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FULL PAPER

TWO LÁSZLÓ MOHOLY-NAGY PAINTINGS ON *TROLIT*: INSIGHTS INTO THE CONDITION OF AN EARLY CELLULOSE NITRATE PLASTIC

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Abstract

It had long been believed that the plastic substrates of László Moholy-Nagy's paintings *T1* (1926) and *Tp 2* (1930) in the collection of the Solomon R. Guggenheim Museum were a phenol formaldehyde resin called *Trolitan*. Recent investigations using a combination of microscopy and instrumental analysis revealed that these plastics are actually cellulose nitrate filled with a significant proportion of gypsum. The pigments, plasticizers and other organic components were also thoroughly characterized. When considered together with archival information, these characteristics indicate that this material should rather be identified as an industrial plastic called *Trolit* produced at the same factory as *Trolitan*: the Rheinisch-Westfälischen Sprengstoff-Fabriken (RWS) in Troisdorf, Germany. This first analytical description of *Trolit* provides new insights into Moholy-Nagy's unconventional material choices, highlights the remarkably good current condition of the works of art, and shows the importance of using scientific analysis to correctly identify historic plastics instead of relying on trade names for their material identification.

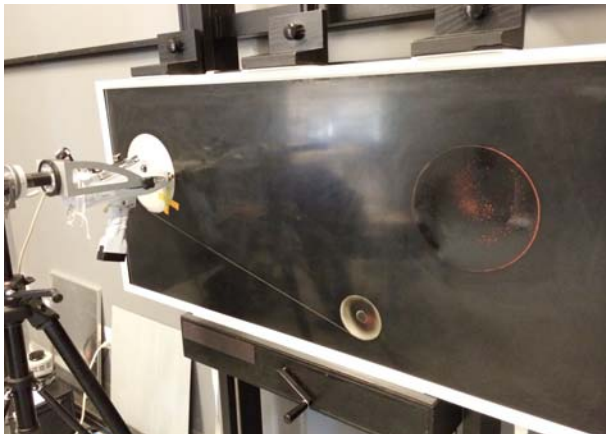

Figure 1. In-situ X-ray fluorescence analysis of *T1* (shown on its side), 1926. Oil, sprayed paint, incised lines, and paper on Trolit, 55 1/16 x 24 5/16 inches, (139.8 x 61.8 cm), Solomon R. Guggenheim Museum, New York. Solomon R. Guggenheim Founding Collection, By Gift. © 2016 Hattula Moholy-Nagy / VG Bild-Kunst, Bonn / Artists Rights Society, New York.

1 Introduction

The present study is part of the first in-depth examination of the materials and painting techniques used by the Hungarian-born Bauhaus artist László Moholy-Nagy (1895-1946).[1,2] A prolific writer and true polymath, Moholy-Nagy was deeply interested in the creative possibilities at the intersection of art, science and technology. Like many at the Bauhaus he embraced new technologies and the latest developments in industrial materials to relentlessly pursue his innovative vision and exploration of light, reflectivity, transparency, surface texture, and motion. A particular focus of this investigation is the artist's use of early plastics as supports for paintings, with an aim to inform the best preservation strategies for these non-traditional artworks. The scientific study of Moholy-Nagy's materials also sheds light on the innovative use of industrial products in modernist art making. Here we present analytical results from two paintings, *T1* and *Tp 2* (Figs. 1 and 2), created by Moholy-Nagy respectively in 1926 and in 1930 while he was living in Germany.

The rectangular dark plastic supports of *T1* and *Tp 2*, respectively black and blue in color and 5 mm and 3 mm thick, have highly glossy, smooth surfaces on the painted sides. The appearance and physical properties of the plastic are fundamental aspects of the works since the exposed plastic constitutes the background of the paintings and the artist incised lines into the support as part of the composition. The good overall state of preservation of these artworks has long been attributed to their plastic formulation. According to museum records, and an early catalog of the Guggenheim collection, these supports had historically been described as either *Trolitan* or *Bakelite*, both

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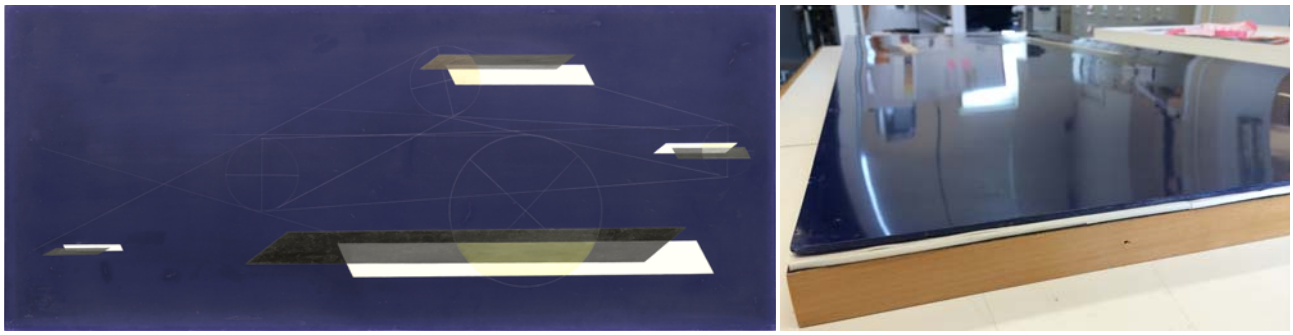

Figure 2. *Tp 2*, 1930. Oil and incised lines on *Trolit*, 24 1/4 x 56 3/4 inches (61.5 x 144.3 cm), Solomon R. Guggenheim Museum, New York. Solomon R. Guggenheim Founding Collection, By Gift. © 2016 Hattula Moholy-Nagy / VG Bild-Kunst, Bonn / Artists Rights Society, New York (left); oblique photography of *Tp 2* showing its highly polished surface (right).

relatively stable phenol formaldehyde resins.[3] Contrary to these records, preliminary analysis using non-invasive *in-situ* reflectance infrared spectroscopy identified both substrates as cellulose nitrate (CN). This result was surprising since CN plastics have been known to undergo severe degradation.[4, 5, 6] Full characterization of microsamples from the substrates was therefore undertaken using a complement of analytical techniques: visible light microscopy, scanning electron microscopy with energy dispersive spectroscopy (SEM-EDS), Fourier transform infrared (FTIR) and Raman spectroscopy, pyrolysis gas chromatography mass spectrometry (Py-GCMS), solid phase microextraction (SPME) GCMS and desorption electrospray ionization-mass spectrometry (DESI-MS). The goal of the analyses was to gain a deeper comprehension of the reasons for the apparent stability of this notoriously labile early plastic as the first step to determining the best storage conditions for the artworks. In addition, knowledge of Moholy-Nagy's choice of plastic supports and their properties leads to a better understanding of his artistic practices.

2 Experimental

Fragments of a few hundred micrometers were sampled from the reverse of the plastic supports of *T1* and *Tp 2* and examined under a Wild M3Z binocular microscope. One fragment from each painting was embedded in epoxy resin (Buehler EpoThin 2) and polished as a cross-section. The cross-sections were examined with a Nikon Eclipse MA200 inverted microscope equipped with a polarizing block. Optical images were captured using a Nikon digital sight DS-FI2 camera.

SEM-EDS was performed on the polished, uncoated cross-sections at 20 kV accelerating voltage using a Hitachi S-3400N-II in low vacuum mode (90 Pa), equipped with an Oxford x-act energy dispersive spectrometer.

FTIR spectra were collected *in-situ* using a Bruker Alpha small footprint portable FTIR spectrometer, with reflectance mode sampling and spectral range 375-7500 cm^{-1}, a measurement spot of 6 mm in diameter, and working distance of approximately 15 mm. 256 scans were acquired at a resolution of 4 cm^{-1}.

Excised samples were further analyzed in transmission mode, after compression in a diamond anvil cell, using a Bruker Tensor 27 FTIR spectrometer with a mid-IR globar source coupled to a Hyperion 2000 automated FTIR microscope with liquid nitrogen cooled mid-band and broadband mercury cadmium telluride (MCT) detectors. The spectra were collected from 4000 to 400 cm^{-1} at a resolution of 4 cm^{-1} (128 scan acquisition).

Raman spectroscopy was performed on an unmounted fragment from each painting using a Jobin Yvon Horiba Labram 300 confocal Raman microscope, equipped with an Andor multichannel air-cooled open electrode charge-coupled device detector (CCD: 1024 x 256), a BXFM open microscope frame (Olympus), a holographic notch filter, and a dispersive grating with 1800 grooves/mm. The excitation line of a He-Ne laser (λ_{exc} = 632.8 nm) was focused through a 100x objective onto the sample and Raman scattering was back collected through the same microscope objective. Power at the samples was kept very low (never exceeding a few mW) by a series of neutral density filters in order to avoid any thermal damage.

Py-GCMS was carried out using a Frontier PY-2020iD vertical microfurnace pyrolyser, with the furnace at 550°C. Samples of c. 10-20 µg were placed in Frontier Lab stainless steel sample cups for analysis. The pyrolyser was attached to a Varian 3800 GC, used with a Restek Rxi-5ms column (30 m, 0.25 mm i.d., 0.25 µm film), and interfaced to a Saturn 2200 MS, transfer line temperature 300°C. The oven was programmed from 40°C, with a 2 minute hold, then increased at 20°C/min to 300°C, and held isothermally for 10 minutes; total run time 25 minutes. The inlet was operated with a split ratio of 1:10. Helium was the carrier gas, with a constant flow of 1 mL/min. The MS was run in scan mode (*m/z* 40-600) with the ion trap at 210°C.

SPME GCMS analysis was carried out on samples of Tyvek ® (spunbonded polyethylene) and Nomex ® (aromatic polyamide) nonwoven materials that had been in contact, respectively, with the reverse sides of *Tp 2* and *T1* in storage as an interleaf, to investigate volatile compounds that might have been emitted by the plastic support. Samples were placed in a 40 mL vial and capped for at least one week. A divinylbenzene /Carboxen/ polydimethylsiloxane SPME fiber (Supelco) was exposed to the vial headspace for 30 minutes. Analysis was performed on an Agilent 6890N/5973 GCMS with an HP5-MS column (30 m, 0.25 mm i.d., 0.25 µm film). Full experimental details have been published by Ormsby.[7]

Desorption electrospray ionization-mass spectrometry (DESI-MS) was carried out on samples from each painting using a Thermo Scientific Exactive mass spectrometer operated in positive and negative ion modes, with the sample secured on a clean glass slide on a

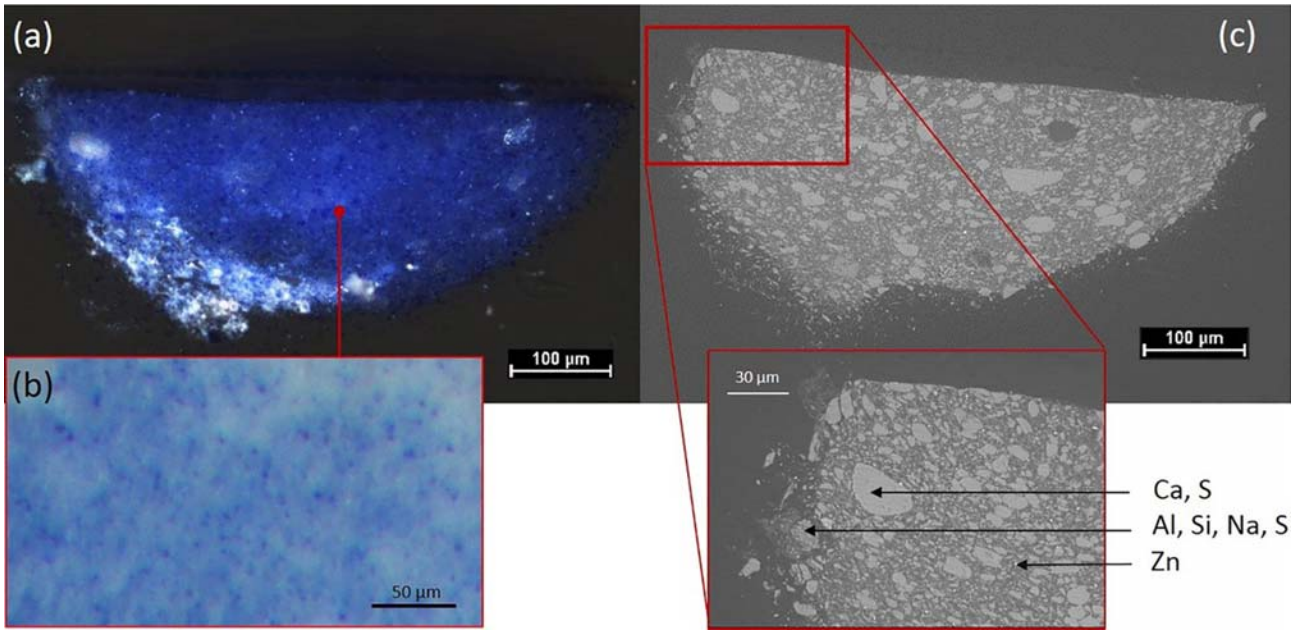

Figure 3. Microscopic images of a fragment from *Tp 2* plastic support: (a) polished as a cross-section; (b) detail of unpolished fragment observed under the microscope; (c) Backscatter SEM image of the cross-section with details highlighting the heavily-filled plastic's different types of particles and their elemental composition.

lab-built stage. The DESI spray was positioned c. 2 mm from the surface at an incident angle of 50°. Nitrogen gas pressure was 180 psi, MS capillary temperature was set to 275ºC and 5 kV was applied to the stainless needle of the syringe used to deliver the DESI solvent (acetonitrile: dimethylformamide 1:1 [v/v], flow rate 3µL/min). Data were collected in the range *m/z* 180-1000.

3 Results

3.1 Extenders and Colorants

When observed under magnification, microsamples from the plastic supports of *T1* and *Tp 2*, respectively of black and blue color, indicated the presence of white particles (sample from *Tp 2* shown in Figs. 3a and b). SEM and EDS revealed that the matrices of both samples are abundantly filled with particles ranging in size from 1 to 50 µm that are calcium- and sulfur-rich (Figure 3c). These were identified as calcium sulfate dihydrate (gypsum, $CaSO_4.2H_2O$) by FTIR analysis (Figure 4). Some small zinc-rich particles (c. 1 µm) were also observed in samples from both paintings and attributed to the presence of zinc oxide.

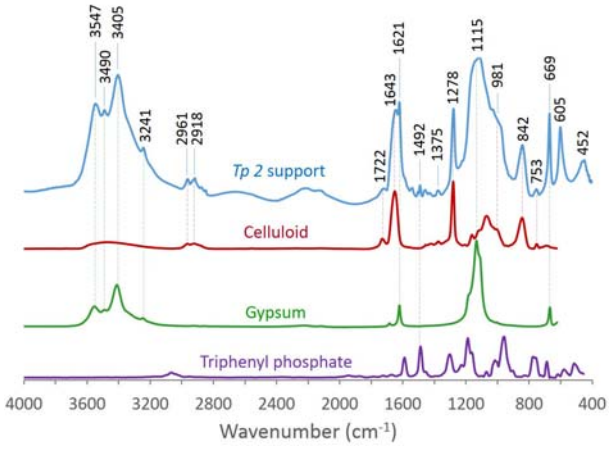

Figure 4. Transmission FTIR spectrum of *Tp* 2 support (in blue) and comparative reference spectra of celluloid (IRUG ISR00066 - in red), gypsum (IRUG IMP00105 - in green) and triphenyl phosphate (Nicolet 381 – in purple).[12]

Different pigments were dispersed in this matrix to achieve the distinctive coloration of the two substrates. The microsample from *Tp 2* showed blue particles (Figure 3b) that correspond in the backscattered images to agglomerates of smaller particles rich in aluminum, sulfur, silicon and sodium (Figure 3c). This composition suggests the presence of the pigment ultramarine ($Na_6Al_6Si_6O_{24}S_4$), which was confirmed by Raman analysis.[8]

In contrast, discrete particles accounting for the dark coloration of *T1* could not be visually discerned, even at high magnification. SEM-EDS analysis of a sample from the support of *T1* indicated that it contains a few barium- and sulfur-rich particles in addition to the gypsum, suggesting the presence of some barium sulfate. A few iron-rich particles were also detected but these are too sparse to suggest the use of an iron oxide black for the dark color of the plastic, which is more likely attributable to a finely dispersed carbon black or possibly an aniline black, although these could not be confirmed by the instrumental analyses performed. Interestingly, DESI-MS analysis of a fragment from *T1* suggested the presence of another synthetic dye. The positive ion MS data, illustrated in Figure 5, show close correspondence to published data for Brilliant Green (C.I. 42040),[9] a cationic triphenylmethane dye discovered in 1879.[10, 11] The data show a prominent ion in the full mass scan at *m/z* 385.3 with MS^2 analysis of this precursor ion producing characteristic daughter ions including *m/z* 355.2 (M-[C_2H_5+H]) and 341.2 (M-[$N(C_2H_5)$+H]). DESI-MS analysis of a sample of the support of *Tp 2* did not reveal any ionic species that could be specifically associated with organic colorants or other additives.

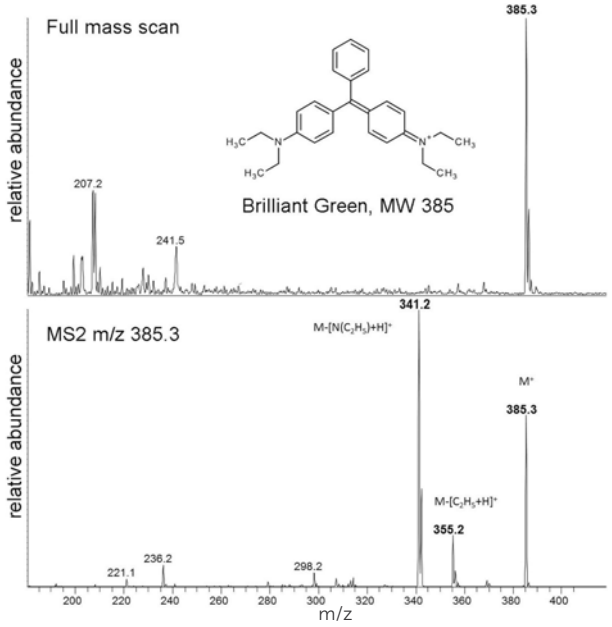

Figure 5. DESI-MS data for sample from *T1* support: full mass scan in positive ion mode (top) and MS^2 data for *m/z* 385.3 (bottom).

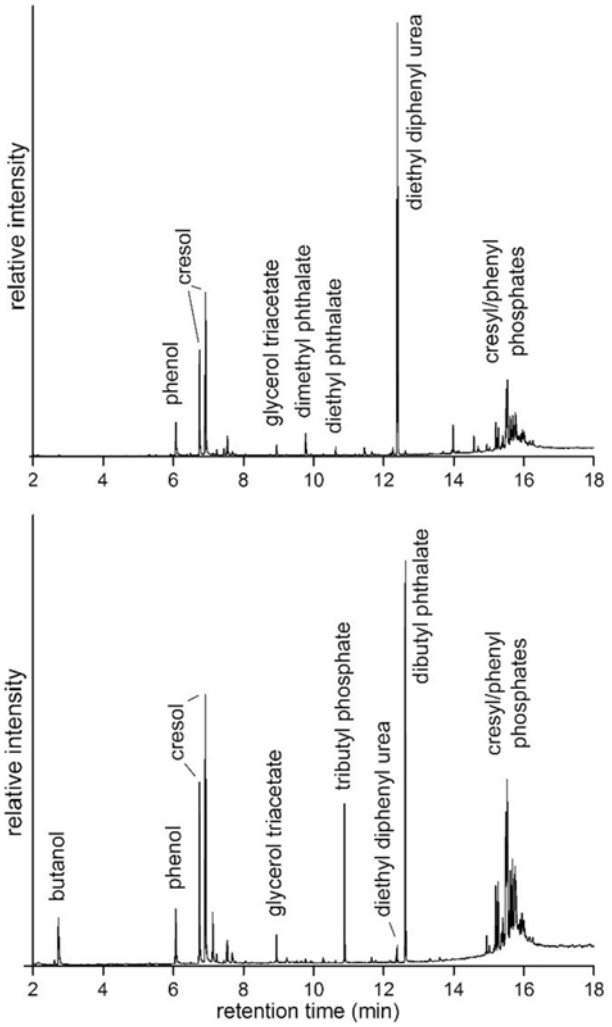

Figure 6. Pyrograms (total ion chromatogram) at 550°C of the plastic supports from *T1* (top) and of *Tp 2* (bottom).

3.2 Plastic Polymer and Organic Additives

FTIR analyses, carried out initially *in-situ* in reflectance mode and subsequently on microsamples in transmission mode, allowed further characterization of the plastics. The two plastic supports exhibit very similar FTIR spectra (Figure 4): in both, bands for CN, consisting of bands of the cellulosic structure combined with characteristic asymmetric and symmetric NO_2 stretching, respectively at 1643 and 1278 cm^{-1}, are confirmed by a close match with a reference spectrum (IRUG ISR00066).[6, 12] The spectra are also dominated by additional peaks corresponding to the presence of gypsum filler in high concentration, as previously mentioned. While no bands for camphor (a common plasticizer for early CN plastics) are observed, a number of smaller peaks, including a sharp band at 1492 cm^{-1} relating to an aromatic ring structure, suggest the possible presence of an organophosphate compound, a finding supported by Py-GCMS (Figure 6). The pyrograms of samples from *T1* and *Tp 2* reveal the presence of organic additives typical for cellulose ester plastics, with some variation observed between the two plastics as summarized in Table 1.[13, 14] Both contain mixed phenyl and cresyl phosphates, diethyl diphenyl urea (more abundant in *T1*) and a small amount of glycerol triacetate. Dibutyl phthalate and tributyl phosphate were detected prominently only in *Tp 2*, and small amounts of diethyl and dimethyl phthalate in *T1*. The different combinations of additives may relate to the particular requirements and compatibilities with the two plastics, or possibly to changes in formulation during this period of production.

Also detected in both pyrograms were phenol and cresols (methyl phenols), and further analyses were conducted to investigate the question of whether these compounds might be contributing to pungent odors that were noticed on examination of the two paintings (clearly perceptible, but distinctive in each case). Repeating the pyrolysis analysis at different furnace temperatures showed variable levels of these compounds, indicating that they appear in the analysis predominantly as analytical artefacts formed by pyrolytic breakdown of the phenyl/cresyl phosphates. However, analysis by SPME-GCMS of a section of the Tyvek ® material that had been in contact with *Tp 2* in storage (and had absorbed the odor) also revealed the presence of phenols and cresols, along with glycerol triacetate, confirming that these compounds are being emitted to some degree from the plastics; the former may reflect either breakdown of the organophosphate additives or impurities from their formulation. Analysis of the Nomex ® material that had been in contact with *T1* in storage did not reveal significant levels of volatiles that could be associated with components of the plastic support, possibly because of the different absorbent properties of this material. Research on cellulose acetate stability has shown that the hydrolysis of triphenyl phosphate may be associated with degradation of this polymer under conditions of high humidity,[15] and so these findings from *Tp 2* stress the need for careful monitoring of the work and maintenance of controlled environmental conditions.

4 Discussion

The data presented in the previous section, and summarized in Table 1, indicate that the plastic supports consist primarily of CN bulked with gypsum. *Tp 2* is

	Polymer	Fillers	Colorant(s)	Plasticizers and organic additives[f]
T1	cellulose nitrate[a,b,f]	gypsum[a,b,c]	zinc oxide[c] probably carbon black (inferred) Brilliant Green or related triphenyl methane compound[d]	diethyl diphenyl urea mixed cresyl/phenyl phosphates dimethyl phthalate (minor) diethyl phthalate (minor) glycerol triacetate (minor)
Tp 2			zinc oxide[c] ultramarine[c,e]	dibutyl phthalate tributyl phosphate mixed cresyl/phenyl phosphates glycerol triacetate (minor) diethyl diphenyl urea (minor)

Table 1: Summary of analytical results from analysis of the plastic supports of *T1* and *Tp 2* (a: in-situ FTIR in reflectance; b: micro-FTIR in transmittance; c: SEM-EDS; d: DESI-MS; e: Raman spectroscopy; f: Py-GCMS).

Product	Plastic type	Starting date of production	Spellings used in Moholy-Nagy translated writings[27] and *Telehor* issue[34]
Trolit	Trolit F: highly filled cellulose nitrate	1920	Trolit, Trolite, Trolithe,Trolitem
	Trolit W: cellulose acetate	1923	
Trolon	raw phenol formaldehyde resin	1924	
Trolitan	semi-finished phenol formaldehyde resin	1925	
Trolitul	polystyrene material for injection moulding	1929	

Table 2. Summary of trademark plastics produced in Troisdorf in the 1920s [23, 24] and transcriptions of *Trolit* in literature.

pigmented with synthetic ultramarine and zinc oxide. In the case of *T1*, zinc oxide and Brilliant Green, or a related organic dye, were detected, and are likely present in mixture with a carbon-based or organic black to account for the opaque, dark color of its plastic support, although a black colorant could not be confirmed. Interestingly, combinations of ultramarine and zinc oxide are described in the early technical literature as a good mixture to create saturated color and opacity in celluloid sheets.[16] Similarly to the *T1* substrate, recipes combining organic dyes with mineral pigments are also reported in recipes to "stain" CN plastics: Brilliant Green is among the common organic colors recommended in a 1912 manual, and green and blue colorants are listed in mixture with blacks in a recipe for an "ordinary black" color.[16] Also identified in the plastics were plasticizers including phenyl/cresyl phosphates, which have an additional function as fire retardants and started to be used as a replacement for camphor from the 1920s-1930s.[6, 17]

Although CN is known to undergo autocatalytic degradation and/or to lose organic additives,[18] *T1* and *Tp 2* appear to be in remarkably good condition. The only clear sign of ongoing molecular change is the pungent odors, as noted above, likely associated in part with the emission of low molecular weight additives or their breakdown products from the plastic.

The apparent excellent current state of preservation of the plastic substrates of *T1* and *Tp 2* may be due to several factors related to their material formulation. First, zinc oxide has been shown to stabilize CN by neutralization of acidic degradation products.[4, 5, 19] Second, it is generally accepted that heavily-bulked materials have increased thermal stability and mechanical strength in comparison with unfilled plastics.[6] Dark-pigmented plastics have also been reported to exhibit diminished photo-catalytic degradation compared to lighter colored or transparent materials.[20] With regard to the organic additives, while triphenyl phosphate has been associated with degradation of cellulose acetate under conditions of high humidity,[15] plasticizers containing aromatic rings, such as phthalates and triphenyl/tricresyl phosphates, are also known to provide a stabilizing effect to plastic substrates.[18] In CN adhe-

Figure 7. Advertisements for *Trolit* from the RWS company from 1926 (top) and 1928 (bottom). Source: Troisdorfer Kunststoff-Museum e.V.

Figure 8. Polishing of celluloid sheets, from Yarsley, Flavell and Perkins, 1964, Cellulosic plastics, Plate 12. Original source: B. X. Plastics Ltd. © The Institute of Materials, Minerals and Mining (IOM3).

sives, for instance, it has been observed that phthalate plasticizers can improve resistance to thermal and photochemical degradation.[17] These observations suggest that, overall, the composition of *T1* and *Tp 2* substrates may have contributed to their state of preservation.

Trolit was a family of cellulosic plastics developed for the electrical industry in the 1920s by RWS in Troisdorf, Germany (Figure 7). RWS patented two methods that formed the main basis for the development of *Trolit* plastics [21, 22] and bear many similarities to the formulation of *T1* and *Tp 2* supports. The first method involves using abundant amounts of both plasticizers and fillers to make cellulose-derived plastics with improved processability and reduced shrinkage. The second method uses a combination of calcium sulfate and phosphoric esters to obtain non-flammable cellulosic plastics. Following the development of these patents, two distinct types of plastic were marketed and sold under very similar names: *Trolit F*, a highly-filled CN first produced in 1920, and *Trolit W*, a cellulose acetate first introduced in 1923. A variety of other plastics including *Trolitan* were later produced at Troisdorf (Table 2).[23, 24]

Early and mid-20th century manufacturing practices of cellulose nitrate sheets for industrial and decorative uses have been described in the literature.[16, 18, 25, 26] The dimensions of *T1* (139.8 x 61.8 cm) and *Tp 2* (61.5 x 144.3 cm) match well the known dimensions of CN sheets, which were of standard size (ca. 24 x 54 in or 60 x 140 cm).[18] The CN sheets were commonly delivered polished (Figure 8), either on one or both sides depending of the application requirements.[16] This information highlights that the plastic panels of *T1* and *Tp 2* were likely not custom-made for Moholy-Nagy

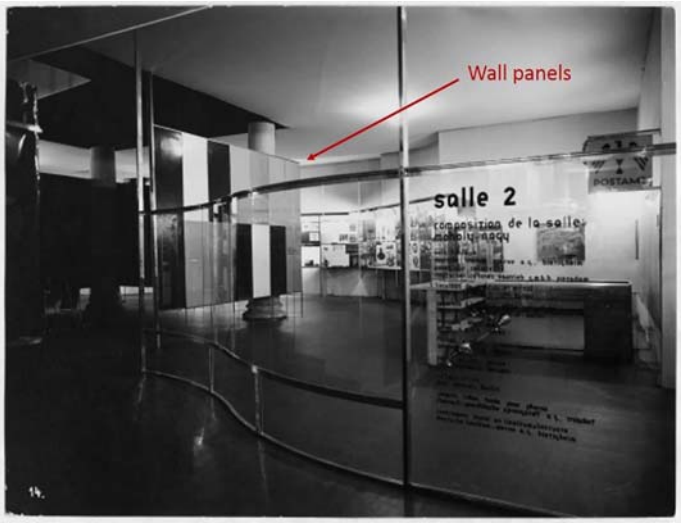

Figure 9. Photograph of the room designed by Moholy-Nagy at the 1930 exhibition in Paris showing a series of elongated rectangular *Trolit* plastic wall panels. Photo: Bauhaus-Archiv Berlin, unknown photographer © 2016 Hattula Moholy-Nagy / VG Bild-Kunst, Bonn / Artists Rights Society. New York.

and that they were probably polished on one side directly by the manufacturer rather than by the artist.

Moholy-Nagy likely knew that the materials he used for *T1* and *Tp 2* had a trade name of Trolit as he mentioned it by this name in his writings as one of the "*valuable artificial materials (...) produced today for the electro-technical industry (...)*".[27] Two photographs of *Tp 2* in the Archives of the László Moholy-Nagy Estate have inscriptions on the reverse in Moholy-Nagy's handwriting describing the work as "Trolite" or "Trolitbild", and a photograph of a work called *Tp 1* (formerly in the collection of Solomon R. Guggenheim*) has an inscription that reads more specifically "blaues trolitbild 1930 (poliert)", suggesting that the support was very similar to that of *Tp 2*.[28] Since the titles of his works often reference their support materials, it is conceivable that 'T' refers to 'Trolit' and "Tp" to either "Trolit poliert" or, less likely, "Trolit Platte". Moholy-Nagy used panels very similar to the plastic substrates of *T1* and *Tp 2* in the walls enclosing the "Kino-Box" (screening room) as part of the Deutscher Werkbund exhibition at the 1930 salon of the Société des Artistes Décorateurs in Paris (Figure 9). These wall panels were described as Trolit in contemporary press accounts of the exhibition, which also noted their intense colors.[29,30] However, whether Moholy-Nagy knew that Trolit was chemically different from the more commonly known Bakelite is unclear since there are inconsistencies in his unpublished correspondences with the Guggenheim Museum: he used the term "Trolitbild", possibly referring to *Tp 2*, in a letter dated from 1930 [31] and on the back of the above mentioned photograph of Tp 2 [28], while he referred to "the Bakelite picture *Tp 2*" in another letter dated from 1941.[32] A complete overview of Moholy-Nagy's use of plastics has been compiled in connection with the production history and trade names of early plastics in the catalog for the exhibition *The Shape of Things to Come*.[33]

*The original *Tp 1* shown in the photograph was damaged and was refabricated by Moholy-Nagy in 1942. The support material for the second version, now in the collection of the Kurt and Ernst Schwitters Foundation, Hanover, is not known.

The long association of *T1* and *Tp 2* with phenol formaldehyde resin may also be due to the fact that their dark colored supports and apparently good overall condition are not often associated with CN. Another factor may have been the confusion over the historic and trade names assigned to the support material in a 1936 special issue of the journal *Telehor* dedicated to Moholy-Nagy's work.[34] There the support of *Tp 2* was identified as "Trolite" with noteworthy inconsistencies in the descriptions of support materials amongst the four languages into which the publication was translated (see Table 2). All these translations likely referred to the CN material *Trolit*, but an erroneous translation of "Trolit" or "Trolite" to "Trolitan" may have been made at some point, thus contributing to its misidentification as a phenol formaldehyde resin.

Prior to the recent examination and conservation, and before it was known that their supports were composed of CN, *T1* and *Tp 2* were stored for at least 10-15 years in acrylic-glazed shadow boxes – that is, enclosed but not in tightly sealed environments – including short periods during which they were exhibited unglazed. For the 2016-2017 retrospective exhibition *Moholy Nagy: Future Present*, and after extensive consultation among conservators, scientists and plastics experts, it was decided to avoid further enclosure of the works and to display the paintings without glazing. The newly-constructed frames incorporated acid-free, buffered mat board backings that provide an absorption capacity for any further emission of volatile compounds that may occur from the panels. During treatment of the works in preparation for exhibition, organic solvents were avoided and exposure to moisture was kept to an absolute minimum. The paintings were displayed at reduced light levels (50 lux or below) more typical for works of art on paper than for paintings. Longer term storage decisions remain to be determined, and will be based on further monitoring and research on these paintings and other objects made from similarly vulnerable materials.

5 Conclusions

Our research has provided a detailed characterization of the plastic supports of *T1* and *Tp 2*, two Moholy-Nagy paintings from 1926 and 1930. These artworks were made with a highly filled cellulose nitrate material called *Trolit,* produced by RWS in Troisdorf. Although modern plastics have been the subject of in-depth investigations in recent years, this is the first reported analysis of one such plastic used as a support for easel painting. The findings illuminate how the precisely engineered formulation of fillers, colorants and plasticizers (which have been successfully correlated in this work with patent and trade literature of the period) may have contributed to the preservation of these objects. These and other findings significantly expand the current knowledge of Moholy-Nagy's practices and exploration of new industrial materials, and provide essential information that will enable optimization of the long-term preservation strategy for these two artworks. These new findings also emphasize the value of combining scientific analysis with art historical, conservation and archival research to identify and interpret artists' media.

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