 MHz at a power level lower than one milliwatt. Each packet is sequentially numbered, contains its own, and the two previous interval's, count data, and is appended with a 16 bit CRC (cyclic redundancy check) code. The transmitter hybrid is one that is often used for consumer remote controls, such as garage door openers. However, the PortaCAT application is rather more demanding than opening garage doors! The CRC code ensures that any doubtful data is discarded. The aerial is merely a short wire (~15cm) as the distance to the receiver in the base instrument is at most 4 metres.

Power for the detector is supplied by two AA size alkaline cells giving an endurance of about 8 hours continuous operation. Two micropower switchers provide some hundred volts of detector bias as well as analogue and digital low voltage rails. Efficient circuit design resulted in a compact package measuring 90x80x40 mm, and this was achieved without resorting to surface mount electronics. Noise was the largest problem. Switching supplies are inherently noisy and separate shielding was not practical in the very confined space available. Careful mechanical layout of the pcbs and orientation of high current switching conductors away from the detector input section was imperative. Use of magnetically shielded inductors was essential in the power supplies. Microphonic detector noise was substantially reduced by rigid counter mounting in a milled aluminium block, and by using a quasi-bipolar signal to drive the discriminator.

4.4. Step motor drives

The step motors are 5V, 1A per phase, with 1.8° step size. Given the amount of movement required for CT data acquisition, they are the major drain on battery power for PortaCAT. In this application, they are required to make a great many small movements accurately. Good torque is required, as well as fast acceleration/deceleration. The inductance of a winding means that the current takes a finite time to build up and to die away as the winding is switched on and off. To achieve a rapid step rate, the windings of a step motor are generally switched in series with resistors. With a series resistor, a higher voltage than the rated value for the motor can be used across the resistor and winding. When the winding is first switched on, the current will rise more quickly than with the case of the rated voltage just across the winding; however, the resistor dissipates power. For instance, running a 5V, 1A motor at 12V requires a resistor of 7 ohms, which will then waste 7 W of power when the rated current is achieved.

Switched mode power supplies are used for PortaCAT step motors. With switched mode operation, the resistor is eliminated. When a step motor winding is energised, it is switched on at regular intervals, and switched off each time the winding current exceeds a set value (in this case 1A). Properly set up, this results in a reasonably constant current through the winding, and no power wastage. Each motor for full stepping mode requires two of four windings energised at any time. Running 5V rated motors at 12V and 0.8A/winding with no mechanical load using resistors theoretically requires about 20W; of this, only 8W is dissipated in the motors. With the switching mode drivers, the power requirement is reduced to about 12W. The driver produces fast maximum step rates, high torque, and good efficiency. A PIC16C71 is used to generate the switched mode interval, and to switch the motor windings in the correct sequence to step the motor. Step timing and direction is controlled by external inputs. In most PortaCAT applications, it is only necessary to energise the winding when the motor is moving, and rely on mechanical friction to hold the source and detector in place.

4.5. System data acquisition and control

A laptop personal computer (PC) in conjunction with a 8-bit 80C552 microprocessor controls the movement of motors and the acquisition of data. The two are connected by a serial line. To save time, motor movements are precalculated according to the particular image and pixel sizes, and stored in tabular form for quick access. Scanning steps are passed to the 80C552, along with the required dwell time. To maintain constant measurement accuracy, each position is held until a preset number of x rays have been counted. Hence, scanner movement is slower at the centre of a projection than at the ends. Acquired data is passed back to the PC only at the completion of each projection. This enables progressive image reconstruction to proceed in parallel with data acquisition, and the final image is available within 10 seconds following completion of scanning. The operator, through the PC, can abort operation at any time. The 80C552 can also be used to report battery voltage.

Because of the need to drive step motors, the drain on the battery from the control electronics is not significant for PortaCAT. However, this is not the case in many other portable instruments. Microcontrollers and peripheral devices need to be low power devices, and preferably have standby or disabled modes that can be used to reduce power use when not in use. For instance, the 80C552 can be put in an "idle" mode when it stops processing, but can be "woken up" by various events. This saves power. Limiting clock speeds of microcontrollers also reduces power consumption — some versions can even programmatically alter their clock speed, allowing fast processing when needed, and lower power use at other times without completely stopping processing. In cases where the internal ROM and RAM of a microcontroller are insufficient, and external memory is added, this generally only needs to be enabled when the microcontroller accesses them e.g. for the 80C552, by tying the code read signal PSEN to both the output enable and chip enable pins of an EPROM. It is a case of “horses for courses” in selecting microcontrollers. Very simple tasks can be performed by “chicken brains”. For instance, a PIC16C71 can use significantly less power than a 80C552 but it can not be used for as complex tasks. Finally, some sensors that have significant power use, but are only measured periodically, can be depowered in between measurements by using a FET or IC analogue switch.

4.6. Image processing and presentation

The software on the PC is written in Pascal, and runs under MS-DOS. The system is complete in that it incorporates data acquisition and control through to calibration, image reconstruction, archiving and final analysis of images. Routine calibration involves running with an empty scanner to record null rates. These are angularly dependent, and can be averaged over several projections. The images produced by PortaCAT are maps of x ray attenuation. These are converted to density pictures by a simple multiplicative factor which should be determined by measurement of attenuation through a known density of similar wood.

As a result of previous experience, it had been found useful to alter the succession of projections so that the second one is at right angles to the first. Image reconstruction of just these two projections then provides a very early indication of any anomalies that might be present within the cross section of the pole. This 'quick' image is however square and, while other reconstruction techniques could produce a rounded image, filtered back projection has the advantage of emphasing defects to provide early indication of loss of pole integrity. An example is given in Figure 6. As expected for the pixel size, the images produced are crude in resolution. However, these are adequate for determination of power pole integrity. The corresponding full image is also given in Figure 6. This has been enhanced in resolution by a factor of two; while the data is unchanged, enhancement aids eye interpretation. 3D density plots are also available. As only raw image data is stored, each only takes 1.7 kB storage.

On the basis of the 'quick' image, the software informs the operator as to whether the pole is suspect or sound. This has been found to be a conservative judgement [1]. If sound, scanning can be aborted, and inspection shifted onto the next pole. This overcomes the necessity of having highly trained operators. Full engineering analysis can be applied to the pole image using the same software. This reports the available maximum and minimum bending moments, and those at 0° and 90° to the image. An example of this is shown in Figure 7.

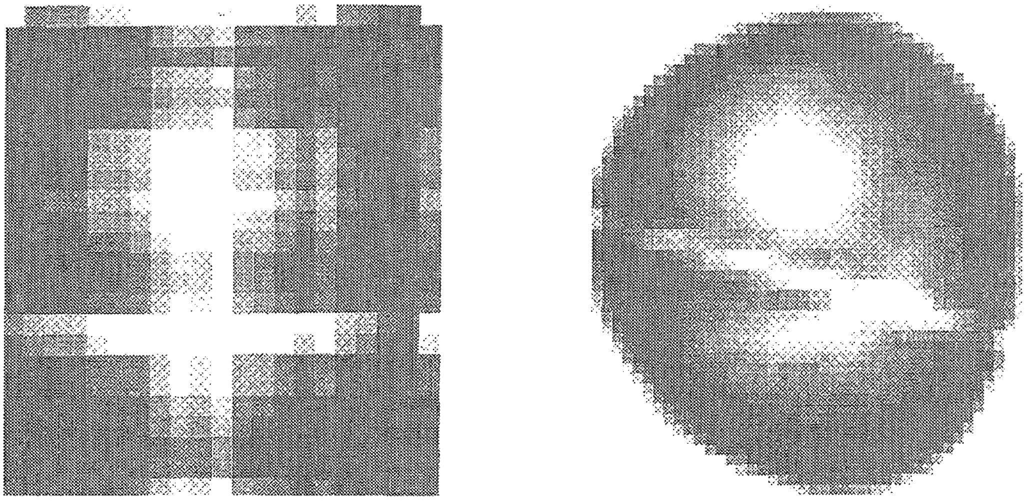
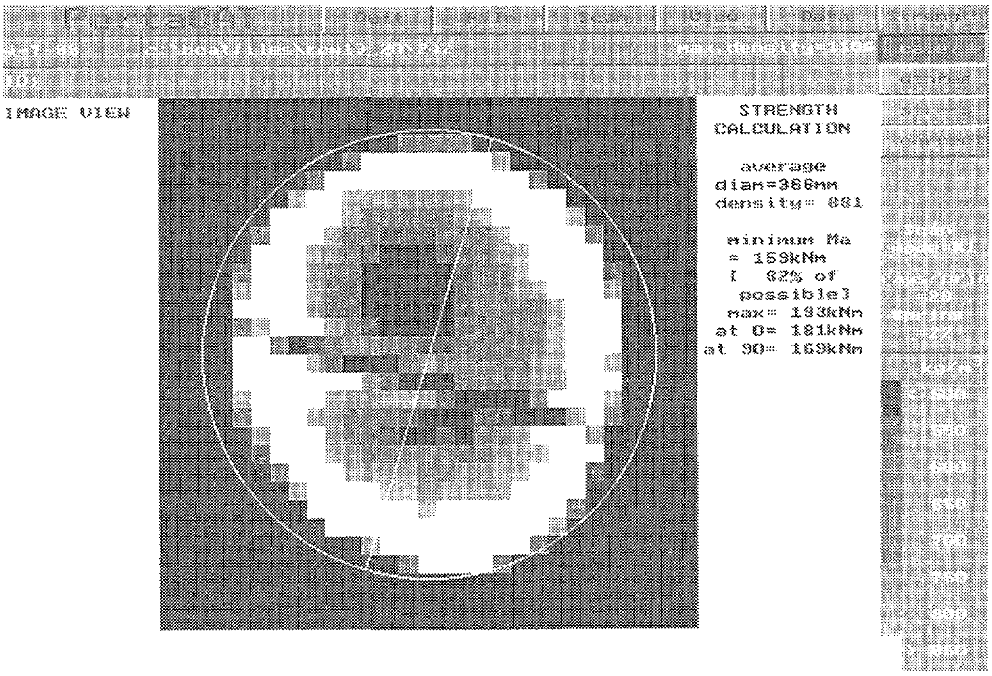


Figure 6: Quick image (left) and full image (right) of cracked pole with interior decay.



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STRENGTH
CALCULATION

average
dian=386mm
density= 881

minimum Ma
= 159kNm
[  82% of
possible]
max= 193kNm
at 0= 181kNm
at 90= 169kNm
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Figure 7: Screen dump of PortaCAT programme showing bending moments calculations.

5. CLOSING REMARKS

In terms of computed tomography, PortaCAT is not a particularly sophisticated imaging device. However, in terms of portable nucleonic instrumentation, it is a successful example of the use of precision engineering, modern electronics and computing power to produce a complex device tailored to a specific need. The following features make it suitable for the detection of internal defects arising from rot or termite activity in wooden power poles:

- two handheld packages: scanner (6.2 kg) and electronics (9.2 kg)
- battery operated; battery lasts 3 hours, quick replacement
- uses compact semiconductor X ray detectors
- compact, long-life, low output radioisotopic source of X rays
- includes unmodified laptop computer running under MS-DOS
- user friendly software, staff easily trained
- simple performance check and calibration
- rapid attachment of scanner to pole, self centring
- scans virtually at ground level, minimum excavation to scan below
- non-destructive and non-invasive examination
- verification of good poles every 3.3 minutes on average
- full images (450 mm, 15 mm pixel) every 11.2 minutes
- move between poles without shut-down: check 5–20 poles each hour
- archival of images for later retrieval and hard-copy
- calculation of available bending moments conforms to accepted engineering requirements
- uncertainty therefore removed on need for replacement of defective poles
- cost-effective because of potential for life extension of distribution networks.

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