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Ultraviolet–visible reflectance and fluorescence spectra of the Shroud of Turin

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The Shroud of Turin is a partially scorched linen cloth containing an apparently bloodstained sepia image of a man lying in a state of repose. It is believed by some to be the burial cloth of Jesus of Nazareth. A team of scientists, under the auspices of The Shroud of Turin Research Project, Inc., performed nondestructive measurements on the Shroud with electromagnetic energy from x ray to the IR to develop data leading to the analysis of the substances making up the body image stains and bloodstains. Presented here are UV–visible reflectance and fluoroescence spectra of the sepia body image area and scorched and bloodstained areas on the shroud.

I. Introduction

This paper describes the techniques used and results of an UV–visible reflectance and fluorescence study performed on the Shroud of Turin in Turin, Italy during the week of 8 Oct. 1978. This study was performed as part of a more complete set of experiments by a team of scientists sponsored by The Shroud of Turin Research Project.

II. Background

The Shroud of Turin shown in Fig. 1 is an old piece of linen ~4.3 m long × 1.1 m wide. The linen bears a faint image of a full-sized bearded man apparently layed out in death; this image appears only on the front face of the cloth and a dorsal image, apparently of the same man, on the other end as if the image had been formed while the cloth was longitudinally folded over a human body. In addition to the body image, there are a number of slightly darker somewhat reddish stains giving the appearance of bloodstains. These bloodstains are placed at various locations over the body image including the wrist, the feet, and the side of the body. Smaller bloodstains appear around the head and on his back. In addition the cloth shows marks resulting from a fire in 1532 A.D. including charred areas, scorched areas of various shades of intensity, and water marks believed to have been left by the successful attempts to quench the burning cloth. Patches also appear on the front of the cloth placed after the fire to cover holes where it had burnt through. At this same time a new piece of linen was sewn to the back of the cloth to preserve its integrity. The cloth today resides in a chapel attached to the cathedral of St. John the Baptist, Turin, Italy. The history and previous scientific work performed on the Shroud are described in detail elsewhere.[1,2]

Because of the belief by some that this cloth is the burial shroud of Jesus of Nazareth, The Shroud of Turin Research Project requested and received permission to perform scientific tests to try to determine the nature of the various stains on the cloth as well as to collect information regarding techniques of manufacture and other information bearing on the cloth's age. A series of nondestructive tests employing electromagnetic energy from x ray through the IR were performed. Results of these tests will serve to build on the data base upon which, at least in part, claims of authenticity may be evaluated.[3,4]

III. Objectives of UV–Visible Spectral Reflectance and Fluorescence Measurements

These nondestructive measurements were made to provide data as an aid to later analysis of the substances making up the various stains on the cloth and to a possible determination of the techniques used in the manufacture of the cloth itself. Specifically these tests were to provide fluorescence and relative reflectance spectra of the image areas of the Shroud and the areas scorched in the 1532 A.D. fire, fluorescence and relative reflectance spectra on the bloodstained areas of the Shroud, and fluorescence and absolute reflectance

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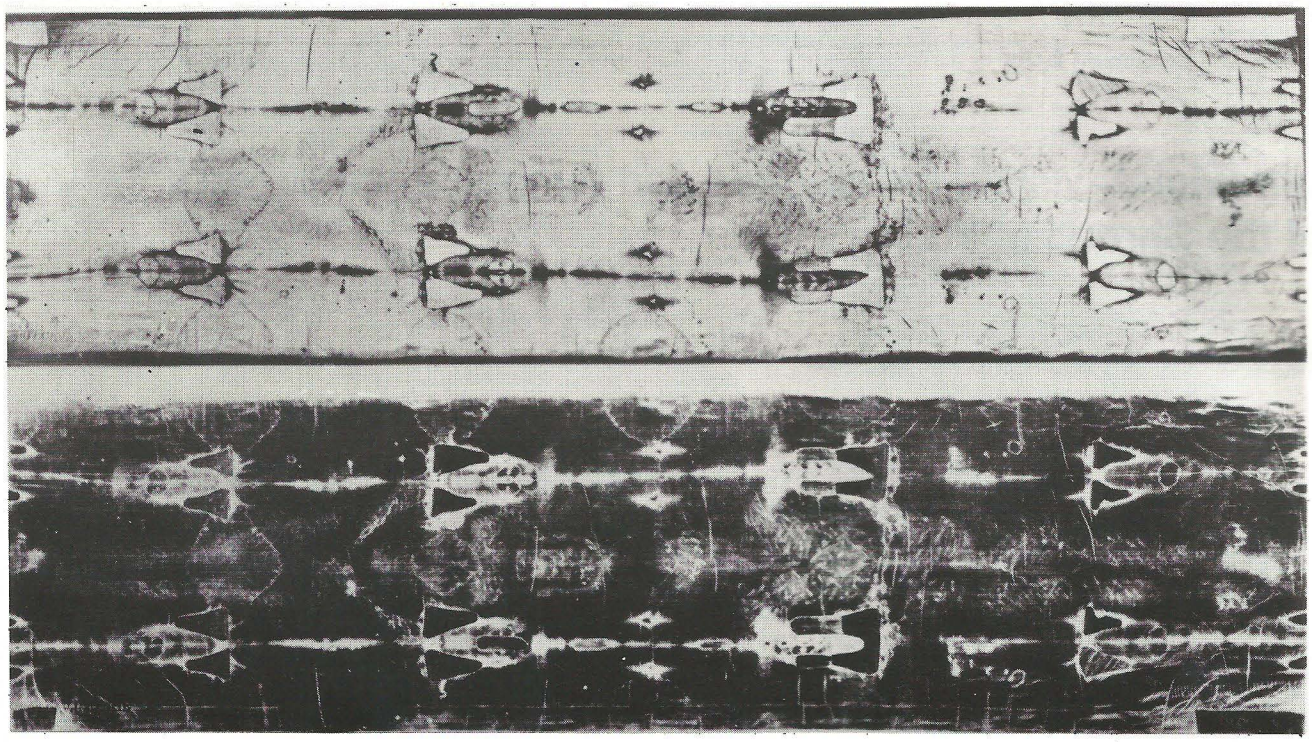

Fig. 1. The Shroud of Turin shown above as a photographic positive and below as a photographic negative. Visible are two parallel lines of scorches and frontal and dorsal images of the body in the center. Apparent bloodstains show in the positive as darker spots on the body image.

spectra on the clear areas of the cloth for possible comparison with other cloth samples. The relative reflectance spectra of the stains mentioned above were the reflectances of the stains relative to that of the clear areas on the Shroud.

IV. Instrumentation

A special reflectometer/fluorimeter was constructed by Oriel Corporation for this purpose (Figs. 2 and 3). The instrument consisted of a source channel irradiating a target area on the Shroud and a detection channel measuring the reflected or emitted radiation from the same target area. The source channel contained a monochromator illuminator, shutter, monochromator (source monochromator), filter holder, and a system of output optics including a concave mirror, two flat mirrors, and a beam splitter. The Oriel model 7292 monochromator illuminator housed both a 150-W xenon arc lamp and a 200-W mercury arc lamp. These lamps were powered by two dc arc lamp power supplies (Oriel model 8500).

Radiation from either of these lamps was focused onto the monochromator entrance slit by a switchable concave mirror. The 125-mm focal length, $f/3.7$ monochromator (Oriel 7240) employed a 1200-line/mm grating blazed at 280 nm. Fixed slits, 0.8 mm wide, provided a bandwidth of 5 nm.

The system of output optics imaged the exit slit of the monochromator onto the target area on the Shroud. The irradiated area was 6 mm high × 3 mm wide. The field of view at the target was ~6°. The beam irradiated the target at a 45° angle of incidence. This incidence angle was chosen rather than 0° to reduce the apparent spaces between the threads of the cloth and, therefore, reduce the contribution of the backing cloth to the measurements.

The detection channel consisted of a similar set of optics to image the irradiated target area through a filter holder onto the entrance slit of a second monochromator (detector monochromator). This monochromator is identical to that described above except that 1.22-mm wide slits were used providing a bandwidth of 8 nm. The target area detected was therefore slightly larger than that irradiated to reduce the effect of minor misalignments of the two channels. The output beam from this second monochromator irradiated the photocathode of a photomultiplier detector with response from 200 to 800 nm (Oriel model 7062).

A voltage proportional to the wavelength of the detection monochromator was fed from the wavelength readout (Oriel model 7289) to the x axis of an x-y recorder (MFE Corp. model 715). The signal from the photomultiplier detector was amplified by a photomultiplier radiometer (Oriel model 7070) and fed to the y axis of the recorder.

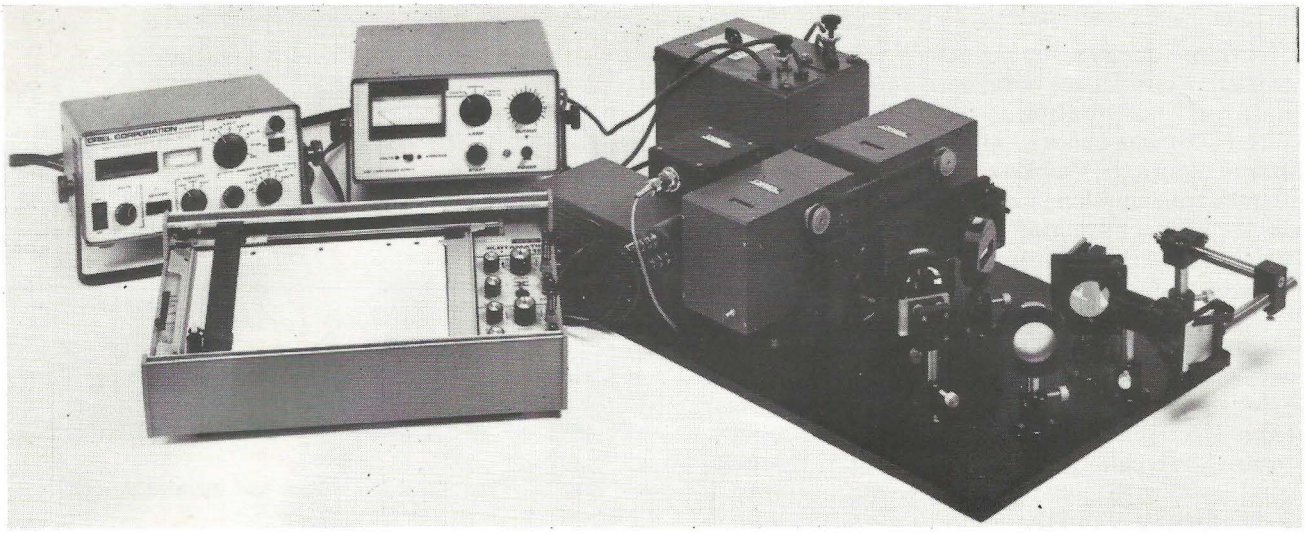

Fig. 2. Oriel reflectometer/fluorimeter with cover removed with lamp power supply, photomultiplier radiometer, and x-y recorder.

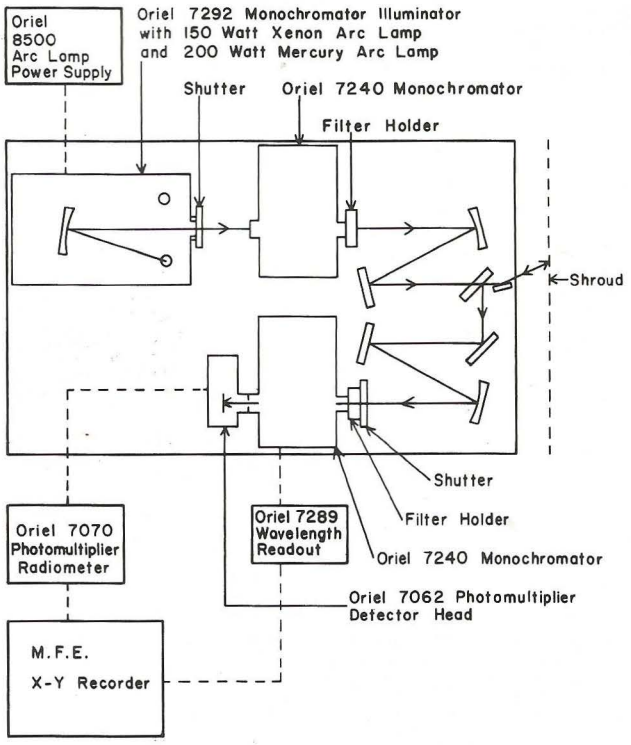

Fig. 3. Oriel reflectometer/fluorimeter schematic layout.

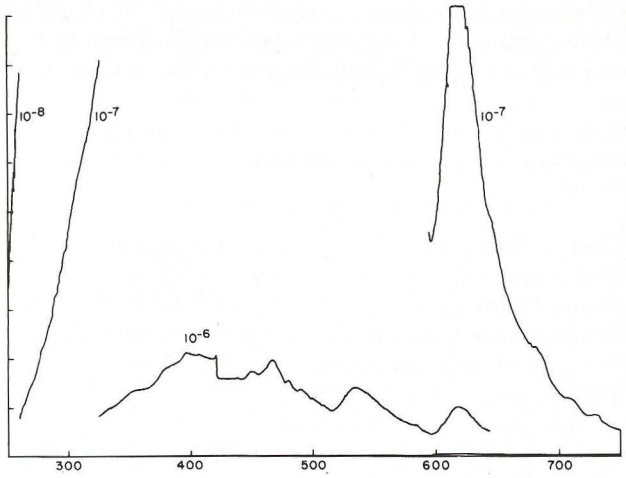

Fig. 4. Typical raw reflectance scan (point B3A-clear).

V. Experimental Procedure

A. Spectral Reflectance

For reflectance measurements the xenon lamp was used; both monochromators were scanned in unison continuously from 250 to 750 nm. From 420 to 750 nm a long pass absorption filter transmitting 50% at 390 nm (Oriel G-772-3900) was inserted before the detector monochromator to eliminate the second order. The effective instrument bandwidth was 5 nm.

Single-beam scans of reflected radiant power vs wavelength were made on seven clear areas on the Shroud, eight body image areas, six scorched areas, five bloodstained areas, and on a magnesium oxide reference surface. A typical single-beam raw reflectance scan is shown in Fig. 4.

The raw response of these single-beam reflectance curves was read and digitized. Those of the clear areas were divided by the response from the magnesium oxide reference surface and replotted as absolute spectral reflectance assuming the reflectivity of magnesium oxide to be 1.0 Relative spectral reflectances of the various stains were determined by dividing the response from the stain area by the response of a mean of five clear areas of the Shroud and replotting the result.

B. Spectral Fluorescence

For fluorescence scans the 200-W mercury arc lamp was used. The source monochromator was set at 365 nm. An UV transmitting, visible absorbing filter (Oriel G-774-3300) was inserted after the source monochromator to reduce the visible stray light. A long pass filter with 50% transmission at 390 nm was placed before the detector monochromator. The monochromator was continuously scanned from 390 to 700 nm using an effective instrument bandwidth of 8 nm.

The raw spectral scans were corrected for the instrument spectral response in the following manner: The source monochromator and detection monochromator were set at the same wavelength. A measurement of the radiant power incident onto the target was measured by a calibrated thermopile. The thermopile was replaced with a highly reflective magnesium oxide reference surface, and the response of the detector was noted. A calibration factor equal to the incident radiant power divided by the corresponding response from the magnesium oxide surface was determined for a series of wavelengths from 390 to 700 nm.

The raw spectral scans were digitized at these wavelengths, multiplied by this correction factor, and replotted as spectrally corrected fluorescence. This method of spectral correction assumes that both the absorbance of the thermopile black surface and the reflectance of the magnesium oxide surface are spectrally neutral.

Fluorescence scans were done on the same areas as the reflectance scans mentioned above. A typical raw fluorescence scan is shown in Fig. 5.

For reference a sample of Whatman 42 filter paper produced a peak fluorescence of 0.10 units at 435 nm (or 0.28 of the most clear area of the Shroud), and a piece of modern white cotton cloth with optical brightener produced a peak fluorescence of 50 units at 438 nm (or 140 times that of the most clear area of the Shroud).

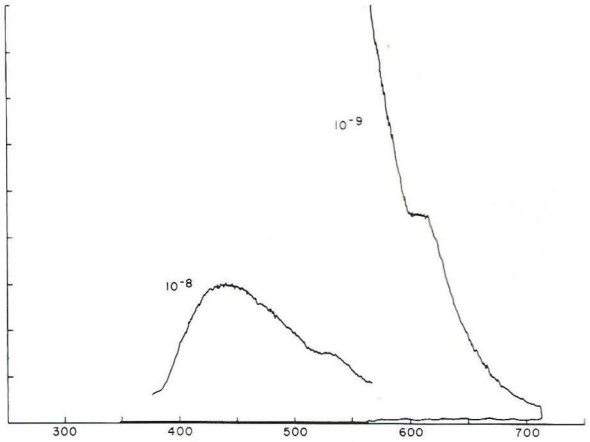

Fig. 5. Typical raw fluorescence scan (point B3A-clear).

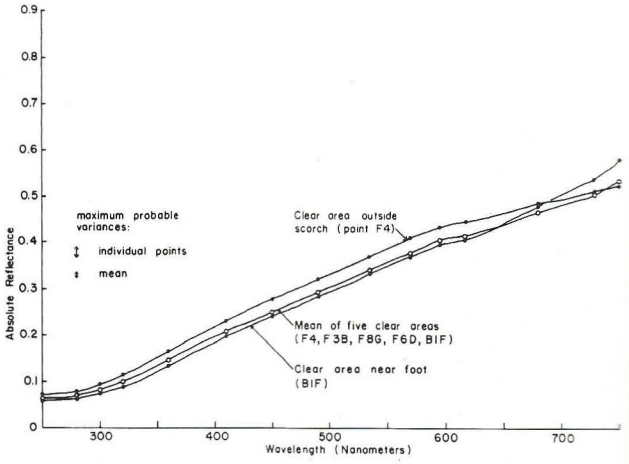

Fig. 6. Absolute spectral reflectance (referred to magnesium oxide) of two clear unstained areas on the Shroud and the mean reflectance of five clear areas.

VI. Probable Errors

The maximum probable instrument error in any one reflectance scan including instrument and curve reading errors is estimated by comparing several runs on the same target surface at ±3%. The range of this maximum probable instrument error has been shown graphically on the ratioed reflectance plots. This was calculated by taking the square root of the sum of the squares of the numerator and denominator errors. When several scans were averaged the resultant errors were estimated by dividing the square root of the sum of the squares of the single scan error by the number of scans.

Substantial differences in the spectral reflectance are found from area to area on the unstained or clear portions of the Shroud due to variations in the weave and miscellaneous local stains. This corroborates visual observation since the cloth has a mottled look, and because the darker areas are brownish in color they tend to absorb more of the shorter wavelengths than the lighter areas. The variation in spectral reflectance from a particular clear area to the mean clear referred to above was generally between ±3 and ±7% across the entire spectrum. This variation represents a background noise level that should be considered when evaluating the reflectance spectra of the image, scorched, and bloodstained points. The effect of the instrument noise and the background noise on the Shroud has been reduced by averaging several areas of a similar type.

VII. Results

The absolute spectral reflectances of two clear (unstained) areas of the Shroud along with the mean of five clear areas are shown in Fig. 6. This mean has formed the basis for the calculation of the relative spectral reflectances described below. Figure 7 shows the spectral fluorescence of four clear areas on the Shroud.

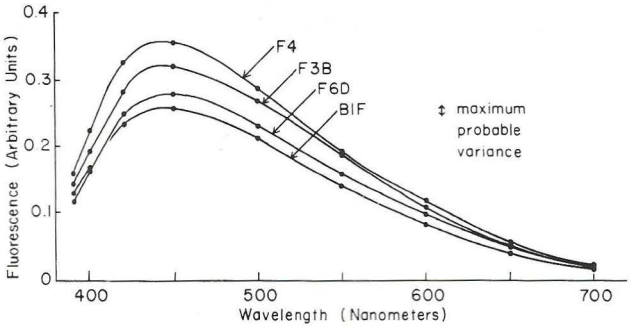

Fig. 7. Spectral fluorescence with excitation at 365 nm of four clear areas on Shroud.

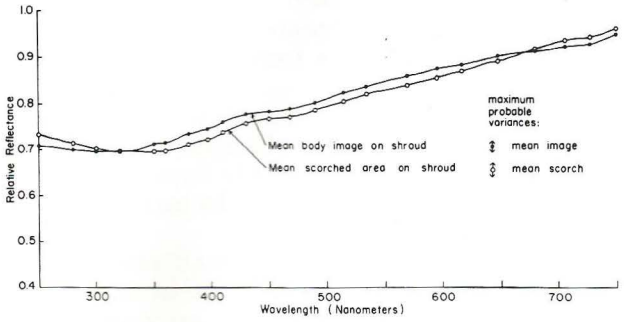

Fig. 8. Relative spectral reflectance of the mean of five body image areas (nose-F8F, cheek-F8E, calf-B1E, two points on back of neck-B6A, $B6A_1$) and the mean of three scorched areas (F8H, B3E, $B3E_1$).

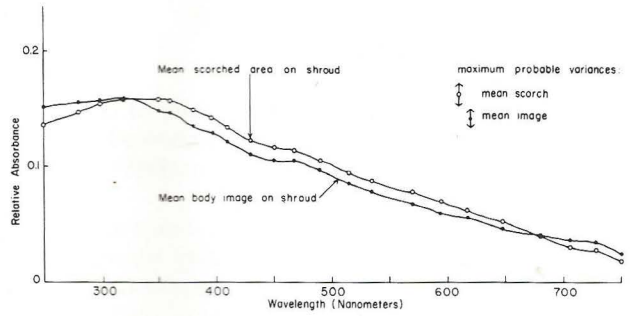

Fig. 9. Apparent relative spectral absorbance of the mean of five body image areas (nose-F8F, cheek-FE, calf-B1E, two points on back of neck-B6A, $B6A_1$) and the mean of three scorched points (F8H, B3E, $B3E_1$).

The relative spectral reflectance of the mean of five body image areas compared with that of the mean of three scorched areas is shown in Fig. 8. The inverse log of these is replotted in Fig. 9 as apparent relative spectral absorbance. Note the close similarity between the body imge area and the scorched area curves.

The relative spectral reflectances of four individual body image areas are shown in Fig. 10. These were all referenced to the same mean clear area. The unusual falloff of reflectance of area F3A > 600 nm may be due to the difference in the underlying cloth more than to the difference in the stain. Compare this with the reduction in slope >600 nm of the absolute reflectance of clear point F4 (Fig. 6), which is located on the Shroud in the same vicinity as point F3A.

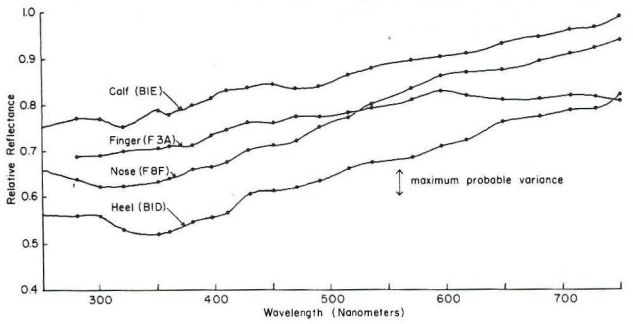

Fig. 10. Relative spectral reflectance of four body image areas on the Shroud (calf, finger, nose, and heel).

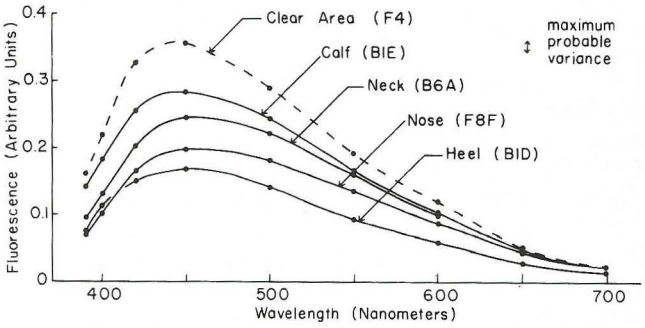

Fig. 11. Spectral fluorescence with excitation at 365 nm of four body image areas on the Shroud (calf, neck, nose, and heel) compared with one clear area.

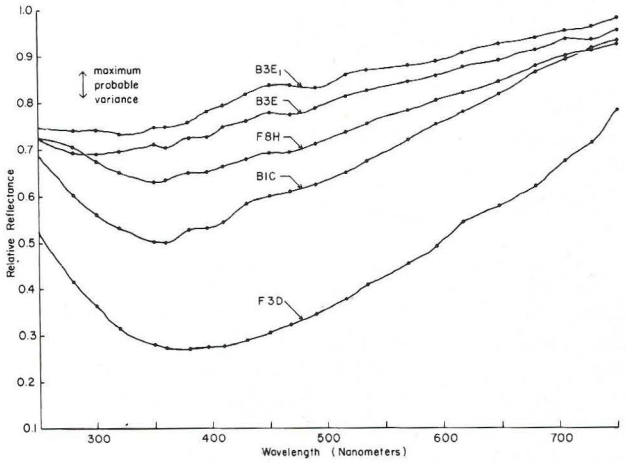

Fig. 12. Relative spectral reflectance of five scorched areas on the Shroud.

Figure 11 shows the spectral fluorescences of four body image areas compared with one clear area. Comparing this with Fig. 10 the lower the reflectance of the area, the lower is the fluorescence. Also as the fluorescence level is reduced, the peak shifts slightly to longer wavelengths.

The relative spectral reflectances of five scorched areas of varying density are shown in Fig. 12. Their

spectral fluorescences are shown in Fig. 13. Again as the reflectance is reduced, the fluorescence is reduced. Also the shift of the peak fluorescence to longer wavelengths as the fluorescence level is reduced is evident.

The relative spectral reflectance and apparent relative spectal absorbance of the mean of four bloodstained areas are shown in Figs. 14 and 15, respectively. The relative spectral reflectances of four individual bloodstained points are in Fig. 16. Figure 17 shows the spectral fluorescences of individual bloodstained points. Again as the reflectance is reduced, the fluorescence is also reduced. There is little evidence of shifting of the peak fluorescence to longer wavelengths.

Figure 18 shows the locations on the Shroud of the areas measured.

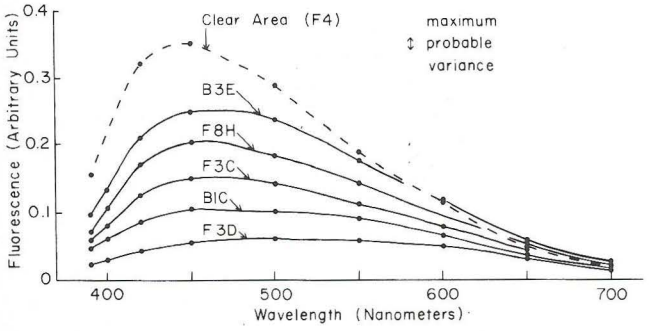

Fig. 13. Spectral fluorescences with excitation at 365 nm of six scorched areas on the Shroud compared with one clear area.

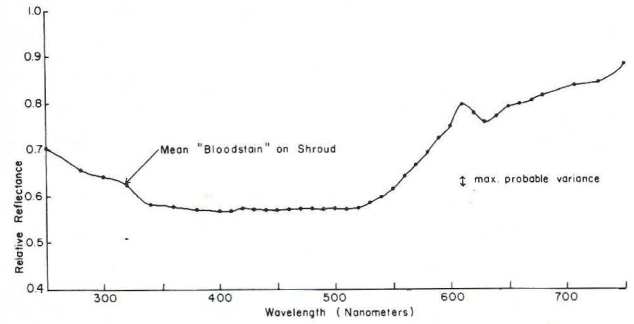

Fig. 14. Relative spectral reflectance of the mean of four bloodstained areas on the Shroud (wrist-F3E, side-F6B, forehead 3 mark-F8C, and back-B3C).

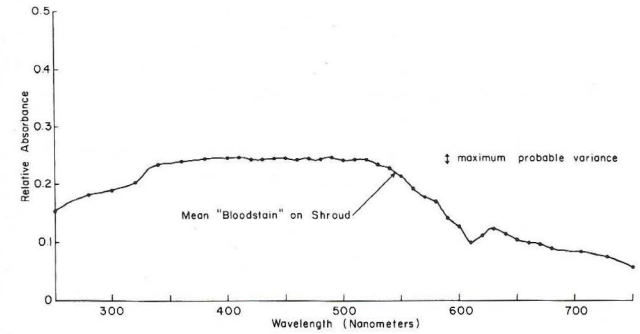

Fig. 15. Apparent relative spectral absorbance of the mean of four bloodstained areas on the Shroud (wrist-F3E, side-F6B, forehead 3 mark-F8C, and back-B3C).

VIII. Observations

The cloth itself is of a medium weight, somewhat heavier than shirt cloth. The weave is very tight. The cloth is in excellent condition, extremely soft and pliable with no readily apparent degradation of strength. It has a somewhat mottled appearance throughout, which corroborates the variations found in the spectral reflectance.

Viewed without magnification the image appears to have the same sepia coloring as the lightest of the scorch marks. The coloring of the image does not seem to come from a particular matter. Under backlighting the image is extremely faint.

In reflection the bloodstains appear darker than the image and are slightly more reddish in hue. With backlighting the bloodstains stand out markedly as dark reddish brown spots.

Microscopic observations were made by other workers and are described elsewhere.

IX. Conclusions

The spectral reflectance characteristics of the body image areas appear identical to those of known 1532 A.D. scorched areas within the variations found on the cloth as a whole (Figs. 8 and 9).

Comparing Figs. 11 and 13 the body image areas and scorched areas have essentially similar fluorescence characteristics. The main effect of these stains seems to be the quenching of the fluorescence of the underlying cloth. In addition these stains seem to exhibit a low level fluorescence of their own in the 600–700-nm region. This lower level fluorescence is somewhat more pronounced with the scorched areas than the body image areas.

The spectral reflectances of the bloodstains on the cloth have a substantially different shape than those of the body image or scorched areas (Figs. 14 and 15). This corroborates the visual observations described above. The bloodstains appear to quench the fluorescence of the underlying cloth but do not appear to be fluorescing themselves (Fig. 17). Others are currently working on further analysis of these so-called bloodstains.[3]

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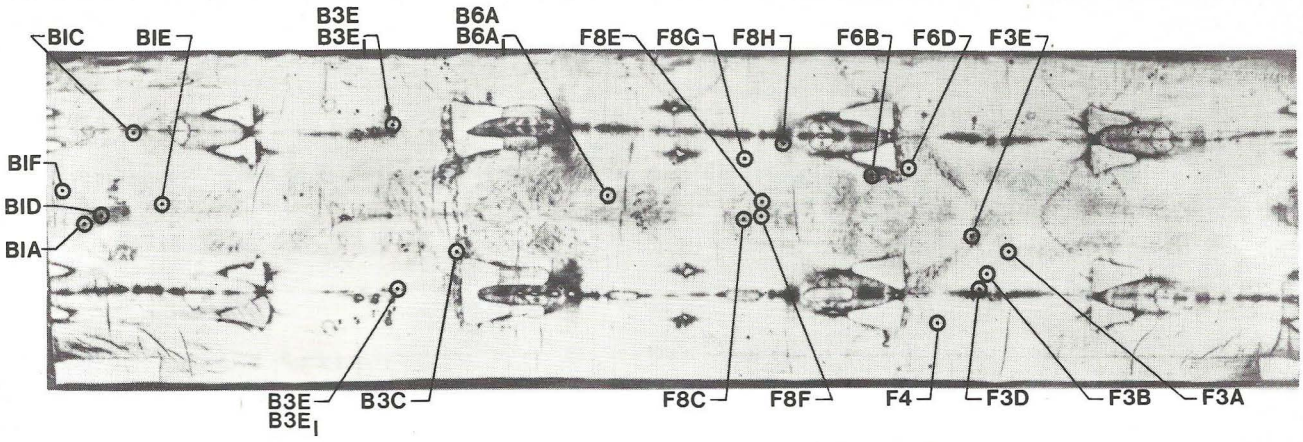

Fig. 18. Shroud showing locations of data points.

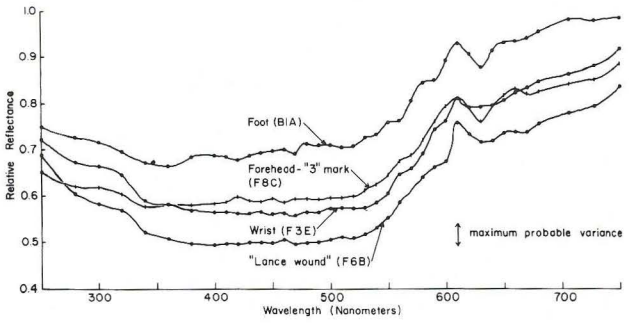

Fig. 16. Relative spectral reflectance of four bloodstained areas on the Shroud (foot, forehead-3 mark, wrist, lance wound).

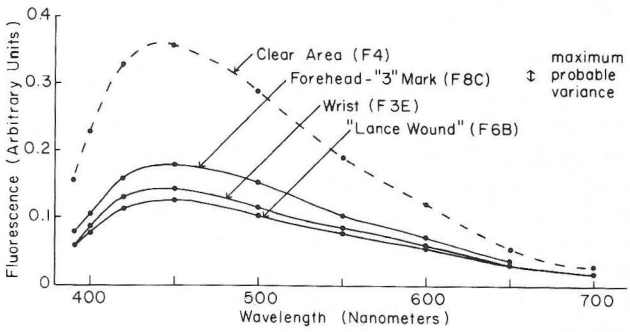

Fig. 17. Spectral fluorescence with excitation at 365 nm of three bloodstained areas on the Shroud (forehead-3 mark, wrist, and lance wound) compared with one clear area.

The authors wish to express their thanks to the members of the STURP research team for their help, advice, and encouragement and to the employees of Oriel Corporation for their assistance in the design, construction, and handling of the reflectometer.

Finally we would like to thank especially Cardinal Ballestrero, Archbishop of Turin, and all the Church authorities who graciously agreed to the performance of these independent investigations and who made us feel so welcome in Turin.

References

1. I. Wilson, *The Shroud of Turin* (Doubleday, Garden City, N.Y., 1978).
2. *Proceedings, 1977 United States Conference of Research on The Shroud of Turin* (Holy Shroud Guild, 294 East 150th St., Bronx, N.Y. 1977).
3. S. F. Pellicori, Appl. Opt. **19,** 1913 (1980).
4. J. S. Accetta and J. S. Baumgart, Appl. Opt **19,** 1921 (1980).