How microwave radiation could have formed the observed image on the Holy Shroud of Turin

by ***Bernard A. Power***

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Introduction

Various theories attempting to explain the image formation on the Holy Shroud have been described and analysed [1,2]. However, only radiation theories can explain the three-dimensional character of the observed image [15,16,17].

In radiation theories it is presumed that some sort of radiation, emitted from the dead body of the Man in the Shroud, passed across the air gap between the Body and the Shroud, was attenuated by the air in the gap proportionally to the width of the gap, and so formed the observed variations in the areal density of the yellow coloured fibrils which make up the visible image. This approach has been studied by the author in a series of papers over the past decade. First, the energy required for image formation has been estimated to lie in the range of about 286 Joules per gram of cellulose fibrils chemically altered to the straw-yellow colour [3,4,7]. Next, the kind of radiation which would furnish this amount of energy was investigated, and it was found from an attenuation analysis to lie in the microwave band at wavelengths between about 0.3 mm and 1 mm [5,6,7].

The present study will now address the problem of whether microwave radiation can indeed interact chemically with the cellulose fibrils of the linen cloth so as to produce their observed yellow colouration, and to cause the observed areal distribution of the yellow coloured spots on the topmost fibrils of the linen threads which make up the image.

Interaction of radiation with cellulose to form the observed Image characteristics

First, we note that the image on the Shroud is formed by some process which has altered some of the cellulose fibrils – those in the image areas only - from the normal colorless state for cellulose to a light straw-yellow. Moran has named these coloured individual image elements “pixels” [8], which he says apparently vary in length along the fibrils from about 200 to 1000 microns (i.e. from 0.2 to 1 mm) (Figure 1). The intensity of the yellow colour is very uniform from one pixel to another, so that the image is formed by the closeness of the spacing of the colour spots in the various areas of the image, that is, in a manner similar to the formation of an image in a half-tone reproduction, where it is the spacing of uniform black print dots that form the print image and not a variation in the blackness of the individual dots themselves.

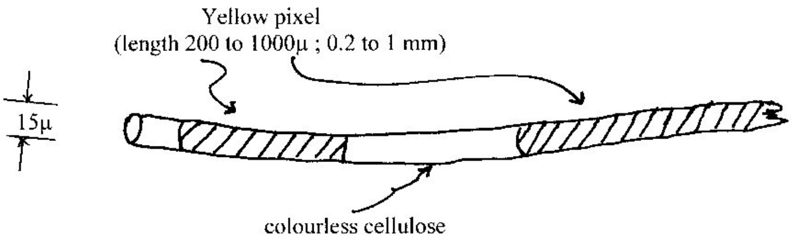


Figure 1. Observed yellow image pixel segments along a Shroud fibril in image area

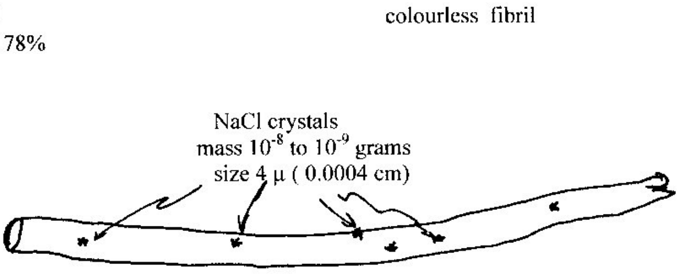
The chemical cause of the yellow colour on the cellulose fibrils is generally accepted to be the formation in the cellulose fibrils of a conjugated, carbon-to-carbon double bond, C = C, which constitutes the yellow "chromophore" on each linen fibril that is affected [1]. A thermal scorch could not have caused the observed image because then the yellowing would be along the entire length of each fibril, instead of only in the short length of each pixel. In the same way, a uniform radiation beam whose energy was absorbed directly by the cellulose might also cause the observed yellowing, but again it would colour the entire length of each fibril, and so a uniform radiation beam acting directly on the cellulose fibrils is apparently also ruled out as a viable image forming means.

To meet this objection to any direct radiation mechanism, we now propose an *indirect coupling,* which still transfers the energy of the radiation to the linen fibrils of the Shroud, but now in such a manner as to form the necessary yellow chromophores only in discrete spots or pixels of the observed lengths (200 -1000 microns) along an individual fibril, leaving the rest of the length of the fibril unaltered in colour.

This proposed new indirect mechanism involves, first, the presence on the fibrils of the Shroud in the Tomb of small water droplets condensed onto the fibrils from the humid air between the body and Shroud <u>at relative humidity less than 100%</u> (Figure 2), and, second, a sudden, intense pulse of microwave radiation which causes a violent superheating of these droplets to well above 200°C (Figure 3) from the absorption of the microwave radiation (which, of course, is known to everyone for its ability to efficiently heat water in cooking). The water droplets turn into superheated steam, which in turn then heats the short segment of the fibril that is in contact with the steam to chemically alter the cellulose and produce the observed pixels of yellow colour having the observed lengths (Figure 3). Immediately following this, the temperature of each superheated steam cloudlet decreases suddenly, because of adiabatic expansion of the steam, cooling it abruptly and ending the chemical action on the cellulose. This abrupt cooling also explains Moran's observations of the very sharp boundary between each pixel and the uncolored sections of the fibrils at each end of the pixel [8].

Having outlined the new radiation coupling mechanism, it is now necessary to examine the condensation of water droplets onto a linen fabric in some detail.

2a. Inert salt crystals of NaCl along fibril at humidity < 78%



2b. Salt crystals condenses water to form micro-droplets along fibril at humidity ≥ 78%

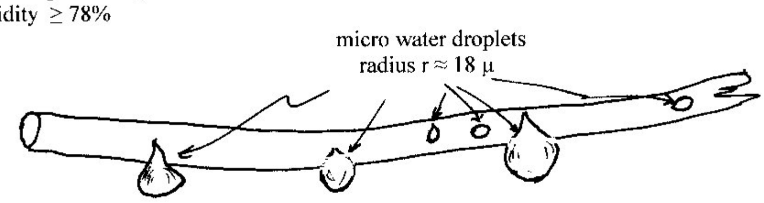


Figure 2. Condensation of water droplets on Shroud fibrils at humidity ≥ 78%

Condensation of water vapour onto a linen fibril

Condensation of water vapor from the air to form liquid droplets of water can take place either (a) *homogeneously*, which is to form droplets of pure water suspended in air, or (b) *heterogeneously,* which is to condense the water vapour onto a solid, insoluble particle or surface, or more importantly for our interest here, onto soluble crystals of common salts such as sodium chloride, potassium chloride, calcium chloride , etc. These rather complicated matters are dealt with in detail in standard treatises on the physics of clouds and precipitation [9,10]. Here we shall outline only the essential elements for our purposes.

(a) Homogeneous condensation of water vapour to form suspended droplets in clouds or fog without the intervention of solid or soluble nuclei requires very large supersaturations i.e. a relative humidity of 300% to 400%. The condensation is governed by the Kelvin equation, Eqn.1 below, but, because of the very high humidity, purely homogeneous condensation will not further concern us:

$$\ln (p/p\infty) = 2\sigma M/r\,RT \qquad \text{(Kelvin equation) (1)}$$

(a) <u>Heterogeneous nucleation on a soluble salt nucleus:</u> The presence of a solid surface, such as a soluble salt crystal, at once greatly reduces the relative humidity requirement. For example, on a tiny microscopic crystal of sodium chloride (NaCl, common salt) condensation can take place at a relative humidity of only 78%, while calcium chloride crystals $CaCl_2$ can start to absorb water vapour from the air to form a water droplet at a humidity of only 35%. The governing equation for this kind of condensation of water vapour [9,10] is as follows:

$$\ln(p/p\infty) = 2\sigma M/\rho rRT - \ln\{imM/W\rho(4/3)\pi\, r^3\} \qquad (2)$$

where p is vapour pressure, p_∞ is saturated vapour pressure, σ is the surface tension of water, M is the molecular weight of water (18.016), R is the universal gas constant, T is the temperature, *i* is van't Hoff's factor, m is the mass of the salt crystal nucleus, W is the molecular weight of the salt (NaCl, 58.44), ρ is the density of water(≈ 1), r is the droplet radius, and ln is the natural logarithm, which is required because the physical process of condensation is exponential in nature.

In Table 1 are listed the weights and sizes of various crystals of NaCl, and the droplet sizes to which they will grow at a relative humidity of 78%.

Table 1

Salt (NaCl) crystal size and condensed droplet radius at relative humidity of 78%

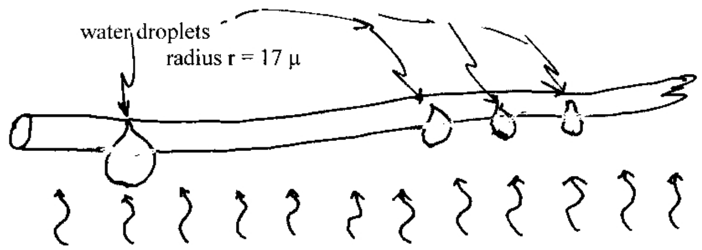
Mass (grams)	10^{-16}g	10^{-15}	10^{-14}	10^{-13}	10^{-12}	10^{-11}	10^{-10}	10^{-9}	10^{-8}
Crystal radius	0.02μ	0.05	0.1	0.22	0.48	1.03	2.2	4.8	10.3
(in microns μ = 10^{-4} cm)									
Droplet radius	0.04μ	0.08	0.2	0.39	0.88	1.85	4.1	8.8	18.5

We can estimate the total volume V of all the water droplets condensed onto the fibrils in the image area of the Shroud as follows:

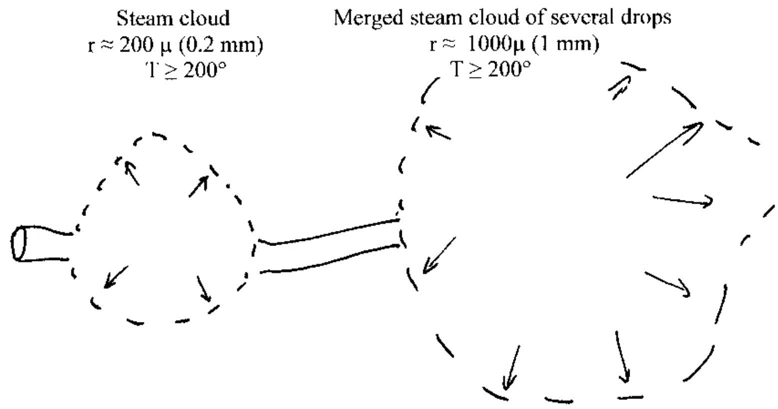
$V = 4\ \pi\ r^3/3$ x (Number of droplets per sq. cm. x area of image)

Here we take the droplet radius r at 17 microns (17μ = 0.0017 cm) which is just over the diameter of a typical fibril (15μ). The number of droplets per square centimeter of image area is estimated to lie between 1000 and 10,000 on the basis of the image definition (i.e. 1000 to 10,000 pixel elements per sq. cm.). The total area of the Shroud is about 400 x 110 = 44,000 sq. cm., and, if we take the image area at half of that, we get 22,000 sq. cm. for the image area. Inserting these values into the formula above we get a total droplet volume V of 0.45 cc for 1000 pixels per unit area, and 4.5 cc for the larger value of 10,000 pixels per unit area of image. The corresponding total masses of water are 0.45 grams and 4.5 grams respectively.

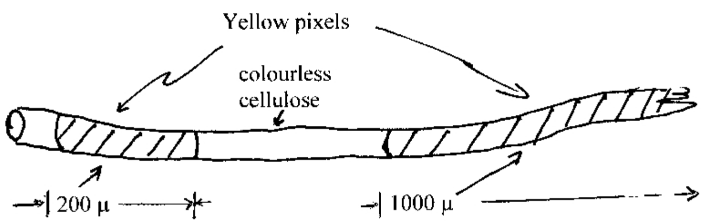
What is envisaged here is as follows: When the Body of the Man in the Shroud was first placed in the Tomb and enveloped in the Shroud, the surface temperature of the body would be perhaps 10° C cooler than the normal living body temperature of 37°C, say about 27° C. The ambient temperature of the air in the Tomb in Jerusalem is estimated at about 15°C year round [20] so that there would be a temperature gradient from the body to the surrounding air of say 12° C (27 – 15 = 12), and this temperature gradient would gradually decrease as the body temperature cooled [13]. In the few hours immediately after death there would be high humidity and even some liquid water films on the skin surface. This would humidify the air in the gap between the body and the Shroud, raising its relative humidity to 70% to 90% or even higher.



3a. **Microwave radiation burst approaches Shroud fibril and suspended droplets**



3b. Droplets vaporize and expand (12 to 1 radius ratio) and merge to form superheated steam cloudlets (T ≥ 200°C)



3c. Steam evaporates and leaves behind yellow coloured segments or pixels on Shroud fibril having lengths of 200 – 1000 microns.

In this moist air, with a temperature initially around 27° C, the relative humidity of 70 to 90% would exceed the condensation temperature or dew point on the inner surface of the Shroud. Consequently, condensation would then take place onto any salt crystals on the Shroud fibrils and water droplets would form (Eqn. 2 and Table 1). That is, as soon as the relative humidity in the air on the Shroud's surface exceeded 78%, sodium chloride salt crystals on the fibrils would become micro-sized liquid water droplets.

In other words, during the first few hours after the Body was placed in the Tomb and enveloped in the Shroud, the evaporation from the skin would form tiny water droplets on the fibrils of the Shroud. As time progressed, and the body temperature cooled, the relative humidity would also drop. However, at any relative humidity above 40%, the brine droplet once formed would not evaporate but would remain as liquid water.

Finally, when the surge of radiation occurred (Figure 3a), the droplets would absorb the microwave energy and superheat to become steam at a temperature above 200°C; the superheated steam would then chemically react with the cellulose to produce the straw yellow colour observed along the length of each affected fibril within the radius of action of the steam droplets (Figure 3b).

Extensive experimental work verifying the absorption of water vapour on salt crystals attached to fibres of spider silk to form water droplets has been carried out by Dessens [11,12] in connection with research into cloud and precipitation physics. Dessens suspended spider web threads with NaCl crystals attached in a chamber and then varied the relative humidity. He found that the salt crystals absorbed water from the moist air to form brine droplets at around 78% relative humidity as expected. Thereafter, when the humidity in the chamber was lowered to below 78%, the droplets which had formed on the salt crystals did not evaporate completely. Instead they shrank slowly in size, but remained as water droplets even down to around 40% relative humidity before they recrystallised..

Are there enough salt crystals on the Shroud of Turin?

First we should point out that a salt crystal with a tiny mass of only 10^{-9} grams (a billionth of a gram) and a size of only 4.8 microns radius (Table 1), would form a water droplet at 78% R.H having a diameter 17.6 microns, i.e. enough to envelop the diameter of a Shroud fibril which is about 15 microns (Figure 2). If now we want to form, say, 1000 pixels of image per square centimeter of image area, this would mean that we would need 1000 drops, making a total salt mass per square centimeter of only one microgram (10^{-6} g), to bring this about by the proposed droplet condensation means.

Now, as reported by Morris et al. [14], there are relatively abundant mineral salt elements all over the Shroud. These are principally calcium, strontium and iron. Ca was the most abundant salt present with 250 micrograms of calcium salts per sq. cm. A trace amount of potassium, slightly above the background noise level of 1 microgram per square centimeter was also found. This indicates that sodium salts were certainly also present in the necessary trace amounts of 1 microgram or less, and undoubtedly other common hygroscopic mineral salts as well, such as calcium chloride and calcium nitrate.

The origin of the salts found on the Shroud was initially ascribed by Morris et al. [14] as being due to deposition of atmospheric dust on the surface of the Shroud, since these salt crystals are abundant everywhere in the atmosphere [9,10]. Later, however, the presence of these salts was traced more definitely by Heller & Adler [1] to the traditional *retting* process by which linen fibres are separated from the husk or outer fibres of the flax plant. In the retting process the flax is first fermented by steeping it in the water of a pond, stream or vat, the waters of which always contain considerable amounts of the common water-soluble mineral salts. During the retting, the linen cellulose absorbs any mineral salts in the water through its pores into the interior of the fibrils [1]. When the linen is subsequently dried, the salt remains inside and on the surface of the cellulose fibrils in the trace amounts needed to later absorb water at higher relative humidity to form the microscopic water droplets required.

What pixel sizes would the superheated water droplets produce on the fibrils?

Moran [8] has photographed image fibrils and observed that the coloured spots or pixels along each fibril range in length from about 200 to 1000 microns (0.2 to 1 mm) We therefore need to show that the condensed water droplets on the Shroud fibrils will, when superheated and vaporized, expand to produce a superheated steam vapour which would then produce the observed yellow pixels in the sizes which Moran claims make up the image. At atmospheric pressure the volume expansion ratio of water to steam is about 1600 to 1 [18], or a diameter expansion ratio of around 12 to 1. Thus a droplet of water of 18 microns diameter would expand to form a steam cloudlet with a diameter of 216 microns, matching Moran's lower limit pixel size of 200 μ. Then, the merging of the vapour clouds from several neighboring vapourized droplets would meet his other requirement for an upper limit to length of the image pixels of about 1000 microns (Figure3b,3c).

Previous energy estimates and the new heat input temperature values

The new indirect thermal coupling via condensed water droplets on the fibrils is physically reasonable as shown above. It should also be compatible thermodynamically with the energy estimates previously made of 286 Joules per gram of cellulose fibrils heated to 200° C, which is approximately the threshold temperature needed to cause thermal yellowing of the cellulose [3,7]. Ideally, to calculate the temperature rise in the water droplets from the radiation beam we should work not just with the energy but with the *irradiance* of the beam, that is to say, with the *power* of the beam in watts per square centimeter. Such a temperature analysis requires further knowledge of the time duration of the microwave radiation pulse, which remains to be examined in later studies.

On the whole, since the specific heat of water is about three time that of cellulose, then 1 gram of water will, for a given energy input, heat up to about three times the temperature of the cellulose. That would give a steam temperature of around 600°C. In practice, however, the expansion of the steam vapour retards the temperature rise so the actual peak temperature reached in the steam will be somewhat less that that. However, it seems quite clear that the total amount of condensed water calculated above (0.45 to 4.5

grams) will easily accept the radiation input of 286 Joules per gram and form a steam cloud with temperature more than high enough to in turn heat the cellulose fibrils up to the 200°C required.

Discussion

The precise chemical and thermodynamic requirements for the thermal yellowing of the cellulose fibrils by superheated steam need to be further studied, both theoretically and experimentally. Also, the thermal reaction of cellulose to form conjugated C=C double bonds by an extremely short, intense pulse of superheated steam at the elevated pressures existing in the initial burst of steam may cause the cellulose degradation reaction to proceed more quickly and at temperatures well below the 200° C ordinarily needed to produce the yellow colour. It may be worth recalling here that even ordinary steady thermal heating applied over a period of many minutes or several hours can turn cellulose yellow [22]. The new indirect steam superheating mechanism proposed here could presumably do the same in a far shorter time period.

We should also note that, since the condensed water droplets contain salt, their boiling point will be higher than that of pure water which is 100°C. In addition, with extremely rapid heating and expansion there may well be *shock wave*s involved, and these also will affect the peak pressures and peak temperatures reached, and may affect the chemical reaction with the cellulose as well. Such effects remain to be studied.

Of course, in the above discussions the sizes of water droplets, salt crystal masses and so on, while very reasonable, are not intended to be precise and are subject to final determination from later analysis or experiment; this will not affect the general conclusions as to the validity of the proposed energy coupling theory.

The presence of salt crystals on the Shroud fibrils can easily be studied experimentally in the manner described by Dessens [11,12] in a humidity box or cloud chamber. However, it must be noted that <u>any fibrils for such a test must be chosen from the non-image areas and NOT from the image areas,</u> since the image areas have by the present hypothesis of image formation already undergone the irradiative superheating described which would vaporize the salt solutions droplets and thus disperse the brine and lower the concentration of any salt remaining on the image area fibrils. Again, the fibrils for any such humidity tests should not be taken from the charred areas on the Shroud caused by the 1532 A.D. fire, for the reason that the fire would also have altered the salt crystal concentrations in those areas as well.

Conclusions

A method of indirect coupling of microwave radiation to the linen fibrils of the Shroud in the image area successfully meets the requirements for forming the image which has the observed characteristics of cellulose yellowing and discrete sizes of image pixels.

The proposed indirect coupling takes place via tiny micro droplets of water condensed at less then 100% relative humidity onto crystals of common salts present on the Shroud’s fibrils. The microwave radiation then superheats the water droplets, thus providing the necessary non-destructive (i.e. non-pyrolitic) thermal energy input; the subsequent rapid adiabatic expansion of the steam provides the necessary cooling that abruptly then stops the chemical reaction and confines its effects to the tiny, discrete coloured spots or pixels observed on the fibrils.

The next tasks will be, first, to further explore the irradiance of the microwave radiation and the thermodynamics of its interaction with the cellulose, and, second, to determine the origin of the radiation.

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Bernard A. Power
255 Touzin Avenue
Dorval, Quebec, Canada
H9S2N1
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