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On Radiocarbon Dating of the Shroud of Turin

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Abstract: In the same issue of Nature that the radiocarbon dating results for the Shroud of Turin were published, Phillips hypothesized that neutron radiation could have altered the reported dates. In addition to making the Shroud appear younger than its true age, neutron radiation would have produced significant amounts of radioactive chlorine ^{36}Cl in the Shroud. Two earlier papers showed that ultraviolet (uv) fluorescence intensity is non-uniform over the surface of the Shroud. The right side of the Shroud fluoresces more than the left side, and the Shroud's dorsal side fluoresces more than its frontal side. The highest uv fluorescence occurs in the center of the Shroud's dorsal side. The shape of the Shroud's average uv fluorescence intensity spatial variations very closely matches the shape of the spatial radiocarbon dating variations calculated by Rucker in his computer simulation of Phillips' neutron hypothesis. Experimental results given here for neutron irradiated modern linen demonstrate that such radiation increases the uv fluorescence intensity of linen. Experimental results also show that neutron radiation greatly increases the ^{36}Cl content of modern linen. Thus, neutron radiation can explain both the Shroud's anomalous radiocarbon dating and its unique spatial uv fluorescence properties. In order to test Phillips' hypothesis additional research on the Shroud is required, and suggestions for such follow up research are given.

Keywords: Shroud, Radiocarbon, Neutron, Radiation, Ultraviolet, Fluorescence Intensity, Radioactive Chlorine

1. Introduction

The Shroud of Turin which consists of linen approximately 14.25 ft long by 3.58 ft wide is one of the most studied relics in history. The Shroud has an image of a crucified man on it, and many believe the image is that of Christ. In 1988 three laboratories carried out radiocarbon (^{14}C) dating of the Shroud [1]. The results of this dating gave a range of AD 1260 to 1390 indicating that the Shroud was a medieval cloth. The statistical analysis of the ^{14}C data given in [1] was subsequently questioned by van Haelst [2] who showed that the data contained a systematic bias. The portion of the Shroud tested was approximately 1.5 inches long by ¾ inch wide and yet the ^{14}C dates differed by over 200 years from one end of the test sample to the other. All the ^{14}C dates should have been close to one another. More recently, a paper by Schwalbe and Walsh in the International Journal of Archeaology [3] raised the question of whether the different cleaning methods used by the three laboratories could be the cause of the differences in their radiocarbon dating results. Casabianca et al [4] carried out a thorough statistical analysis of the raw data that were collected during the 1988 ^{14}C dating study. It took a court order for this data to be released by the owner of the data, the British Museum. Casabianca et al [4] conclude that their statistical analysis reinforces the argument against the goodness of the ^{14}C dating of the Shroud, and suggests the presence of serious incongruities among the raw measurements. They further state that the measurements made by the three laboratories on the Turin Shroud samples suffer from a lack of precision which seriously affects the reliability of the 95% AD 1260–1390 interval. All authors recommend that additional testing be done on the Shroud.

By contrast to the ^{14}C results, essentially all other data on the Shroud, including floral, numismatic, fabric and historical data, point to a much earlier origin. Recent research by Fanti and Malfi using both FT-IR and Raman spectroscopy and mechanical property testing [5] date the Shroud to Christ's time. Fanti and Malfi's dating results are: FTIR 300 BC ± 400 yrs, Raman 200 BC ± 500 yrs, and mechanical testing 372 AD ± 400 yrs [5]. All three results are compatible with Christ's time.

Since the publication of the ^{14}C dating results a number of explanations for the medieval dates based on the idea of contamination of the sample site have been presented. In 1990 Harry Gove, who pioneered the mass spectrometry method used for the ^{14}C dating, addressed the contamination issue [6]. Gove states:

"Even if it did exist in the form of contemporary organic carbon, which is one way the apparent age can be reduced, 64% of the Shroud sample would have to be such contamination and only 36% of 2000-year-old carbon to change the measured date from the first century AD to the 14th century. Visible inspection by the author of the Shroud sample received by Arizona before it was cleaned made it clear that no such gross amount of contamination was present."

A later paper [7] presented results on an examination on a piece of the Shroud that was split from one of the Arizona samples ^{14}C dated in 1988. These authors found "no evidence of either coatings or dyes and only minor contaminants." More recently Rucker [8] has provided a detailed discussion about why the carbon dating of the Shroud is not explained by normal contamination. Rucker's calculations indicate that anywhere from 60 to 80% of the carbon in the Shroud sample would have to come from contamination, and such a large amount would be easily visible. In spite of the statistical questions raised and considering that contamination can be ruled out, the fact that the ^{14}C dating would be off by over 1000 years does not seem possible. The very large discrepancy between the medieval ^{14}C dates and the first century appears very likely to be due to another cause, and it does not appear that the ^{14}C dating was significantly affected by sample contamination.

At present science cannot explain how the image on the Shroud was formed, and as a result other, alternative explanations have been put forward. In a 1989 correspondence to the journal Nature [9] Phillips hypothesized that a neutron flux could have increased the ^{14}C content in the Shroud thereby affecting its ^{14}C dating. The neutron radiation would also have produced radioactive chlorine ^{36}Cl and radioactive calcium ^{41}Ca in the Shroud. Rinaudo [10, 11] worked on Phillips' hypothesis and expanded it to include a radiation mechanism for formation of the Shroud image itself in addition to the change in the ^{14}C date. This paper discusses two measureable effects that would have been produced if Phillips' hypothesis were true. These effects are: 1. the spatial uv fluorescence properties exhibited by the Shroud which could result from fluence correlation between neutron flux and uv fluorescence intensity of linen; and 2. the production of ^{36}Cl in neutron irradiated linen. To test Phillips' hypothesis additional experimentation on the Shroud is required.

A very interesting simulation study of Phillips' hypothesis was carried out by Rucker [12]. He used a computer software package, MCNP (Monte Carlo N-Particle [13]), that was developed at the Los Alamos National Laboratory to calculate neutron distributions due to neutron emission and diffusion. Rucker developed a very detailed geometric model of a tomb that would have existed in the first century AD. Then he carried out extensive simulations using the MCNP software. Rucker's calculations showed that there would be a very wide range of ^{14}C dates if samples were taken from various areas of the Shroud. A summary of Rucker's simulation results is given below. A very detailed description of Rucker's rationale, simulation method, and results is given in his paper [12].

In two earlier papers twenty two of the uv photos of the Shroud that Vern Miller took in 1978 as a member of the Shroud of Turin Research Project (STURP) were analyzed [14, 15]. The uv photos were cast into the CIE L*a*b color space [16] to get pixel intensity. It was shown that the Shroud exhibits very unique spatial average uv fluorescence intensity characteristics. Its right side fluoresces more than its left side and where comparisons can be made the fluorescence from the dorsal side of the Shroud is stronger than fluorescence from the frontal side. Lastly along the center of the Shroud, average fluorescence intensity is stronger near the center of the image on the Shroud than near the image of the head or feet. Rucker's MCNP simulation of neutron irradiation of the Shroud [12] exhibits almost identical properties in terms of predicted ^{14}C dates. A comparison of the predictions of Rucker's MCNP simulation and the average uv fluorescence properties of the Shroud is given in this paper.

The strong spatial agreement between Rucker's simulation results and the average uv fluorescence intensity results determined from photos of the Shroud, raises the interesting question of whether neutron radiation and uv fluorescence of linen can be related to one another. A series of neutron irradiation experiments on modern linen have been conducted with the result that neutron flux and uv fluorescence intensity are indeed correlated. As the neutron flux to which linen is exposed increases, so does its uv fluorescence intensity. Experimental results for the neutron radiation experiments are given in this paper, and they together with Rucker's simulation and average uv fluorescence intensity results support Phillips' hypothesis that the Shroud could have been exposed to neutron radiation. Finally a new experimental result on the production of ^{36}Cl in neutron irradiated linen that supports Phillips' hypothesis is also discussed.

This paper consists of five parts: 1. a review of Rucker's simulation of Phillips' hypothesis; 2. a review of uv fluorescence intensity results for the Shroud; 3. new experimental results on the correlation between neutron flux and uv fluorescence intensity of linen; 4. a new experimental result on the production of ^{36}Cl in neutron irradiated linen; and 5. a summary and recommendations for additional research.

2. Rucker's MCNP Simulation Results

At the 2014 St. Louis Shroud Conference Robert Rucker gave a presentation in which he used a computer software package [13], MCNP (Monte Carlo N-Particle), that was developed at the Los Alamos National Laboratory to simulate neutron emissions. Rucker stated that the main assumption in his simulation is: 'that the thermal neutrons were emitted homogeneously (uniformly) from within the body and isotropically (uniformly) in all directions.' The total neutron fluences simulated by Rucker ranged between ~1.x10^{14} and 1.25x10^{15} n/cm^2. Experimental results for neutron irradiation of modern linen in this fluence range are discussed below. Rucker's simulation calculated how emitted neutrons would have affected the ^{14}C dating over the entire Shroud [12]. Figure 1A gives a plot of the predicted ^{14}C dates along the midline of the body ([12], p. 25).

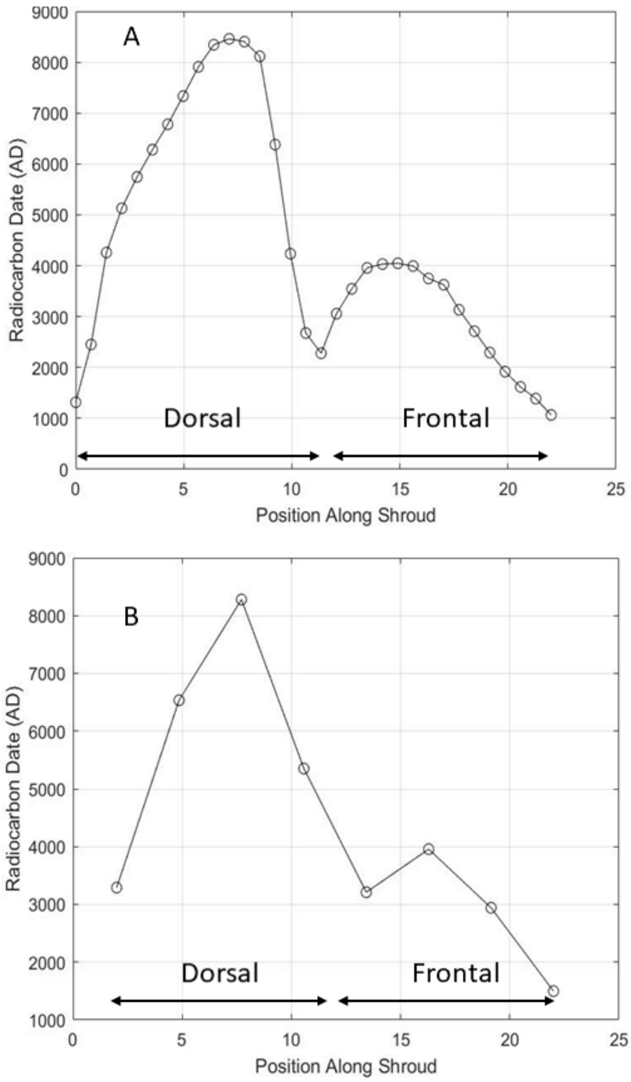

Figure 1. *A. Midline ^{14}C calculated dates [12]. B. Averaged midline ^{14}C calculated dates [12].*

As can be seen the predicted ^{14}C dates go through 2 maxima. The space between the dorsal and frontal arrows is where the Shroud wraps around the head. It can be noted that Rucker's simulation predicts that many areas of the Shroud would date to the future because of the effects of neutron radiation. Rucker's simulation was normalized to the 1260AD ^{14}C date determined in 1988 for the corner of the Shroud that was ^{14}C dated [1]. His simulation had a slope of ^{14}C dates that matched that of the three laboratories that carried out the ^{14}C dating. Additional information is given in [12]. If additional ^{14}C testing of the Shroud is carried out Rucker's predictions can be tested. Rucker calculated 32 points along the simulated midline of the Shroud. The x axes in Figure 1 plot these points from 0 to 22 so that the plots can be compared to the average uv fluorescence intensity plots below, which are based on the grid layout used by Vern Miller for his uv photography.

The following are Rucker's very interesting key conclusions about ^{14}C dating of areas of the Shroud [12]:

The values (^{14}C dates) are higher near the elbows than near the knees because the elbows are closer to the center of the body mass and so would be closer to where more neutrons would be emitted.

The values (^{14}C dates) are higher near the back (dorsal) image than near the front image because neutrons reflected from the limestone bench below the dorsal half of the cloth would have caused a higher fraction of the neutrons to pass through the dorsal half of the cloth multiple times, thus causing a greater shift in the predicted dates.

The values (^{14}C dates) on the right side of the image are higher than on the left side of the image because the locations on the right side of the image would have been closer to the back wall of the tomb, assuming the head was toward the right side as the body lay on the back bench in the tomb. This is because neutron reflection from the limestone wall at the back of the tomb would have caused a higher fraction of the neutrons to pass through the right side of the cloth multiple times, thus causing a greater shift in the predicted dates.

Conclusion 1 is indicated by the fact that there are 2 maxima in Figure 1A at the midsection of the body wrapped in the Shroud; Conclusion 2 is indicated by the fact that the frontal maximum shown in Figure 1A is lower than the dorsal maximum. If neutrons affect the uv fluorescence intensity of linen then there should be a correlation between the simulated ^{14}C dates and uv fluorescence intensity. The uv fluorescence intensity of the Shroud is discussed next.

3. Shroud uv Image Intensity Results

3.1. Images Studied

In 1978 over 30 scientists involved in the Shroud of Turin Research Project (STURP) carried out an extensive scientific study in Turin Italy. A technical photography team was included in the STURP project. Vern Miller was the lead photographer on the STURP team. Approximately 1000 high quality images of the Shroud were taken by the STURP photographers [17]. In April 2019 199 high quality photos taken by Miller were published on the web (https://www.shroudphotos.com/). Included in Miller's photos were 44 uv images, 22 of which were analyzed in earlier papers by McAvoy [14, 15].

The uv photos Miller took were induced visible fluorescence photos in which an exciter filter was used on a uv source to eliminate visible light and a barrier filter was used on the camera to eliminate uv reflectance. The uv light source induces fluorescence in the object being photographed. With fluorescence, absorbed uv light is re-emitted at a longer wavelength in the visible light range. Eight of Miller's uv photos (E3, E6, E8, E12, E15, E17, E20, E22) covered the right side of the Shroud and another eight the left side (B2, B5, B9, B12, B15, B17, B20, B22). Each of these 16 images cover a different region of the Shroud which is approximately 1.79 ft by 1.85 ft in size. The remaining 6 images (D3, D8, D12, D15, D17, D21) analyzed by McAvoy were taken down regions in the center of the Shroud and they are approximately 1.79 ft by 1.85 ft in size. Details of how these images were produced and transferred to the web are given by McAvoy [15].

The 22 uv images were downloaded from the web, resized and converted from the RGB (red, green, blue) color space to the CIE L*a*b color space [16] in which L gives the image intensity and color is contained in the a-b plane. It was shown that Miller's uv lighting was not uniform [14, 18]. As a result in order to compare the uv images to one another in terms of their fluorescence intensity, L, it was necessary to average the intensity over each image. Recently McAvoy showed that 3 of the center D images analyzed in [14] should have been different, since they were produced with different camera parameters and color filters than the other 19 uv images analyzed [15]. McAvoy also showed how to correct the web images back toward their original color [15]. In this paper the 3 new images plus the other 19 images, corrected toward their original color, are analyzed. Color corrected web image D8 from the center of the Shroud is shown in Figure 2A [15].

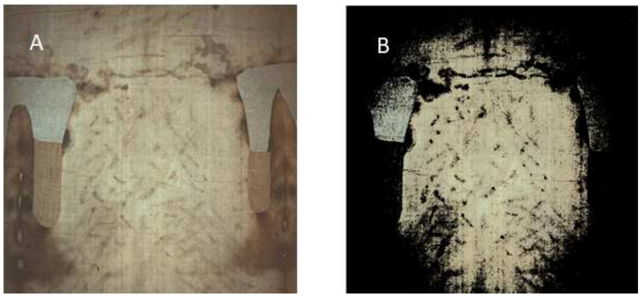

Figure 2. *A. Color corrected image D8 from web [15]. B. Cluster of image D8 with highest intensity.*

3.2. Uv Fluorescence Intensity Results

When the average fluorescence intensities of Miller's uv Shroud images are compared they show some very unique and interesting spatial properties [15]. A plot of the center and two side average uv intensities using the 3 new images plus the other 19 images, corrected for color, is shown in Figure 3A. The y axis gives the average uv fluorescence intensity of a region and the x axis is the position along the Shroud, e.g. for D8 it is 8, and for E17 it is 17, etc.

Note that the Shroud was folded over and the feet are associated with both positions 2, 3 and 21, 22. The dorsal side is associated with positions up to and just shy of 12, and the frontal side with positions just past 12 and up to 22. The gap near position 12 is where the Shroud was folded over the top of the head. Points at position 12 are predominately associated with the dorsal side of the Shroud. The average uv fluorescence intensity at red point E8 is missing due to the fact that image E8 was an outlier [14]. Also only 6 center images were available for analysis since image D6 was an outlier [14]. As Figure 3A shows the average uv fluorescence intensity varies over the area of the Shroud. This pattern of spatial uv intensities is very interesting since one could have anticipated that there would be only a small variation in fluorescence intensity over the Shroud. Along the left side of the Shroud (blue curve) there are 8 points. Frontal and dorsal points at the same part of the body can be compared for the blue curve by comparing the following pairs of points along the x axis: points 2 and 22, points 5 and 20, points 9 and 17 and points 12 and 15. For the right side of the Shroud (red curve) points 3 and 22, 6 and 20, and 12 and 15 can be compared. Since red point 8 is missing an 8-17 comparison cannot be made. For the center of the Shroud (green curve) points 3 and 21, 8 and 17, and 12 and 15 can be compared.

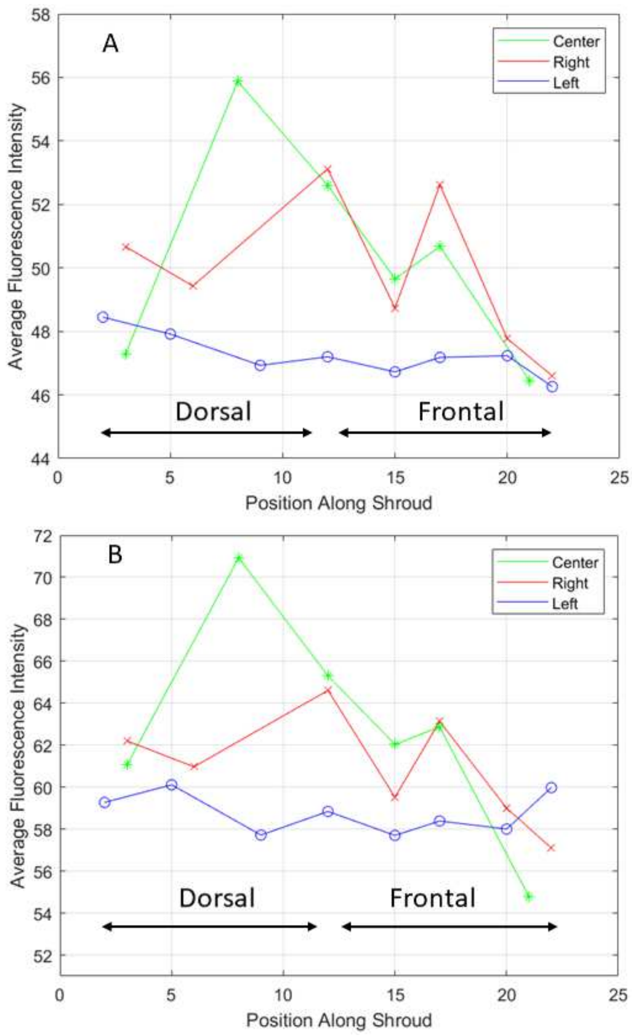

Figure 3. *Average fluorescence intensity at points along Shroud. A entire image [15], B most intense cluster.*

The following is a summary of the unique spatial average uv fluorescence intensity properties of the Shroud [15]:

Average uv fluorescence is highest in the mid-section of the dorsal image on the Shroud (green point D8).

Except for the left side blue (B9 B17) comparison the other nine comparisons show that the dorsal side of the Shroud fluoresces more (has higher average intensity) than the frontal side

All of the right side sections of the Shroud (red curve) fluoresce more (have higher average fluorescence intensity) than the corresponding left side sections (blue curve).

Along the center D green images average uv fluorescence intensity goes through 2 maxima at points 8 and 17.

Along the center D green images average uv fluorescence intensity drops off sharply toward the feet.

These uv fluorescence patterns are unique and very interesting. An explanation for them is important in attempting to understand the Shroud.

To compare the average uv fluorescence intensity properties of the Shroud to Rucker's simulation, the results in Figure 1A were averaged to give Figure 1B. Since 8 uv images covered the length of the Shroud using Miller's grid and there are 32 points in Figure 1A, groups of 4 points along the Shroud were averaged to generate the 8 averaged points in Figure 1B. The first point in Figure 1B is the average of points 1 to 4 in Figure 1A, the second point the average of points 5 to 8, and so on. The 8 averaged points are evenly distributed between 2 and 22 on the x axis.

The center images in Figure 3A (green curve) can be compared to Figure 1B. As can be seen there is a very strong agreement between the shapes of these 2 curves. If one takes Rucker's 3 simulation conclusions discussed above and substitutes uv fluorescence intensity for ^{14}C dating values, the uv conclusions and Rucker's conclusions line up very closely with one another. Compare uv conclusions 1 to 3 above with Rucker's simulation conclusions 1 to 3. Figure 1B shows double maxima in predicted ^{14}C age, which agrees with uv conclusion 4. Similarly Figure 1B shows that ^{14}C dates drop off sharply toward the feet, in agreement with uv conclusion 5. The fact that the uv fluorescence intensity results and the results from Rucker's simulation line up so closely raises the question of whether there could be a relationship between neutron radiation and uv fluorescence intensity. As a result, experimental research on this question was carried out.

4. Experimental Results for Neutron Irradiation of Modern Linen

4.1. Linen Used and Radiation Facility

The linen used for the neutron experiments was purchased from Rawganique USA, Inc (https://www.rawganique.com). The linen was Evening Sand Dunes natural linen. According to the company the linen is made from 100% organically grown European flax. The linen is chemical free, unbleached, undyed and it is woven in house at Rawganique Atelier in Europe for true purity.

For neutron irradiation the linen was cut into pieces approximately 4.5 in by 2.75 in. The linen was then rolled up and placed in semi-clear polypropylene cylindrical vials 2 7/8 inches high and 1 inch in diameter. These vials were placed in the nuclear reactor used for this study. Neutron irradiation was carried out at the University of Massachusetts Lowell Research Reactor (https://www.uml.edu/Research/RadLab/Neutron-Facilities.aspx). The reactor has various in-core sample facilities capable of producing a thermal neutron flux level of $2x10^{12}$ n/cm^2-s at the maximum operating power of the reactor. The reactor power can be adjusted to decrease the thermal neutron flux as needed. The linen samples packaged in polyethylene vials were inserted into sealed aluminum tubes. The aluminum tubes were placed into the reactor sample location for irradiation. The thermal neutron flux and irradiation time were adjusted to match the desired thermal neutron dose for each sample and the fast fluence variation through the sample thickness was minimized via a single 180° rotation of the sample canister at the midpoint of the irradiation period. Eight linen samples within different polypropylene containers were irradiated at neutron fluences (n/cm^2) of $2.5x10^{14}$, $5x10^{14}$, $7.5x10^{14}$, $1x10^{15}$, $2.5x10^{15}$, $5x10^{15}$, $7.5x10^{15}$, and $1x10^{16}$. Lind, et al. [19] presented experimental results for the production of ^{14}C by neutron radiation of modern linen. Lind et al. [19] found experimentally that a neutron fluence of only 1.07×10^{14} n/cm^2 could produce a quantity of ^{14}C that could change the ^{14}C date of the Shroud from 33 to 1260 to 1390. The ^{14}C is produced primarily by neutron absorption by nitrogen in the linen.

4.2. Photography Procedure and Computer Processing of uv Images

In taking the uv photos a chemistry lab stand was used to support the camera and the uv flashlight employed. The uv flashlight was held approximately perpendicular to the base of the lab stand on which the linen was placed and the camera took images at an angle. The set up used is shown in Figure 4.

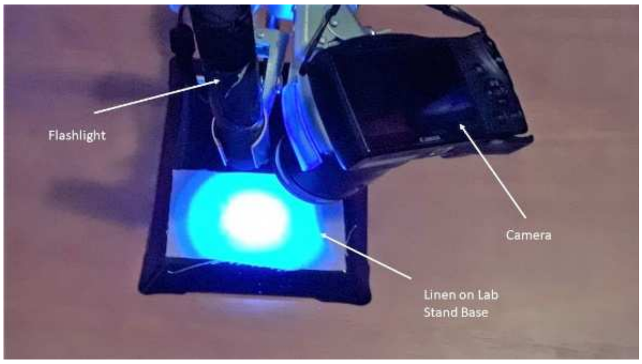

Figure 4. *Uv camera set up.*

Details on the uv flashlight, camera, and uv filters employed are given in the Appendix 1.

The height of the flashlight above the linen photographed was determined by trying to duplicate the power that Miller used in photographing the Shroud [20]. A discussion of how the height of the flashlight was calculated is given in the Appendix 2. The linen samples were placed on the base of the lab stand for photography. The photos were taken in a darkened room and 2 replicate photos of each image were taken. Four different locations on all linen samples were photographed, giving a total of 8 images for each sample. Figure 5A shows a photo taken of a sample of non-irradiated control linen. This photo has a pixel size of 6000x4000 and it was analyzed using a program written in MATLAB®.

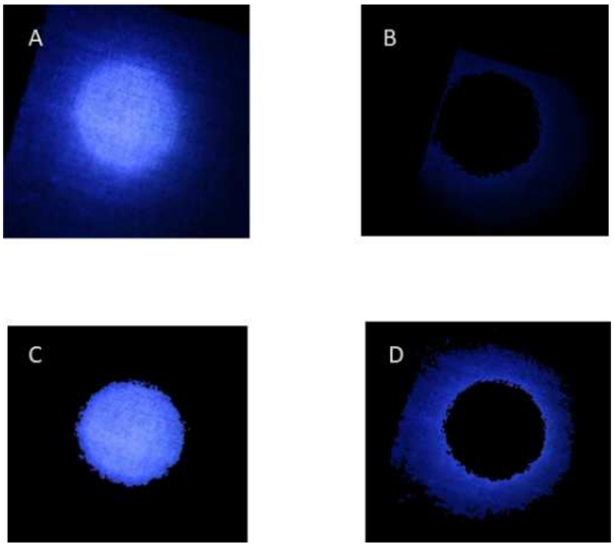

Figure 5. *A uv photo of modern linen. B to D cluster images.*

The following steps were used in the MATLAB® analysis. The photo was input into MATLAB® and the rgb2lab routine used to convert it to the CIE L*a*b color space [16]. Next the MATLAB® imsegkmeans function was used to cluster images into 3 clusters based on their fluorescence intensity values, L, in the converted image. Figures 5B to 5D show the three clusters calculated for the image in Figure 5A. After clustering the average fluorescence intensity for each of the 3 clusters was calculated. Only the cluster that had the largest average intensity, cluster 2 in Figure 5C, is used in the analysis below. This cluster was always the one associated with the intense circular region generated in the center of a sample by the uv flashlight. It was also the cluster that had approximately the same watts/in^2 as Miller used for his photos.

4.3. Comparison with Miller's Setup

A comparison with the uv filter setup that Miller used can be made by referring to Figure 1a of his paper with Pellicori which gives % transmittance [20]. Miller used two xenon uv light sources that were focused at 45 degrees on the section of the Shroud being photographed. An exciter filter was used on the uv source and a barrier filter was used on the camera. Transmittances for the exciter and barrier filters can be estimated from Figure 1a in his paper [20]. In [20] it is stated that "the filters needed to attenuate to a level of 10^{-4} since visible light from the xenon tubes would completely swamp the weak fluorescence signals." The product of the transmittances of the exciter and barrier filters gives the fraction of light from the xenon sources that enters the camera. Using estimated transmittances it was found that the filtering Miller used exceeds his specification by a factor of approximately 2.4 to 2.5 in the 410-415 nm region. The small amount of non-filtering of light in the 410-415 nm region could have increased the intensity of Miller's uv fluorescence images.

5. Results from Modern Linen Experiments

A total of 80 uv photos were taken and Figure 6A gives the results for the mean fluorescence intensity, L, of the most intense, center cluster of the modern neutron irradiated linen and two controls (0 fluence). Figure 6A shows that there is a variation in CIE L*a*b fluorescence intensity, L, with the four positions photographed on a sample. Figure 6B gives a plot of the average of the mean CIE L*a*b fluorescence intensities, L, for the 2 control samples and for the irradiated samples.

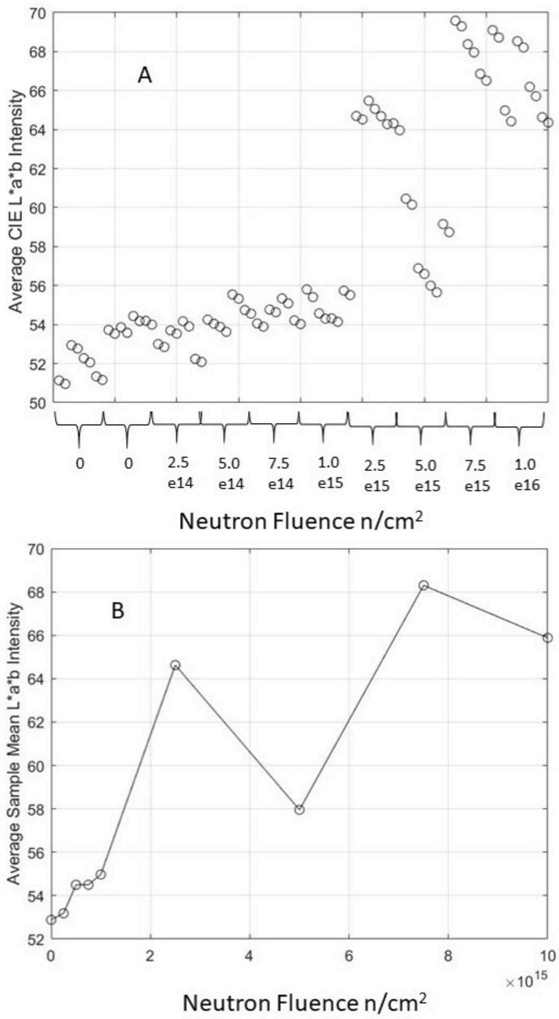

Figure 6. *A. Mean uv fluorescence intensity of modern linen versus neutron fluence for all 80 photos. B. Average sample mean uv fluorescence intensity of modern linen versus neutron fluence with 2 control samples combined.*

In Figure 6B the intensities of the 2 control samples are averaged and there is only a single point at 0 fluence. As can be seen there is an increasing trend in average fluorescence intensity, L, with neutron fluence. Figures 6A and 6B show that there is a dramatic increase in average fluorescence intensity that occurs between fluences $1x10^{15}$ and $2.5x10^{15}$ n/cm^2. It is not clear why the average fluorescence intensities for the $5x10^{15}$ and $1x10^{16}$ n/cm^2 fluences are lower than those of the preceding fluence in each case. The trend in average uv intensities is confirmed by the Mann Kendall statistical test [21, 22] which gives a probability p=.0012 for no trend. For the range of neutron fluences used in Rucker's MCNP simulation, ~$1x10^{14}$ to $1.25x10^{15}$ n/cm^2 the trend in average uv fluorescence intensities can also be seen, particularly in the raw data shown in Figure 6A. Since average fluorescence intensity increases with neutron fluence, neutron radiation is a potential candidate to explain both the average uv fluorescence intensity spatial patterns measured in the photos of the Shroud of Turin as well as its anomalous ^{14}C dating.

Samples of modern linen were artificially aged by heating to determine if such heat aging affected fluorescence intensity. The procedure used was the same as that discussed by Needles and Nowak [23]. These authors heated linen samples at 180 ^{o}C for times ranging up to 10 hours. Results for heating control linen samples for 1, 3, and 5 hours are shown in Figure 7. Eight uv photos were taken for each control sample. As can be seen heating at 180°C results in very large changes in the linen's average uv fluorescence intensity, from approximately 53 to 77. The heated control samples were noticeably darker compared to the non-heated control samples.

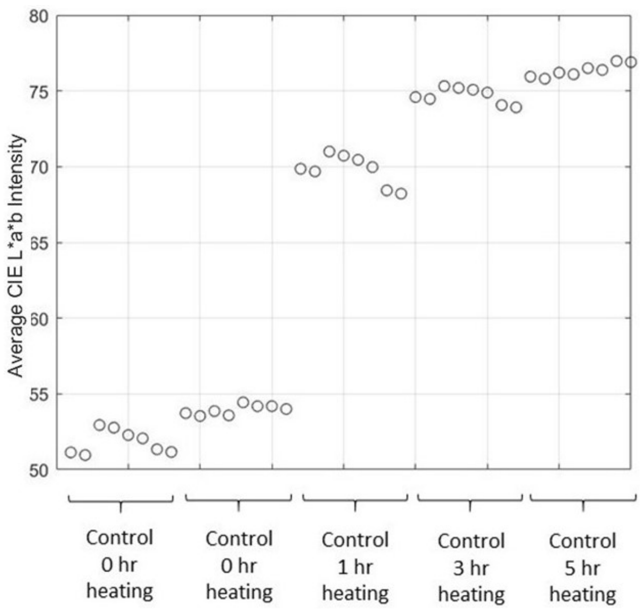

Figure 7. *Mean intensities for heating control linen linen's average uv fluorescence intensity, from approximately 53 to 77. The heated control samples were noticeably darker compared to the non-heated control samples.*

The results for modern linen can be compared to those for the Shroud images on the web [15]. To do so these images were clustered using 3 clusters to determine the most intense cluster, which always occurred in the center of an image. Then the average uv fluorescence intensity of the most intense cluster was calculated. Figure 3B gives a plot of the average uv fluorescence intensity, L, results. As can be seen from Figure 3B the range for the average uv fluorescence intensities of the most intense cluster for the Shroud is roughly 55 to 71. For modern linen Figure 6B shows that the range is very similar, roughly 53 to 68. For the neutron fluence range simulated by Rucker, ~$1.x10^{14}$ and $1.25x10^{15}$ n/cm^2 [13], Figure 6B shows that the change in average sample uv intensity of modern linen is much smaller, approximately 3.5 units, from 53 to 56.5.

There are a number of explanations that can be given for these differences in the fluence range simulated by Rucker. First, the Shroud linen is aged and aging could affect its fluorescence properties. The results obtained by artificially heat aging linen show that such heating can have a very strong effect on increasing uv fluorescence intensity. As Figure 7 shows, only 1 hour of heating raised the uv fluorescence intensity from approximately 53 to 70. Natural aging could have a similar effect. Second, as pointed out above in describing Miller's setup it is stated that "the filters needed to attenuate to a level of 10^{-4} since visible light from the xenon tubes would completely swamp the weak fluorescence signals" [20]. However as discussed above, this level of attenuation was exceeded in the 410 and 415 nm range. Thus, reflected uv light though small could have added to the small fluorescence effect that Miller photographed. Third, camera settings and setup used to produce the web images and to photograph the modern linen affect the uv intensity of images. In this study the fstop was 3.5, shutter speed 1/200 sec., and film ISO 400. Increasing the fstop or decreasing the film ISO or decreasing the shutter speed results in lower fluorescence intensities for the irradiated modern linen and vice versa. Images of modern linen taken with an ISO setting of 200 lowered all intensities shown in Figures 6 and 7 by approximately 10 units. Also, the distance between Miller's camera and the Shroud was much larger than the distance between the camera used here and the modern linen. Fourth, the linen used in this study is different from the Shroud linen. Fifth, the uv source and camera filters used in this study have different characteristics than those used by Miller. Sixth, the Shroud sections have burn marks, patches, and blood marks on them, and the blood does not fluoresce [20]. The modern linen has none of these characteristics. All of these factors could contribute to the difference in fluorescence intensities measured in this study compared to those measured from Miller's photos for the fluence range simulated by Rucker. Ultimately to determine whether the hypothesis that the Shroud was exposed to neutron radiation is correct requires additional testing of it.

A possible mechanism for neutron radiation affecting uv fluorescence properties of linen involves proton recoil reactions resulting from the radiation. Gilfillan and Linden [24] studied the effect of neutron radiation on the strength of yarns. They hypothesized that neutron radiation could cause proton recoil reactions in the fibers studied and that these reactions could affect cross linkage in the fibers which in turn could affect fluorescence. An important question that needs to be addressed is what physical mechanism produced the spatial difference in average uv intensities of the Shroud. Neutron radiation is one potential answer to this question.

6. Measurement of ^{36}Cl in Neutron Irradiated Modern Linen and Its Implication for the Shroud

Lind, et al. [19] presented experimental results for the production of ^{14}C by neutron radiation of modern linen. A sheet of unbleached modern plain-woven flax linen was used in their study. Lind et al. [19] found experimentally that a neutron fluence of only 1.07×10^{14} n/cm^2 could produce a quantity of ^{14}C that could change the ^{14}C date of the Shroud from 33 to 1260 to 1390. A piece of irradiated linen from Lind, et al's experimental work was obtained by the author. A small sample of this linen was sent to Lawrence Livermore Laboratory in California to be tested for ^{36}Cl.

Prior to being neutron irradiated the modern linen was thoroughly washed to remove any sizing. The washing should also have removed most inorganic chlorine present in the linen. After washing, the chlorine content of the modern linen was measured as 56 ppm. This chlorine was presumably present primarily as organic chlorocarbons. The sample sent for analysis weighed .1509 gms. The lab measured that the sample contained $1.904\text{x}10^9$ atoms of ^{36}Cl per gm of sample. The weight of ^{36}Cl per gram of sample can be calculated as $(1.904\text{x}10^9)\text{x}35.97/6.02\text{x}10^{23} = 1.1377\text{x}10^{-13}$ gms ^{36}Cl/gm sample. From this value the ratio of gms ^{36}Cl to gms Cl can be calculated using the measurement of 56 ppm Cl in the sample as: ^{36}Cl/Cl ratio $= 1.1377\text{x}10^{-13}/5.6\text{x}10^{-5} = 2.0316\text{x}10^{-9}$. This chlorine ratio is significantly higher than that which naturally would exist in the modern linen or in the Shroud of Turin. In order to demonstrate this point it is necessary to estimate a base line value of ^{36}Cl that would have existed in the Shroud. The same estimate should apply to both the linen studied by Lind et al [19] and to the Sudarium of Oviedo [25].

In the Appendix 3 a detailed discussion on estimating a base line value of ^{36}Cl from the literature is given. It is shown that a reasonable estimate for an upper limit for ^{36}Cl/Cl ratio in the Shroud is 10^{-12}. The laboratory measured value for the ^{36}Cl/Cl ratio in the modern linen studied here is over 2000 times the upper limit estimated for naturally occurring ^{36}Cl in linen. Thus, if similar levels of ^{36}Cl can be detected in the Shroud and/or the Sudarium, that detection would be significant and strongly indicate that these linen cloths had been exposed to neutron radiation. One potential problem with testing the Shroud for ^{36}Cl could come from the fire to which it was exposed in 1532 [26]. The heat from the fire could have been enough to vaporize ^{36}Cl present in the Shroud. This problem should not exist for the Sudarium.

7. Conclusions and Recommendations for Additional Research

This paper has examined Phillips' hypothesis that the Shroud of Turin could have been exposed to neutron radiation. If so, such radiation would have affected the ^{14}C dating of the Shroud and made it appear younger than it is. The results presented here show that neutron radiation can potentially explain the unique spatial uv fluorescence intensity properties of the Shroud. For neutron irradiation of modern linen it has been shown that neutron fluence correlates with the linen's average uv fluorescence intensity measured from photos. This result helps strengthen the case that Phillips hypothesis about neutron radiation affecting the ^{14}C dating of the Shroud is potentially correct.

For the new experimental results modern linen samples were exposed to neutron fluences in the range $2.5\text{x}10^{14}$ to $1\text{x}10^{16}$ n/cm^2, and uv fluorescence photos of the samples taken. It has been shown that for this range of neutron radiation fluences there is a statistically significant increase in average uv fluorescence intensity, L, with fluence level. The average uv fluorescence intensities of modern linen were compared to those of the Shroud calculated from the published images of it. For the fluence range simulated by Rucker, $\sim1.\text{x}10^{14}$ and $1.25\text{x}10^{15}$ n/cm^2, the change in uv fluorescence intensity with neutron fluence is small, compared to the spatial variation in uv fluorescence intensity of the Shroud. A number of possible explanations for this difference are given including: the effect of aging on the Shroud linen, uv leakage in the original Shroud photos, different camera parameters, differences between the modern linen and Shroud linen, and differences between the uv sources and filters used for the photography.

New experimental results have also been presented that agree with Phillips' hypothesis that neutron radiation would create ^{36}Cl in linen. A linen sample irradiated with a neutron fluence of 1.07×10^{14} n/cm^2 was tested for its ^{36}Cl concentration. It was determined that the ^{36}Cl/Cl ratio in the irradiated line was at least 2000 times greater than the maximum value which would occur naturally in linen.

If neutron radiation did not cause the unique uv fluorescence spatial properties of the Shroud an important question to answer is what was the cause. Several additional research projects almost all of which would be non-destructive to the Shroud itself can be suggested to try to answer this question, and to determine if neutron radiation was involved. When Miller took his Shroud uv photos his lighting setup produced uneven illumination [14, 18]. Additional uv photos of the Shroud using even uv illumination should be taken. Such photos would allow the calculation of uv fluorescence intensity at every point on the Shroud so that one would not have to resort to using average values as was done by McAvoy [14, 15, 18]. These new uv photos would allow one to determine the exact spatial variation of the Shroud's fluorescence intensity. In addition to using a standard camera hyper-spectral imaging [27] should be done. Such imaging would help to more clearly define the important wavelengths where the Shroud fluoresces. Hyper-spectral imaging could also be applied to neutron irradiated modern linen to potentially develop a fingerprint of how neutron radiation affects the fluorescence of linen. This fingerprint could then be compared to that found from the Shroud. Finally, vials containing charred material from the Shroud that resulted from the fire in 1532 are available. ^{14}C dating of this charred material, or indeed samples from several different locations on the Shroud could show whether the Shroud was exposed to neutron radiation. If the Shroud were exposed to neutron radiation this radiation would have created very long-lived radioactive isotopes, i.e. ^{36}Cl (half-life 301000 yrs) and ^{41}Ca (half-life 102000 yrs), at levels well beyond those that occur naturally. It may be possible to test the charred material from the Shroud or the Shroud itself for these isotopes. If these isotopes are found at abnormally large levels in the Shroud that finding would help support the neutron radiation hypothesis. In summary neutron radiation has the potential to explain both the Shroud's unique fluorescence properties as well as answer the question about its ^{14}C dating.

Appendix

Appendix 1. Ultraviolet Flashlight, Ultraviolet Filets and Camera

The flashlight used as a uv source was a Convoy S2 model (https://www.naturesrainbows.com/single-post/2017/03/01/365nm-Flashlight-Torch-The-Most-Significant-Innovation-in-UV-Mineral-Lights-in-Years) equipped with a 2 mm thick Hoya U-340 bandpass filter (https://www.ultravioletphotography.com/content/index.php/topic/3161-torch-filter-u-340-vs-u-360/). This flashlight uses an LG 365 nm LED (model - LEUVA33U70RL00) to produce uv light (https://www.nichia.co.jp/specification/products/led/NCSU276A-E.pdf). This LG uv source outputs a sharp peak in uv light centered at 365 nm and ranging between 340 and 400 nm. The 2 mm Hoya U-340 filter cuts off essentially all uv light at and above 400 nm. It does transmit some light above 660 nm. The Hoya filter was the exciter filter. Transmission characteristics of the U-340 filter were estimated from published graphs and they are given in Table 1.

The camera used was a Canon EOS Rebel T7 which was equipped with a Tiffen 52 mm Haze-2A visible and infrared longpass filter (https://tfma.temple.edu/sites/tfma/files/site-pdfs/Tiffenfilter-lens.pdf, pg. 6). Transmissions for the Tiffen Haze-2A filter were estimated from a published graph (https://tfma.temple.edu/sites/tfma/files/site-pdfs/Tiffenfilter-lens.pdf, pg. 6) and they are given in Table 1.

The Tiffen-Haze filter was the barrier filter. The Tiffen-Haze filter transmits an estimated 50% of light at 418 nm and it peaks out at 90% transmission. The camera was set to manual mode with the following parameters: fstop = 3.5, shutter speed (length of time camera shutter is open) 1/200 sec., and ISO 400.

Table 1. *Transmission characteristics of camera uv filters used.*

Wavelength (nm)	Hoya U-340 (estimated)	Tiffen Haze-2A (estimated)
320	.89	0
340	.91	0
360	.76	0
380	.20	0
400	10^{-8}	0
410	0	.28
415	0	.40
420	0	.54
430	0	.70
440	0	.82

Appendix 2. Calculating the Height of the Flashlight Above Linen

The height of the flashlight above the linen photographed was determined by trying to duplicate the power that Miller used [20]. In his setup two 200 watt lights were used, and these lights were focused at 45 degrees on the center of a section of the Shroud being photographed, which can be designated as the intense region of the section. The Shroud is 14.25 by 3.58 ft^2 in area and the 16 photographs taken down the 2 sides cover the entire Shroud. Thus, each photograph covered an area of (14.25*3.58)/16 ft^2 or 3.19 ft^2. The size of the intense region was estimated by clustering 10 of the web based Shroud photos [B5 B12 B17 D8 D12 D15 D17 E6 E12 E17] into three clusters based on their image intensity, L, in the CIE L*a*b space by using the MATLAB® imsegkmeans function. This function segments image intensity into k clusters by performing k-means clustering [28] and returns the segmented labeled output. The cluster with the highest intensity always occurred near the center of each image. Figure 2B shows the clustering result for image D8 in Figure 2A. If Figure 2B is compared to Figure 2A it can be seen that using 3 clusters eliminates fluorescence from most of the blood marks and the patches.

From the clustering results for the uv web images of the Shroud, it was determined that the average fraction of an image covered by the intense region was 0.368. Using this average the power/in^2 that was focused on the intense region on each of the web based Shroud images can be calculated as $400/(3.19*.368*144) = 2.37$ watts/in^2. The flashlight used had an estimated power of 2 watts (https://www.naturesrainbows.com/single-post/2015/05/01/Convoy-S2-365nm-False-Power-Claims) and it generated a circular intense region on the modern linen tested. Varying the height of the flashlight above the linen affected the area of this intense circle. The radius of the circle that matched the power/in^2 used by Miller [20] can be calculated as the square root of $2/(\pi*2.37)$ or .518 in. The flashlight height was adjusted until the intense circle had approximately this radius.

Appendix 3. Estimating a Base Line Level of ^{36}Cl in the Shroud

In determining how much of a change in the $^{36}Cl/^{35}Cl$ ratio resulted from neutron radiation of the Shroud one needs to have a base line value for the ratio. Wikipedia [29] gives a $^{36}Cl/^{35}Cl$ ratio value of (7-10) x10^{-13}. This can be converted to a $^{36}Cl/Cl$ ratio by multiplying by the mass fraction of ^{35}Cl, 0.7576, to give (5.3-7.6)x10^{-13}. ^{36}Cl is produced naturally in the upper atmosphere via nuclear reactions and within solid materials on the earth's surface [30]. The atmospheric ^{36}Cl then falls down to Earth with rainfall.

The following steps are involved in fabricating linen from flax. First, rainfall brings ^{36}Cl to the Earth's surface where it mixes with any ^{36}Cl already present in the soil. Second, water containing ^{36}Cl is taken up into the flax plant. Third, ^{36}Cl is washed out of the flax when it is retted prior to producing linen.

Rainfall ^{36}Cl: Numerous papers have been published on the ratio ^{36}Cl to total Cl in nature ($^{36}Cl/Cl$). One paper [31] that measured the ratio in rainwater in Israel gives ratios of .018 to .5 × 10^{-13}. This paper also reported a value of .116 × 10^{-13} for Jerusalem. Interestingly in this paper sequential testing at a site showed that the $^{36}Cl/Cl$ ratio increased during a rainy period rather than decreasing through wash out as would be expected. The authors attributed this increase to the rain stirring up dust that contained ^{36}Cl and adding this ^{36}Cl to the rainwater sample.

Concentration of Cl by Plants: A number of papers [32-34] have reported on the uptake of ^{36}Cl by plants. Plants can significantly concentrate ^{36}Cl and Cl compared to that in the soil. Sheppard et al [32] used stable Cl as a surrogate for ^{36}Cl and presented results for plant soil concentration ratios (CR equals Cl in plant/Cl in soil). In determining CR's both the plant and the soil samples were dried. Sheppard et al found that CR's in agronomic plants and plant parts sampled at one site varied between 4 and 120, with a geometric mean value of 10. In [32] the highest value reported is for winter rye straw having a CR of 237. Kashparov et al [33, 34] also published CR values for stable chlorine in agricultural plant species. Published results show that plants can significantly concentrate chlorine from the soil into the plants.

Leaching of Cl During Retting: Before using flax to produce linen, the flax plants are retted. According to Wikipedia [35] natural water retting employs stagnant or slow-moving waters, such as ponds, bogs, and slow streams and rivers. The stalk bundles are weighted down, usually with stones or wood, for about 8 to 14 days, depending upon water temperature and mineral content. Kashparov et al [34] discuss an experiment they carried out with plants that had acquired ^{36}Cl that had been sprayed onto the soil in which they were grown. They placed two types of cereal straw in distilled water and measured how much ^{36}Cl was leached from each straw. They found that after 4 hours 93-95% of the ^{36}Cl had been leached from the straw. Leaching was complete after 22 hours. This result strongly suggests that retting flax for 8 to 14 days will remove a very significant amount of any ^{36}Cl that it contains.

Additional data published in [32, 33] can be compared to what was determined for the modern linen sample studied here to help estimate a baseline value for ^{36}Cl in the Shroud of Turin. Reference [32] gives a value of 3600 ppm for the Cl concentration of barley stalks. Reference [33] gives a value of 5330 ppm for the Cl concentration of winter rye straw. Pea straw had an even higher concentration of 8585 ppm. By contrast the Cl concentration of the linen sample studied here was 56 ppm, which is 64 to 153 times lower than the values in [32, 33]. This relatively low value indicates that retting probably leached most of the Cl from the flax prior to the time that the linen was produced.

In section 2 of reference [36] it is stated that the natural $^{36}Cl/Cl$ ratio varies between 10^{-12} and 10^{-15}. The upper value is similar to that in Wikipedia which gives $^{36}Cl/Cl$ ratios of 5.6-7.3x10^{-13}. Based on the above discussion it is reasonable to estimate that an upper limit for $^{36}Cl/Cl$ ratio in the Shroud is 10^{-12}. The real value is probably smaller. Due to retting this upper limit should also apply to both the modern linen studied here and the Sudarium.

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