THE SHROUD OF TURIN: RADIATION EFFECTS, AGING AND IMAGE FORMATION

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Abstract
Many claims have been made that some kind of radiation is "the only way" that the image on the Shroud of Turin could have been produced. This paper investigates the effects produced by different kinds of radiation interacting with flax fibers. Comparisons are made between image fibers and non-image fibers. It is concluded that the image could not have involved energetic radiation of any kind; photons, electrons, protons, alpha particles, and/or neutrons.

Science should proceed by developing hypotheses to explain problems, and the hypotheses should all be tested rigorously against the same observations, facts, and laws of nature. When natural laws or observations disagree with any critical component of a hypothesis, it should be rejected. Many highly improbable hypotheses (often called "theories") have been proposed for the formation of the image on the Shroud of Turin (1). Many of these "theories" involve some kind of energetic radiation. This paper investigates the interactions of radiation with flax fibers.

The flax fibers that were spun to produce the yarn from which the shroud was woven are nearly pure cellulose. Cellulose is a polymer of glucose sugar units in very long chains. Most of the polymer appears in a crystalline form, but some is amorphous. The two kinds of polymers react in different ways (2). The amorphous part is much less stable than the crystalline part; however, crystals that are subjected to radiation and/or heat suffer specific changes in both their crystalline structure and composition. In flax fibers, any photon or particle with an energy above about 3 eV (e.g., light with a shorter wavelength than green) can directly break a few bonds in the crystallized polymer chains. This produces free radicals and distortions in the crystal.

In a crystalline material, the broken bonds may remain broken for a long time, until they are able to recombine with some reactant. The free broken bonds are called "free radicals." They cause considerable strain in the crystal. Even when they recombine with another part of the cellulose chain, the crystal lattice does not return to its original ordered structure, and it remains strained at the location of the defect. This strain changes the birefringence of the crystal, and we can observe the effect with a polarizing microscope.

The most important effect of any radiation is to produce heat. Feller describes irradiation as follows (3): "…the primary step in photochemistry is the absorption of radiation followed by the dissipation of that energy through heat, emission of radiation (fluorescence or phosphorescence), transfer of the energy to another molecular entity, or the direct breaking of bonds." However, ionizing particles can leave "ion tracks" through organic crystals. These are strained, disordered sites that are more reactive than the original fiber.

The crystals of flax fibers are "birefringent"; i.e., the velocity of light is different in different directions. The crystals show birefringence between crossed polarizers: they appear bright and colored in some orientations and dark in others (Fig. 1). When the crystal axes are parallel to the planes of polarization, the crystals are dark. We say that they are "at extinction." A perfect cellulose crystal in a freshly-retted flax fiber is perfectly black when the stage of a petrographic microscope is rotated to align the crystals with the polarizers. A crystal with imperfections like ion tracks shows birefringence at the location of the defects. All strains can be observed with a petrographic microscope.

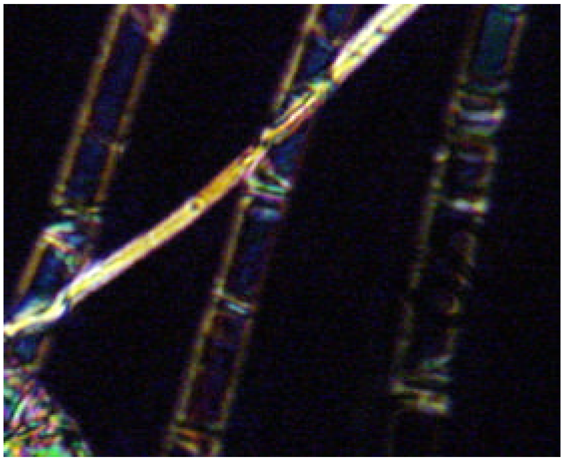

FIGURE 1

Some perfect, modern flax fibers between crossed polarizers (dark), 800X. Some growth nodes appear as brighter rings. The bright fiber is not at extinction.

The bright bands across the fiber are caused by the birefringent growth nodes of flax. They are a normal, diagnostic part of all flax fibers. They make a flax fiber look like a tiny length of bamboo.

The environment at the surface of the earth is continually bombarded by a significant amount of natural radiation. A relatively small fraction of this is from cosmic rays; most comes from natural terrestrial radiation. Primary cosmic rays are very energetic, but very few reach the earth. They interact with the atmosphere to produce showers of secondary cosmic rays. Most of the secondary cosmic rays reaching the surface of the earth are muons; however, they do not produce any significant effects in matter. Some secondary cosmic rays can affect matter. Of the energetic, ionizing particles, about 85% are protons (hydrogen nuclei) and 12% are alpha particles (helium nuclei). The largest amount of natural radiation is alpha particles that come from radon (Rn). Radon is produced by the radioactive decay of naturally-occurring thorium (in rocks and soil), it is a heavy, inert gas, and it collects in low places in buildings. It can easily diffuse into storage containers such as the reliquary that was used for the Shroud of Turin. Alpha particles are extremely effective at causing defects in materials, but they do not penetrate very far in either gases or solids. Only Rn atoms near a fiber when they disintegrate will have an effect on the cellulose.

A flax fiber integrates defects as a function of time. They have properties similar to the dosimeters used in nuclear and x-ray laboratories Older linens have been bombarded by several different kinds of radiation, and they tend to contain more defects than newer ones. Different kinds of defects are produced by the different kinds of radiation. Light and heat also produce characteristic defects. Figure 1 shows some modern flax fibers that have not been damaged by any kind of ionizing radiation, light, or heat. Figure 2 shows a modern fiber that has been irradiated with protons at an energy of about 1.4 MeV (4). The straight ion tracks crossing the fiber can easily be seen.

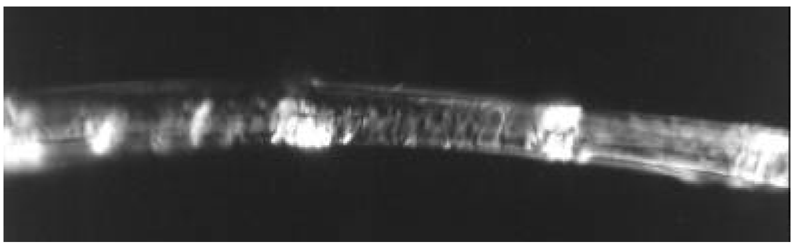

FIGURE 2
A flax fiber with tracks caused by irradiation with protons, 800X. The bright features are the birefringent growth nodes.

Because it is a gas, the probable source for most radiation that would affect the shroud is radon. It has a half-life of 55.6 seconds and emits a 6.28 MeV alpha particle as it decays to polonium. That will penetrate about 4 micrometers of flax fiber.

In order to demonstrate radiation effects of different kinds, it is necessary to have a source of known activity. Such sources are very difficult to get under current laws; however, Robert Villareal (Los Alamos National Laboratory) observed that old Coleman lantern mantles were treated with thorium. He found an unused one, and we irradiated unstrained flax (figure 1) with this as the radiation source. Its measured properties were the following: 20,000 alpha particles per minute at the surface, 120,000 beta particles per minute at the surface, and about 1.5 mR/hr of gammas at the surface. Figures 3 and 4 show the effects on the flax.

FIGURE 3
Flax fiber after 92.25 hours of irradiation with the thorium source, 800X.

Some background "haze" can be seen fairly soon after irradiation is started. The effect is easily seen after 92.25 hours (figure 3). It is the result of gamma irradiation. A few very dim beta tracks can be seen; however, the bright defects are the result of alpha particles. They are approximately 4 micrometers long.

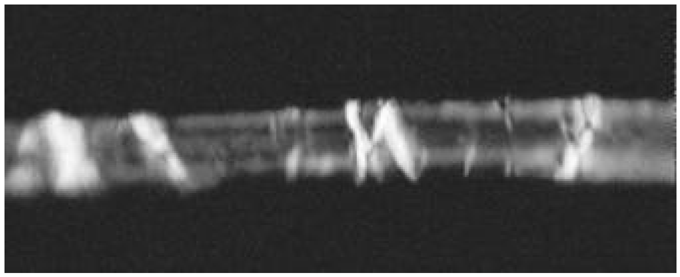

FIGURE 4
Flax fiber after 145 hours of irradiation by the thorium source, 800X.

Figure 4 shows much more general birefringence from the gamma irradiation. It also shows several more alpha tracks. Remember that tracks come in from several directions, and we see only those that are long enough to be resolved.

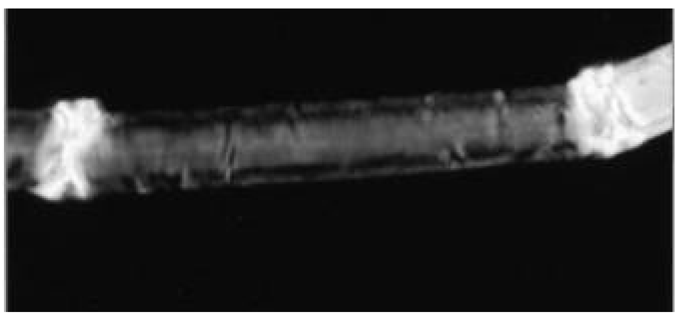

FIGURE 5
A 4000-year-old Egyptian flax fiber. It shows several kinds of defects. Most of the defects appear to have been annealed with age, leaving holes in the fiber. The fiber is brittle.

Figure 5 shows a very old flax fiber. The background is birefringent as a result of electromagnetic radiation (light and gamma rays from cosmic radiation), and there are many voids that appear to be caused by the annealing of defects from ionizing radiation. The defects have had enough time for the free radicals to recombine or decompose. Defects are "high-free-energy zones," and they decompose much more rapidly than normal crystals. The defects would be brightly birefringent in newer samples. The bright spots are growth nodes.

FIGURE 6
A fiber from the Holland cloth (ca. AD 1532). Most defects are still birefringent.

Figure 6 shows a fiber from the Holland cloth backing of the shroud (before 2002, when a new cloth was substituted). It was produced between about AD 1532 and AD 1534. Many of the defects are still brightly birefringent. It takes a long time for the strains to relax.

At first thought, it seemed logical to use defect populations for the estimation of the age of a linen cloth. Unfortunately, storage conditions vary greatly with location. Some samples have been exposed to more alphas than others, because the buildings where they were stored contained more radon. Yet the large, stone buildings that produce significant radon also shield the cloth from secondary cosmic rays. I have not yet been able to determine age more accurately than "old" or "young." Observations of fibers from the Shroud of Turin (figure 7) indicate that it is quite old, similar to flax fibers from the Dead Sea scrolls (dated to about AD 70). Once again, several "dark defects" can be seen, which I am beginning to interpret as indicating advanced age. The short, bright defects were probably made by more recent alpha particles.

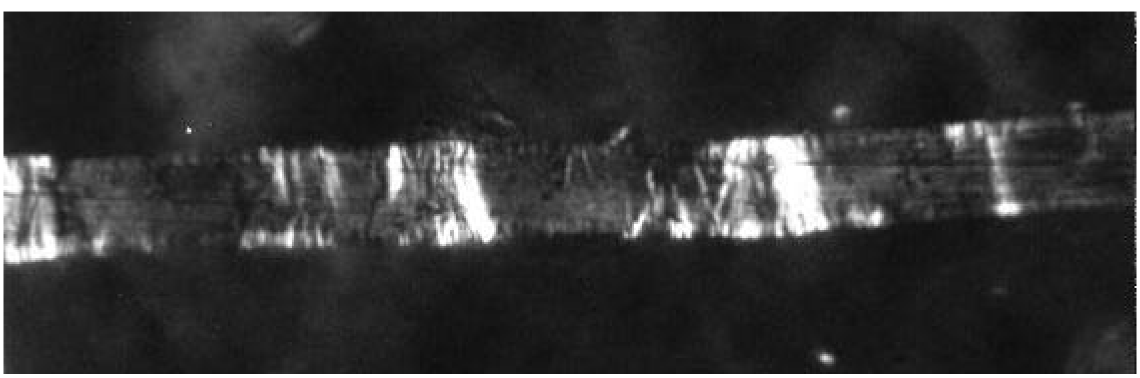

FIGURE 7
A shroud fiber from the wrist of the image, 800X. The background haze was caused by electromagnetic radiation,; the short bright tracks were caused by alpha particles, and the longer tracks were caused by protons and/or electrons. Some tracks are fading, becoming dim. Many aged defects (dark) can be seen.

Although the attempts to use defect types and/or populations for age determination have been disappointing, they can be used to compare different areas of the same cloth. All parts of the shroud are the same age, and all parts have been stored in the same location through the centuries. Therefore, all parts should have been exposed to the same kinds and amounts of radiation. Any additional radiation effects found in image areas would indicate excess radiation in that location.

Direct comparisons between image and non-image parts of the shroud show exactly the same amounts and types of radiation damage in the two types of areas (e.g., figures 7 and 8). This suggests that the image was not produced by any mechanism that involved heat, light, or ionizing radiation.

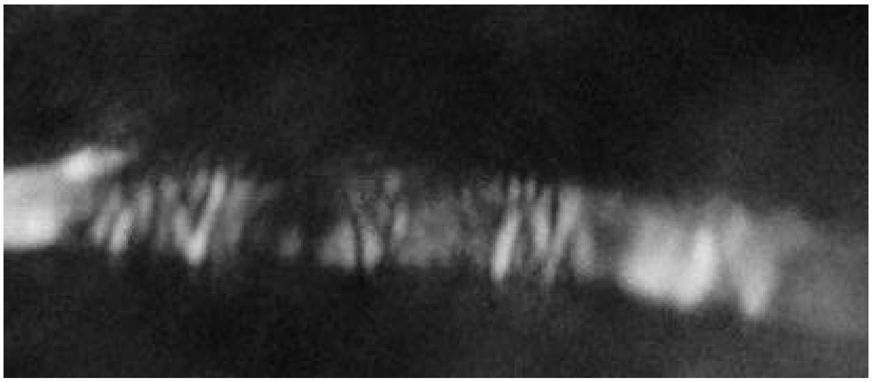

FIGURE 8
A fiber from a non-image area. Defect populations and types are the same as shown in figure 7.

Photomicrographs do not tell the whole story: more is learned by dynamic viewing through a microscope. Different features can be emphasized with different mounting media, lighting systems, degrees of polarization, and focus.

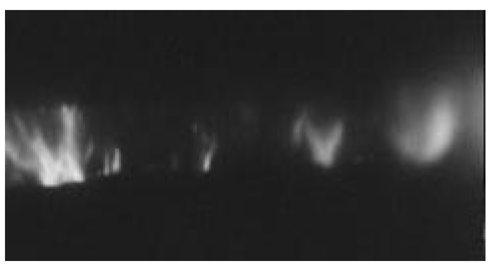

FIGURE 9
Egyptian linen that was irradiated with reactor (2200 m/s) neutrons and some associated gamma rays.

Although neutrons are not ionizing radiation, when they hit a proton in an organic material, they produce a "recoil proton." These protons are ionizing particles, and they can be observed. Figure 9 shows a neutron-irradiated fiber from an Egyptian mummy. When you look very closely, you can see a few short, dim tracks from recoil protons in the middle of the fiber. Such features are extremely rare in shroud fibers.

FIGURE 10
A flax fiber from AD 1890 Algerian linen, 800X. It shows defects from machine spinning and weaving, few ionizing-particle tracks, and some electromagnetic haze.

Figure 10 shows fibers from an Algerian linen that was produced about AD 1890. They can be compared with figure 1. They show defects caused by machine spinning and weaving and some electromagnetic haze. The cloth was very supple, and it appeared to have been washed many times. It may have been ironed, but it was almost certainly dried in the sun. Modern linen can quite easily be differentiated from ancient linen.

Whatever caused the shroud image did not affect the crystallinity of the flax fibers. Image formation did not involve any kind of intense heating, radiation, or stress that exceeded the mechanical limits of the material.

Image formation proceeded at normal temperatures. Image-color formation did not require neutrons, protons, high-energy photons, or mesons. I can not eliminate some very mild heating that would not have affected the cellulose crystals but could have changed less stable impurities; however, it would have taken considerable heating time to color the least stable impurities that have been found on the shroud. Any heating event could not have been accompanied by energetic electromagnetic radiation, as is the case with plasma or corona discharges.

One hypothesis for image formation that keeps coming back involves a corona discharge. In any scientific investigation, it is imperative to start with a clear, succinct statement of the hypothesis I have not seen one for this hypothesis; therefore, I have extracted the following statements from correspondence.

1) A voltage of sufficient magnitude to produce a corona discharge in air was produced in Jesus' body at some time while it was in the tomb and covered with the Shroud.
2) The corona discharge was not sufficiently intense to oxidize a significant amount of the cloth, and the potential difference was not great enough to produce sparks or arcs.
3) The corona "activated" the surface such that aging (and/or heating) produced a color.

A high voltage is required to ionize air and produce a corona discharge. A corona discharge is one type of plasma. One hypothesis is that the ionizing voltage appeared at the instant of resurrection, thus proving the event's miraculous nature. It has also been suggested that the voltage was produced by the piezoelectric effect during an earthquake, although electrical connections between the body and slip zone have never been elucidated. Whatever the voltage source, a corona discharge (or plasma) will produce specific effects on and in linen. If those effects are not observed, this image-formation hypothesis must be rejected.

In order for the body to charge to a high voltage, it must not be grounded. Because there is no such thing as a perfect insulator, materials in contact assume the same potential. Without a potential difference, ionization is impossible.

During a corona discharge, air is ionized in a high-voltage field to produce free electrons and positively-charged ions. The plasma is neutral; the number of electrons is the same as the number of charges on the positive ions. Neither the electrons nor the positive ions attain high velocities like beta particles or fission fragments. They do not become penetrating, ionizing particles.

When electrons recombine with ions, light is emitted. Among other things, a corona discharge (plasma) produces energetic ultraviolet light. The predominant energy produced by a corona discharge that would be expected to produce high-free-energy zones in cellulose or impurities on its surface is its uv radiation. Colors form as a result of chemical reactions at high-free-energy zones.

Any corona in air will produce atomic oxygen and excited oxygen molecules: both *will* oxidize the material of the cloth. Such a process is used in commercial textile manufacturing. Given enough time or intensity, a plasma in air will completely consume a linen sample. Even a short exposure will erode the surface of flax fibers.

Some controlled corona/plasma experiments were run by APJet of Santa Fe, NM, a manufacturer of equipment for plasma treating textiles. The plasma was produced at 27 MHz in a 1% oxygen atmosphere. Conditions were modified from those in normal air to prevent arcing and slow the rate of erosion of the linen; otherwise, the cloth would have been badly damaged. This fact must be considered in making claims about corona effects in image formation. The plasma nozzle was cooled, and the plasma temperature was only 85ºC. Plasma energy was 220 W. The plasma jet was 6 mm in diameter, and the cloth was 4 mm from the tip of the nozzle. Exposure was 30 seconds, producing about 10^{19} free oxygen atoms. No sparks or arcs were formed. The linen sample was produced by Kate Edgerton (Norwalk, Connecticut, deceased), following the methods used in the Near East in Roman times.

The nap of the cloth was removed in the area subjected to the plasma. The fibers were oxidized without any charring by the energetic oxygen atoms and molecules even though the temperature was not high enough to dehydrate and color the cellulose. The electrically-neutral plasma completely penetrated the pores of the cloth. Because plasma is neutral, it does not charge the surface of an insulator, ultimately repelling itself, as does an electron beam. It penetrates the entire structure. It should be remembered that the image color on the Shroud of Turin does not appear in the pores of the cloth.

Both the effects of surface erosion and the crystal defects caused by ultraviolet irradiation can be observed with a petrographic microscope (figures 11 and 12).

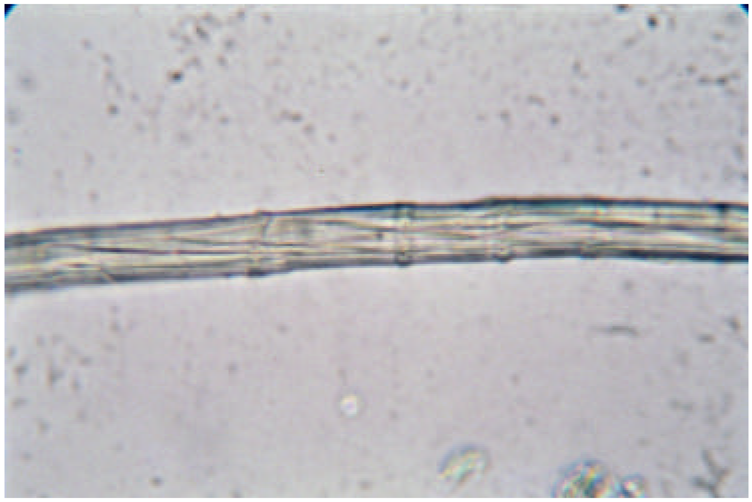

FIGURE 11
A single fiber from the treated cloth sample. Hemicelluloses and pectins have been oxidized, leaving most of the more-stable cellulose. The spiral structure of the cellulose ultimate cells is visible.

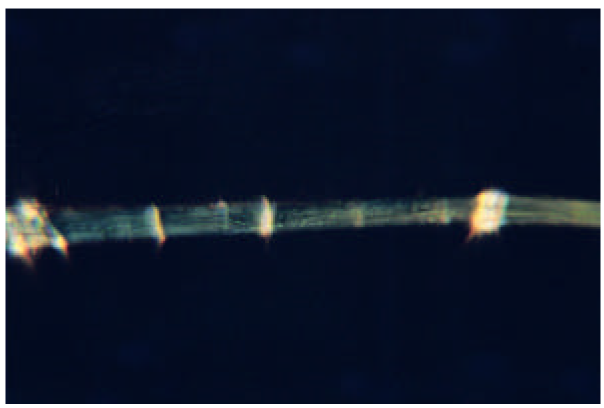

FIGURE 12
The same fiber as figure 11 is shown between crossed polarizers. The bright birefringent spots are the growth nodes of the fiber. The white birefringent haze was caused by uv-induced defects in the cellulose crystals. The uv radiation was produced by the plasma discharge.

It is clear that a corona discharge (plasma) in air will cause easily observable changes in a linen sample. No such effects can be observed in image fibers from the Shroud of Turin. Corona discharges and/or plasmas made no contribution to image formation.

I believe that the current evidence suggests that all radiation-based hypotheses for image formation will ultimately be rejected.

Acknowledgements:
Neutron-irradiated linen samples were produced by Mario Moroni. Proton-irradiated samples were produced by Jean-Baptiste Rinaudo. The AD 1890 samples were supplied by Marcel Alonso. The Egyptian sample was supplied by the Museum of Egyptology in Turin. The plasma-treated primitive-type linen was plasma treated at APJet of Santa Fe, NM, USA.

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