# STUDIES OF SCINTILLATING FIBRES FOR A SPAGHETTI CALORIMETER TO BE USED FOR THE H1 BACKWARD UPGRADE PROJECT

ALBIN WALTHER for the H1–Collaboration
*Abteilung für Physik, Universität Dortmund, Otto-Hahn-Str. 50*
*44221 Dortmund, Germany*

and

RAINER BARSCHKE
*DESY, Notkestr. 85, 22603 Hamburg, Germany*

ABSTRACT

The H1 collaboration intends to upgrade the backward region of the detector by exchanging the present lead scintillator sandwich calorimeter by a new spaghetti calorimeter. This calorimeter will be divided into an electromagnetic and a hadronic section with lead to fibre ratios of 2:1 and 4:1 and fibre diameters of 0.5 mm and 1 mm, respectively. To achieve a good energy resolution and homogeneity it is important to use scintillating fibres which have a large light yield and a long attenuation length. As the detector will work in a region of H1 with a high radiation level the fibres must be in addition very radiation hard. We therefore measured the light yield, absorption length and radiation hardness of various fibres from Bicron, Kuraray and Pol.hi.tech.. The influence of radiation on the light yield and absorption length and the effects of mirroring the fibre ends are discussed. In test beams at DESY and CERN a resolution of the electromagnetic section of $7.2\,\%/\sqrt{E} \oplus 0.6\,\%$ has been measured.

## 1. Introduction

### *1.1. Physics Goals*

The electron–proton collider HERA provides the unique possibility to probe the parton structure of the nucleon over a wide range of kinematic conditions. Recently interest has grown to investigate the low–x regime (in the quark–parton picture x can be interpreted as the fractional energy of the nucleon carried by a parton) of the nucleon structure[1].The events originating from low–x processes are characterized by boosts in the backward (electron) direction. This means that both the scattered electron and the hadronic final state are to be detected in the backward scattering region down to the lowest measurable scattering angles.

The current H1 detector is equipped in the backward scattering region with an electromagnetic calorimeter allowing electron reconstruction down to polar angles of 173° relative to the proton direction. The new backward electromagnetic calorimeter is designed to measure the scattered electrons down to angles of 177°

thus giving for the first time access to a substantial range in $Q^2$ at $x = 10^{-4}$.

*1.2. Layout of the new Calorimeter*

The heart of the new design in the backward scattering region (polar angle $> 152°$) is a high resolution lead–fibre calorimeter (SpaCal) with an electromagnetic and hadronic section[2]. It extends from $152°$ to very large backward angles of $178°$. To achieve our physics goals the electromagnetic calorimeter has to fulfill the following requirements:

- Energy resolution at 30 GeV better than 2%;
- Spatial homogeneity better than 1% and spatial resolution 1 mm;
- Time resolution better than 1 ns and high granularity to distinguish true ep collisions from upstream proton background already at the first trigger level;
- Absolute calibration better than 0.5%;
- Detection of single minimum ionizing particles;
- Probability to misidentify hadrons as electrons of less than 1% for electron momenta larger than 3 GeV;
- Radiation hard;
- Small radiation length and Molière radius to achieve a compact calorimeter with very good containment near the beam pipe;
- Operation in 1.2 Tesla magnetic field.

To meat this requirements we choose a lead to fibre ratio of 2 and a fibre diameter of 0.5 mm for the electromagnetic calorimeter leading to a radiation length of 0.9 mm and a Molière radius of 2.5 cm. The total length of the calorimeter will be 25 cm with a length of the fibres of 29 cm because 4 cm are needed to bundle the fibres.

As the calorimeter has to operate in a 1.2 Tesla magnetic field the only choice for photomultipliers are mesh dynode photomultiplier tubes. The only producer of this tubes is Hamamatsu Photonics. The types R3432–01 (1") and R2490–05 (2") yield a sufficient number of dynodes and match the granularity of the proposed calorimeter. The spectral sensitivity of the bialkali photocathod with a borosilicate window matches the emission spectrum of blue fibres.

Besides the intrinsic non uniformity which contributes to the constant term a further, instrumental effect plays a very important role, namely the finite light attenuation length of the fibres and fibre to fibre fluctuations of the light output. If the attenuation length $\lambda_{att}$ is less than 1 m, the longitudinal fluctuations of electromagnetic showers will lead to not acceptable 1 % variation of the light output. Also radiation damage of fibres, especially if not constant along the fibre length is crucial. We therefore measured the attenuation length of various fibres, tried to improve the attenuation length by mirroring and using filters and investigated the effect of radiation damage on light yield and absorption length.

## 2. Results from Fibre Research

A program[3] has been started to gain know-how and experience with the handling and properties of 0.5 mm diameter blue scintillating fibres of different manufactures. To measure the optical properties of scintillating fibres we built a test bench in which a fibre is fixed in a support structure and coupled to a light mixer. The light mixer is coupled to a photomultiplier and the current of the photomultiplier is measured while the fibre is irradiated with a beta source. To kill the cladding light 1 cm of each fibre is painted black at the end near to the photomultiplier. The other end of the fibres is painted black to avoid reflexions or aluminized to improve the attenuation length. Our measurements show that it is sufficient to paint only a few mm of the fibre black to kill the cladding light completely.

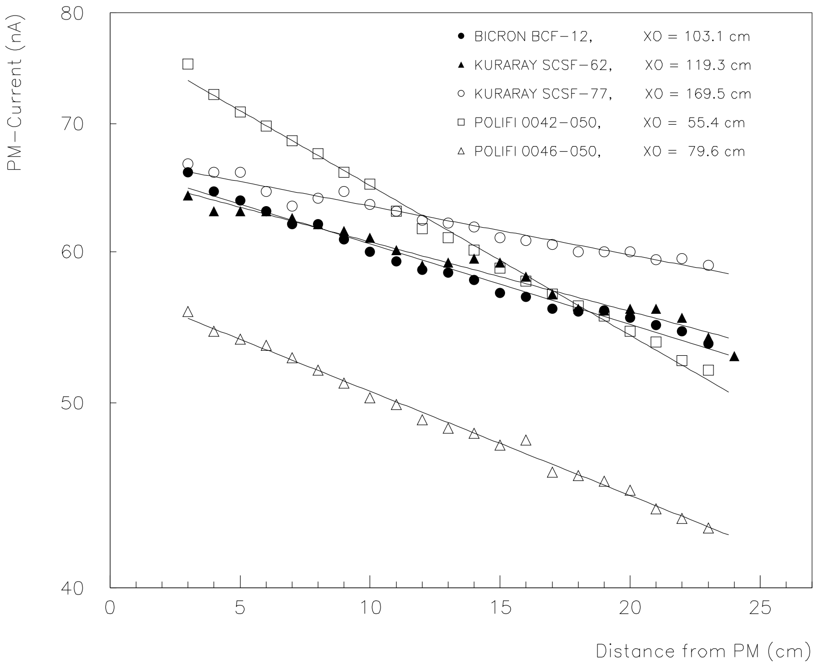
### *2.1. Attenuation Length and Light Yield Measurements of raw Fibres*

The light attenuation length for long fibres is of the order of several meters. For short fibres a very different behaviour is observed[4]. The attenuation is much faster for short fibres. This is attrubuted to the light which is trapped inside the cladding of the fibre. The acceptance for this light is much larger, but the attenuation by reflexion on the outside of the fibre is also much stronger. Thus at very small length the cladding light is dominating. Therefore it is necessary to kill the cladding light and to measure the attenuation length of short fibres very carefully.

Figure 1 shows the results of attenuation length measurements for different fibres from Bicron, Kuraray and Pol.hi.tech.(Polifi). Although the attenuation length differ by a factor of 3 between Pol.hi.tech. and Kuraray fibres the differences in light yield are much smaller. The Kuraray SCSF–77 fibres provide the longest attenuation length. However, these fibres were available to us only on rolls and not straight. This made it close to impossible to place them in the groves of the lead profile. The Bicron fibre BCF–12 combines a long attenuation length with sufficient light output. We used this fibre in the first prototype. For the light yield distribution we measured a RMS of 7.9 %, including a systematic uncertainty of 3 %. The average attenuation length was measured to be 108 cm with a RMS of 21.8 %. Here more efforts of the manufacturer are clearly needed to reduce this fluctuations. The second candidate is the Polifi 0042–50 which proved to have good mechanical tolerances and light yield with a RMS of 5.8 %. However it has a shorter attenuation length of only 61 cm with a RMS of 13.7 % due to the lower peak of the emission spektrum. In addition the measurements from two different lots of the same Polifi fibres indicate that there are relative large fluctuations from lot to lot. This also can not be excluded for other manufactures at the moment. We therefore will have to monitor carefully the quality of the fibres during the production process of our calorimeter.

In general the measurements of raw fibres show that the measured attenuation length is either to small (Polifi) or the variations are to large (Bicron) if aiming for a small constant term of the energy resolution. We therefore tried to improve the attenuation length by mirroring the ends of the fibres and by using filters.

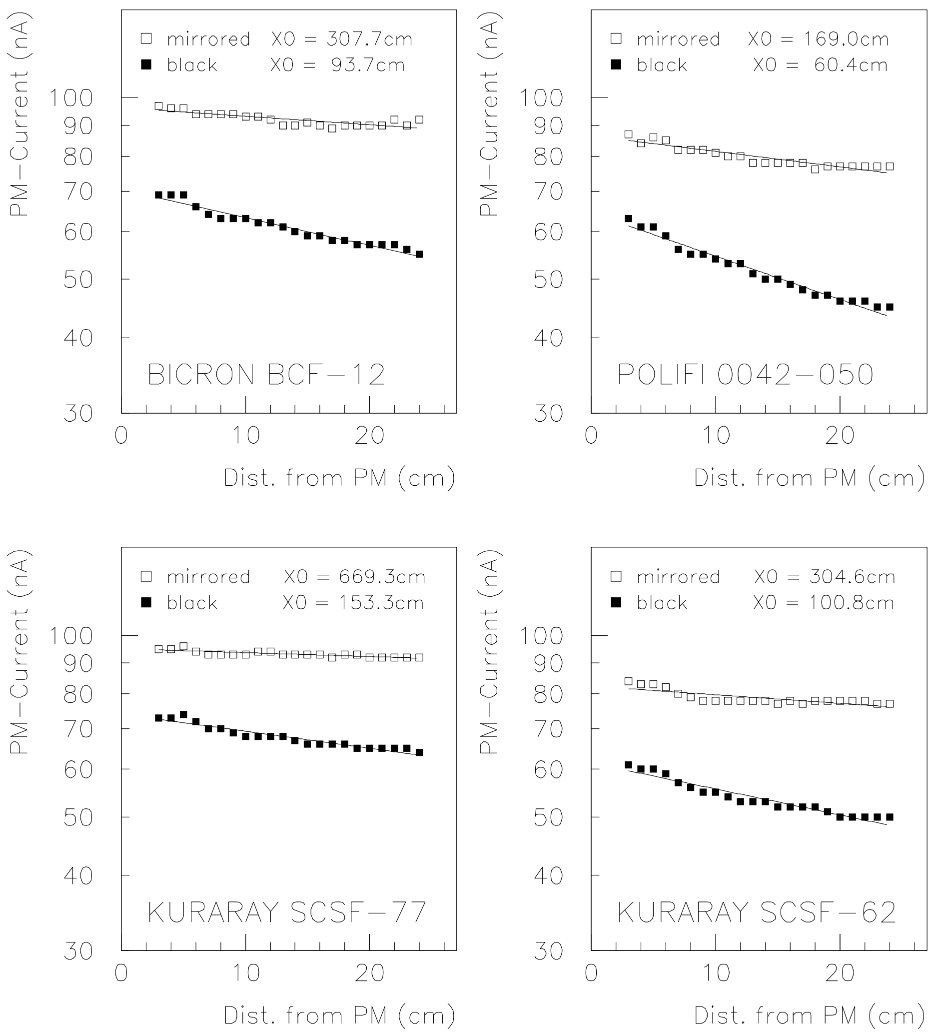
**Figure 1:** Attenuation lengths of various fibers measured for single fibres.




*2.2. Results from mirrored Fibres*

To mirror the fibres we cutted and polished the fibre ends. Then the fibre ends were vaporized with aluminum in vacuum leading to a mechanical very stable aluminum surface. Any vaporization of the cladding of the fibres was avoided. A reflexion coefficient of 60–70 % has been achieved so far. In fig. 2 the measurements of different fibres before and after mirroring are shown. The attenuation length increases by a factor of 3 and more together with a significant increase of the light yield. All fibres showed an effective attenuation length of longer than 150 cm after aluminization which is sufficient for our needs. For the light yield distribution of the Bicron BCF–12 fibres we measured a RMS of 7.6 %. The same distribution for the Polifi 0042–50 fibres gave a RMS of 4.6 %. Thus mirroring leads to a slight decrease in the fibre to fibre variations and does not add additional fluctuations.

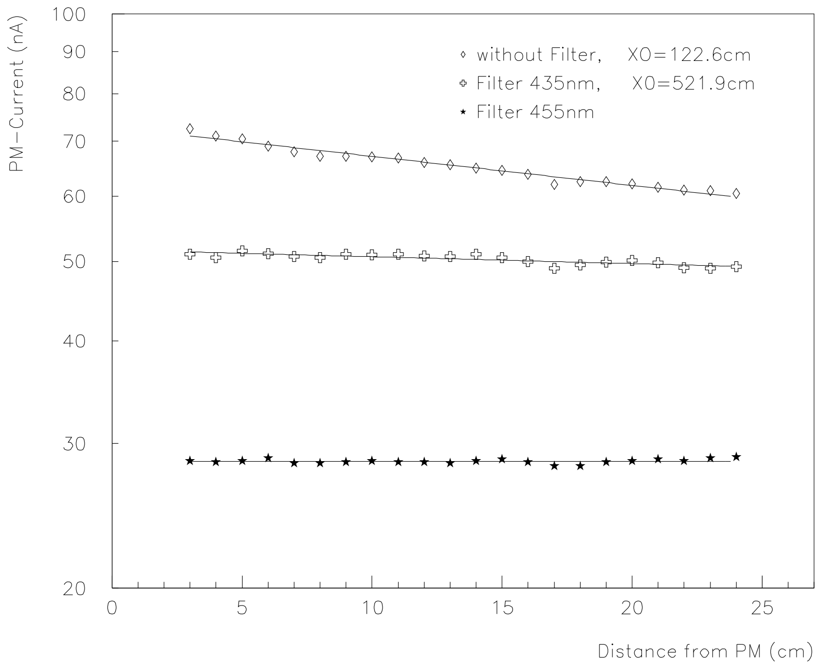
**Figure 2:** Attenuation lengths of various mirrored fibres.




*2.3. Results from Filter Measurements*

As the attenuation length for short wave lengths in the fibre is shorter than for long wave lengths the use of filters will increase the effective attenuation length. In fig. 3 the measurements with filters that cut off wave lengths shorter than 435 nm and 455 nm, respectively, are compared to measurements without filter. For all three measurements the same fibre was used. The large increase in the attenuation length has to be paid by significant losses in the light yield. The use of filters in addition can help to reduce the effects of radiation damage because this mainly leads to stronger light absorption in the short wave lengths range. Due to the large reduction of the light yield we will not use filters in our calorimeter.

**Figure 3:** Attenuation lengths measured with filters.



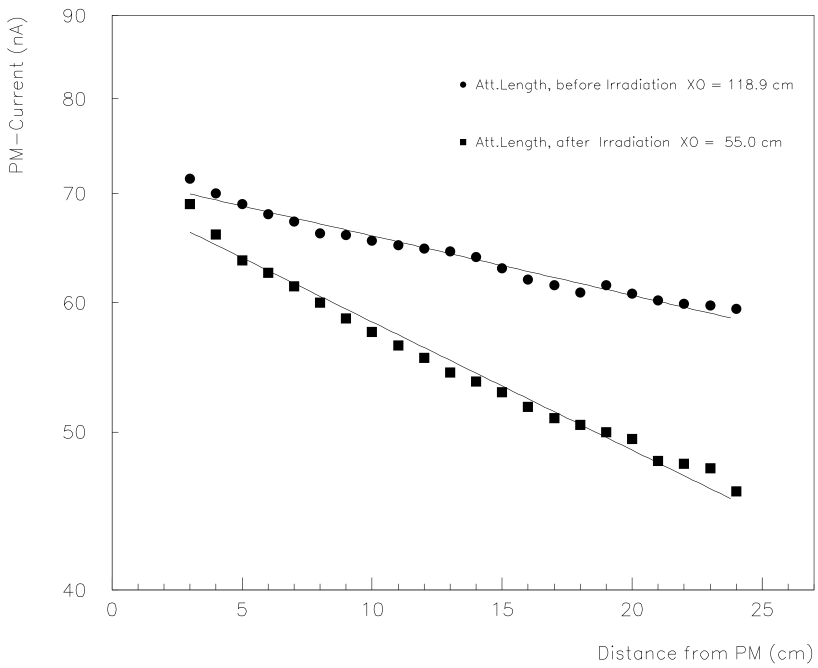

*2.4. Influence of Radiation Damage on Attenuation Length and Light Yield*

The most inner part of our calorimeter near to the beam pipe must stand radiation exposure of approximately a hundred krad per year. To measure the effects of radiation damage we irradiated fibers with $\gamma$–radiation from old reactor elements at GKSS (Geesthacht, Germany). In fig. 4 the attenuation length measurements for a Bicron BCF–12 fibre before and after irradiation with 500 krad are compared. While the attenuation length decreases by a factor of 2 the light yield stays nearly unchanged.

The strong decrease of the attenuation length due to radiation damage forces to use fibres with rather long ($> 3$ m) attenuation length so that the remaining attenuation length even after a few years of running stays well above 1 m. With mirrored Bicron BCF–12 fibres irradiated with 500 krad we measured an attenuation length of 99 cm whereas the Polifi 0042–50 is down to 50 cm despite the aluminization. The higher sensitivity to radiation is caused by the shorter wave length of the emission peak.

The radiation damage of the fibres can partly recover depending of the 'treatment' and surrounding material of the fibre. To study the influence of glue on the radiation damage small modules were built in which the fibres were either embedded into the lead profile without glueing or different glues were used to fix the fibres in the groves of the lead profile. After irradiating this modules with a dose of 2 Mrad the effective light output of the glued modules was reduced to 10% where the not glued modules still gave 40% of the original light output. This behaviour of course is expected because it is already well known[5,6] that oxygen plays an important role for healing of radiation damage. On the other hand radicals from the glue may lead to additional light absorption in the fibres. We therefore decided not to glue the fibres into the lead profile making the manufacturing of the calorimeter much more difficult.

**Figure 4:** Attenuation lengths after irradiation.




## 3. Prototype Results

The outer dimensions of the first prototypes were 12 x 12 x 25 cm². Within the first prototype the fibres are grouped into a matrix of 4 x 4 each cell being about 30 x 30 mm². The fibre ends were not mirrored. A second prototype had 9 cells of 40 x 40 mm² and aluminized fibres. At one end of the lead profile the fibres are bundled together and then glued with black glue (epoxy LY/HY–5052) over a depth of about 2 cm to kill the cladding light and also to provide a solid base for the subsequent machining to obtain a good optical surface. A light mixer is mounted in close distance of 0.8 mm air gap in front of the fibre bundle. The light mixer is coupled to the photomultiplier with optical grease. We used fine mesh dynode photomultipliers (Hamamatsu R3432–01) with a diameter of 1". The measurements of the modules were done at DESY and at the CERN SPS.

Both the SpaCal prototype modules were mounted on a movable table which allowed x–y and angular scans. Scintillator hodoscopes defined the beam and provided the trigger.

An energy scan was performed at an angle of $5^\circ$ in the horizontal and $3^\circ$ in the vertical direction to avoid channeling. Linearity was maintained up to 80 GeV to better than 1 %. Figure 5 shows the energy resolution of both prototypes for a central cell combining both DESY and CERN results. For the DESY measurements 72 MeV and 56 MeV have been subtracted in quadrature in order to account for the finite momentum resolution of the beam. For the CERN data a coherent noise contribution of 150 MeV and 500 MeV had to be subtracted for the first and second prototype, respectively. The large noise corrections for the CERN data affect only the 10–20 GeV data, which have been removed from the fit to the energy resolution.

For the first prototype a common fit to the CERN and DESY measurements yields a scaling term of 7.1 % and a constant term of 1.3 %. The scaling term varies from cell to cell from 7 % to 8.5 % indicating an imperfection within the module. We attribute the large constant term mainly to the non-uniformities within the module. Evidence for large non-uniformities is seen in longitudinal scans. Better results have been obtained for the second prototype with a significantly smaller constant term: dE/E = $7.2\,\%/\sqrt{E} \oplus 0.6\,\%$. For both modules we found a resolution of better than 2 % at 30 GeV. A non-uniformity of about 5 % is observed in scans across cell boundaries. This affect is under investigation.

The light yield has been determined by comparison with a LED to be $2.2 \pm 0.2$ and $2.8 \pm 0.3$ photo electrons per MeV for prototype 1 and 2, respectively. For minimum ionizing particles we observe an energy deposition of 350 MeV to 400 MeV.

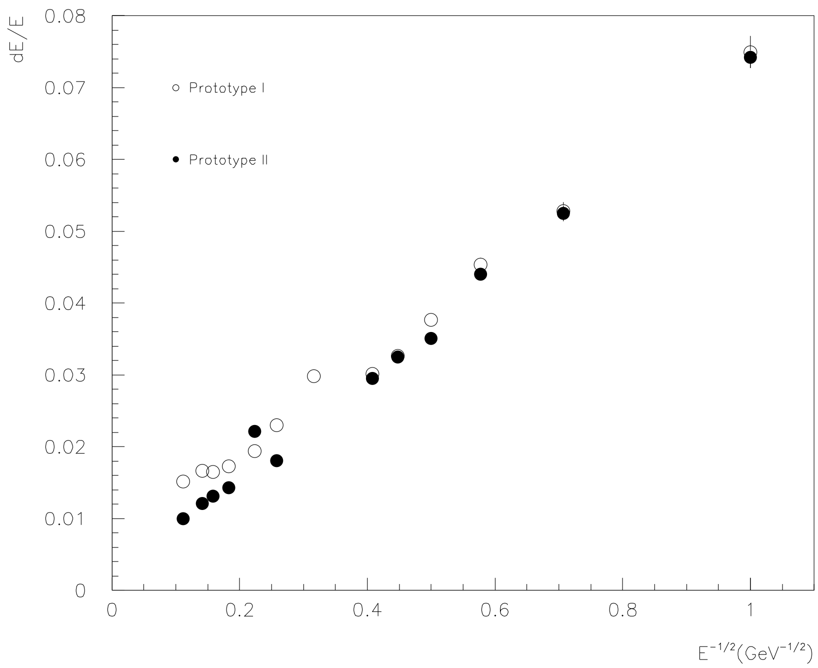
The time resolution of both prototypes was better than 1 ns for electrons and hadrons.

Channeling effects have been observed in all SpaCal calorimeters whenever a particle traverses parallel to the fibres or at small angles but still parallel to one of the main symmetry axes. We observed strong effects up to angles of more than $5^\circ$ within the plane of the fibres. To avoid such effects in our detector we will orientate the Pb matrix always in such a way, that its symmetry axis is never parallel to the particle trajectories.

## 4. Summary

The detector concept for a new electromagnetic backward calorimeter of the H1 detector has been described. Main emphasis was put on the R&D activities to achieve long attenuation length and large light yield with small fibre to fibre variations for 0.5 mm blue scintillating fibres. Test measurements showed that we have met our goals in terms of energy resolution by using mirrored fibres. Some further improvements are needed to reduce the non-uniformities at the cell boundaries. This will lead to a further reduction of the constant term.

**Figure 5:** Energy resolution of first and second prototype.




## 5. Acknowledgments

It is a pleasure to thank K. Thiele and G. Falley (DESY) for their permanent competent technical help. We acknowledge the permanent support and stimulating interest of the backward upgrade group of the H1–collaboration. Thanks also to the organizers for a very enjoyable and interesting workshop at Notre Dame University. This work was supported by the Bundesministerium für Forschung und Technologie, Germany, under contract number 6DO57P(6).

## 6. References


1. . Ali and J. Bartels, in *Small–x Behaviour of the deep Inelastic Structure Functions in QCD*, Proceedings of a Meeting held at DESY, Hamburg, Germany, May 14–16, 1990. **D25** (1982) 2015.
2. H1–Collaboration, *Technical Proposal to Upgrade the Backward Scattering Region of the H1 Detector*, **PRC 93/02**, March 8, 1993.
3. . Barschke, Diploma thesis, Hamburg University, in preparation.
4. . Bianco et al., **LNF-91/061 (R)**, 1991
5. . Acosta et al., *Nucl. Instr. Meth.* **B62** (1991) 116.
6. .W. Hertzog et al., *Nucl. Instr. Meth.* **A317** (1992) 506.