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Moisture Mapping of Aeronautical Museum Depot and Galleries by IR Thermography

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The paper presents the results of moisture detection in the depot and galleries of the Aeronautical Museum in Belgrade. The moisture and changeable temperature conditions are the main causes for corrosion in historical buildings and museum artefacts. The main purpose of the tests was to determine these conditions in the museum where very important metal artefacts are exhibited and deposed, including the only surviving example of the Fiat G50 aircraft, by applying passive IR thermography. The advantages of thermography in a rapid and accurate detection of moisture in the walls, ceilings and floors of the museum are analysed. Active IR thermography is used for the determination of the composite structure and the characterisation of hidden corrosion in some parts of the Fiat G50 aircraft. The recorded thermograms indicate the damage due to corrosion in many parts examined in detail by radiography and the XRD method.

Key words: **thermography, IR thermography, moisture, corrosion, testing, museum, museum exhibits.**

Introductiona

INFRARED thermography (IR) as a measurement and testing method is a very powerful tool for many areas of science, industry, medicine, military and also for cultural heritage preservation [1-18]. Recently, new developments have been done in the field of IR instrumentation (high sensitive array detectors without cooling and high spatial resolution, digital signal processing), leading to the improvement and further spreading of IR measurement and testing methods into many application fields [2,3].

The IR thermographic technique can be used to investigate the structure and composition of walls, by detecting different inertial thermal behaviour of materials within the first centimetres. The surface temperature of walls is influenced by internal heat propagation that in turn is influenced by environmental conditions. A variation of such conditions, either natural or artificially induced, causes a thermal disequilibrium that can be easily visualized through IR thermography [2,4,6-14,17].

In addition, thermography, as a contactless method of testing, is used to detect heat loss or moisture in walls and roofs which characterize thermal insulation, structural damage, etc. An IR camera can detect moisture very quickly, identifying the location and size of moisture-damaged areas. The presence of water in the structure and its changes of phases (vapour-liquid) are responsible for the damage of materials, for damage of stock supplies inside buildings and even for sickness of people who live in them. Moisture in museum buildings is a big problem in cultural and technical heritage preservation [6-14,17,18].

Due to moisture and a number of aggressive substances in the environment and atmosphere, metal items are subjected to the process of corrosion and oxidation. Corrosion of metal artefacts takes place very rapidly in wet museum depots and galleries because moisture and oxygen in the environment react chemically with elements in artefacts. During this process, corrosion products are formed both inside objects and on their surface. Corrosion can cause serious failures [12, 14,17,18]. Thermography is a contactless method for corrosion detection. The application of this method for a special, world unique artefact, the Italian Fiat G.50 fighter aircraft, is presented in this paper.

Moisture mapping (digital thermal and photo images, taken from the same vantage point, showing the affected areas) is an extremely valuable procedure for many museums affected by water damage.

A part of the thermographic inspection of the Aeronautical Museum building, especially its depot and galleries, concerning moisture mapping, is analyzed in this paper. The most valuable items of the Museum collection are fighter aircraft and fighter-bombers, including specimens of the German Messerschmitt ME-109, the English Hurricane and Spitfire, the Russian Yakovlev Yak-3 and Ilyushin Il-2 and the American B-47 Thunderbolt. To these should be added The German Focke-Wulf 190 and the Russian Yak-9P, and then there is the Italian Fiat G.50 fighter aircraft, the only one of its kind in the world. Many of them are kept in the Museum depots [16].

The moisture in the ceilings, walls and floors of the depot and galleries can permanently deteriorate metal items. Extreme care is needed to prevent this. Preservation of cultural and historical property for the future is one of the most important activities.

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The aim of the paper is to present some results of the moisture detection in the depot and galleries of the Aeronautical Museum in Belgrade where the metal items of interest are deposed.

Moisture detection by thermography

Infrared thermography is a process in which an infrared imaging system (an infrared camera) converts the spatial variations in infrared radiance from a surface into a two-dimensional image, in which variations in radiance are displayed as a range of colours or tones. As a general rule, objects in the image that are lighter in colour are warmer and darker objects are cooler.

IR thermography is a method of contactless temperature measurement providing temperature distribution on the surface of the observed building. The use of thermography in engineering for building assessment purposes opens up large possibilities for construction quality control. Besides giving insight into the state of the building insulation quality, IR thermography can be successfully applied in the evaluation of the building envelope: for detecting different defect types (flaws and damage) – for detecting locations where the plaster layer is detached from the wall base with possible presence of air or moisture in the layers beneath the outer plaster. This technique can be applied for estimation of the plain roofs state - detecting locations where the roof cardboard is detached from the base.

According to the fundamental Law of Planck, all objects above absolute zero emit IR radiation. This radiation only becomes visible to the human eye when the temperature is above about 500^{o}C. IR monitoring equipment which can detect IR emission and visualize it as a visible image has been developed. The wavelengths of IR radiation for the camera (sensitive range) are between 2 and 14 microns. The 2-5.6 micron range is generally used to visualize temperatures between 40^{o}C and 2000^{o}C and the 8-14 micron range is used for temperatures between -20^{o}C and ambient temperatures.

Infrared thermography can be used both as qualitative and quantitative tool. Some applications do not require obtaining exact surface temperatures. For example, to identify hidden structure or adhesion of frescoes, or moisture areas, it is sufficient to acquire thermal signatures. This method of a qualitative visual inspection is based on image interpretation. On the other hand, a quantitative analysis requires a rectification of thermal images to provide a correct length or surface measures.

Besides different limitations, IR thermography is recognized as a thermal, nondestructive testing method, which holds many advantages with respect to the other methods of nondestructive testing. The method enables an instant analysis of a building, in situ, and the control of relatively large surfaces in a short period of time. In addition, the post-analysis enables a relatively straightforward estimation of thermal insulation quality, of the building's heat losses as well as the estimation of the structure beneath the plaster layer of the building.

The thermograms taken with an IR camera measure the temperature distribution on the surface of the object at the time of the test. It is important to point out that this temperature distribution is the result of a dynamic process. IR thermography has the advantage of nondestructive testing while it allows investigating and mapping large surfaces. An IR camera can detect moisture quickly and nondestructively, identifying the location and size of moisture-damaged areas, due to the effects of evaporative cooling. The transition from the liquid to vapour states for water involves an energy absorption of the order of 106 J/Kg (heat of water vaporization). The cooling effect can range from a few tens to more than 10°C depending on the characteristics of the material and the evaporation flux value.

The measures can be repeated in time to monitor the phenomenon of raising water or drying. The temperature of the areas with moisture can be colder than that of dry ones, because of surface evaporation, or can be warmer, because of higher thermal inertia of water content versus building materials. The apparent discrepancies between the two results are due to the different microclimatic conditions of the scanning.

There are many techniques suitable for the moisture detection by thermography [1,3]. The simplest one is a passive technique working in a steady state, where data is processed by a statistical tool. Thermography is based on the changes of the optical properties of the surface due to the presence of moisture. Emissivity varying in the IR measuring band and absorptivity in the visual band could create false alarms. The water staining of the surface and actual water content of each point are not proportional. Such a visual indication is symptomatic but sometime misleading, because it appears suddenly when moisture concentrates, but remains after the surface dries out.

The time analysis is quite important for moisture control, but it requires normally a long lasting observation time and a correlation with seasonal and weather events [4]. Generally, the choice of the right time to perform the test is of great importance, because various phenomena are activated by moisture accumulation.

Two basic types of water intrusion that affect interior walls and that are detectable with IR cameras are tracing water and deep seated moisture conditions. The thermal patterns associated with these are different. Tracing water conditions are best seen during rain events or shortly after. In most cases, the thermal anomaly will be cold as a direct result of the actual water temperature being cooler than its surroundings or because the water evaporates as it is exposed to the interior air. Tracing water patterns are generally long, thin, amorphous patterns. In some cases, one can trace water marks back to their source, where water enters the building.

Water intrusion inside a building shows a specific leak site, for example, around a window frame or door jam. Moisture formed of water vapour can also produce water damage on interior walls and this damage can be readily detected with IR techniques.

Thermographic inspection

The thermo CAM T-335 IR camera, FLIR Systems, has been used for recording thermograms. The camera resolution is 320x240 pixels with a possibility of Figure-in-Figure mode, displaying a thermal image superimposed over a video image. It can be positioned at a different distance (minimum 0.5m) related to the sample surface. The camera sensitivity is 0.05°C at 30°C, the field of view can be 45° x 33.8° and 25° x 19. The detector type is Focal Plane Array, non-cooled micro bolometer [3]. The camera spectral range is 7.5 to 13μm, whereas the temperature range is from -20°C to +650°C, with a precision of ±2°C.

In order to calculate the temperature of the monitored object from the radiation reaching the camera sensor and link it with moisture, it is necessary to know emissivity of the object surface, temperature of the surrounding objects, camera distance from the tested object, thermal losses, air temperature and relative humidity.

The thermographic inspection was made twice, first in September and then in December. The indoor temperature T_i, the outdoor temperature T_{ou} and the humidity h were recorded simultaneously near the surface. During the first tests, the average values were: T_i=15°C, T_{ou}=19°C, h=78%. The weather had been rainy for a few days before the measurements were done and it was cloudy, without wind during the measurement.

The ambient parameters during the inspection in December were: T_i=11°C, T_{ou}=5°C, h=81%. The weather was rainy, without wind.

Results and discussion

The results of the inspection are presented with thermograms in iron palette, digital records, isotherms and diagrams of the temperature distribution across the line.

For the real-time and static image analysis, the associated software was used because it contains powerful measurement and analysis functions for an extensive temperature analysis, including isotherms, spots, line profiles, time plots, area histograms, image subtraction capability and many more [3]. With the help of the Quick Report PC Software for Analysis & Reporting, the measuring areas were positioned on the thermograms. The results of the museum depot, galleries and building inspection are given with the diagrams of the temperature distribution and the colour isotherm areas.

Museum building and galleries

The museum building is very attractive. The modern architecture of this facility and a great value and diversity of original aircraft, aircraft engines and air force weaponry bring visitors to the Museum's exhibitions. The museum has numerous documents that testify to the development of the national and international aviation in the 20[th] century as well.

Some results of the museum building inspection are presented in Figures 1-4.

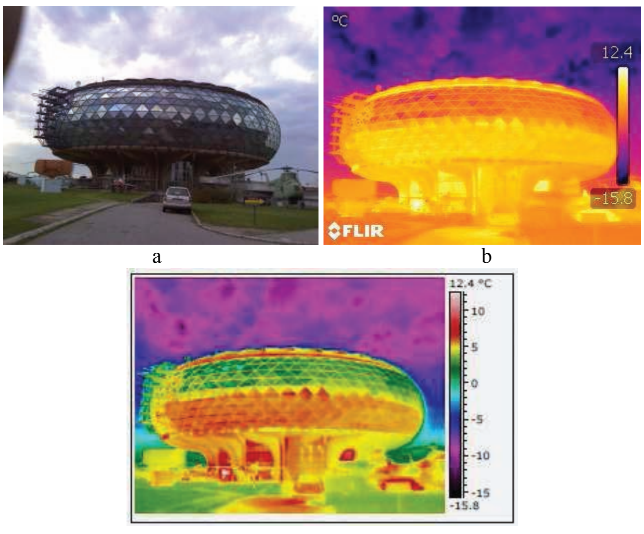


Figure 1. Aeronautical museum building in Belgrade, a - photo, b- thermogram in iron palette and c - thermogram in rainbow palette

A more detailed temperature processing of thermograms by line tool, has enabled the determination of variations in the temperature along the line shown in Fig.2b. The line includes both the hot and the cold zone. The temperature difference is over 10°C (Fig.2c). The zone with active moisture has the temperature of about 1°C lower than the surroundings temperature. The darker area between the first and the second pillar is the place where the atmospheric water penetrates inside. The presence of water inside the walls can be considered as one of the most important causes of degradation in buildings. The evaporation flux from the wall surfaces can be estimated quantitatively by measuring the surface temperature since it depends on the evaporation rate. The value of the surface temperature, in equilibrium conditions for all different heat exchange contributions to the wall, depends on the evaporation rate, material thermal conductivity as well as temperature and ventilation experimental conditions.

Inside the museum dome, the brighter, warmer areas present the penetration of warmer air from the lower part of the museum through the technical tunnels (Fig.2b).

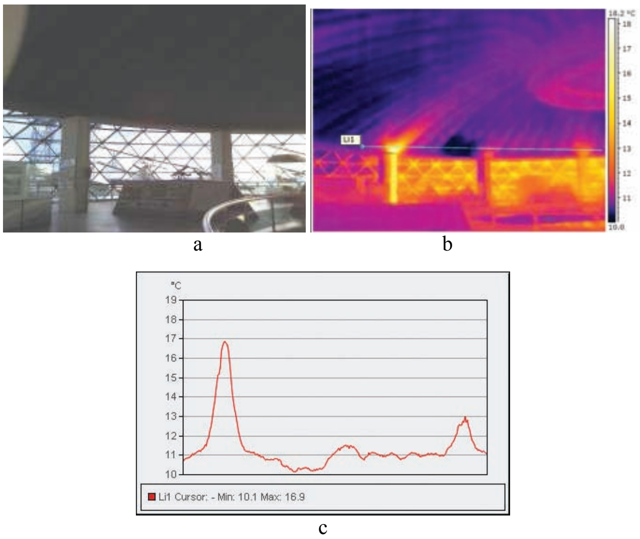


Figure 2. A part of the museum gallery, a - photo, b - thermogram of this part and c - temperature change diagram along the line

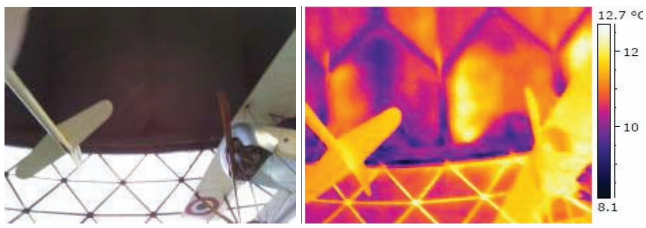


Figure 3. Details of the ceiling, the temperature oscillations recorded on the roof construction are the results of poor thermo insulation

Figure 4. Photo and the thermogram of the gallery dome

Museum depot

The photo and the thermal images of one corner in the museum depot, galleries and building in general as well as the dew point area obtained by the isotherms function are shown in Fig.5. Thermographic tests were conducted in the exhibit rooms and on the roof structure as well. In this paper, the experimental results related to the depot and the galleries are presented.

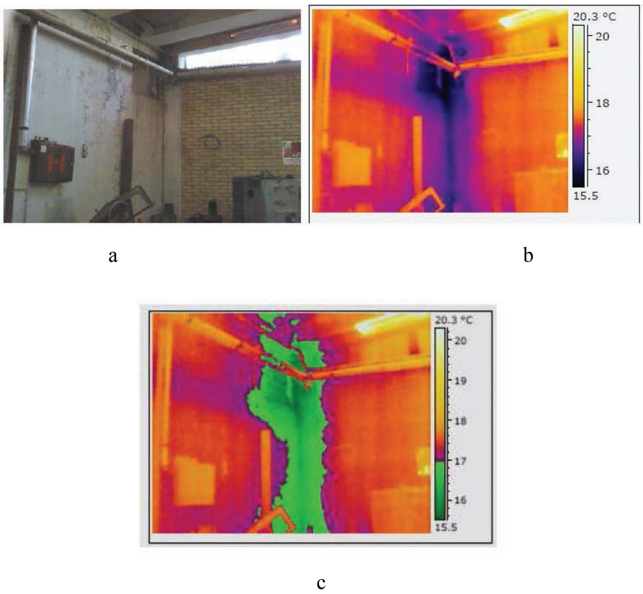


Figure 5. a - Photo and b - thermal images of one corner in the museum depot, c - wet area obtained by isotherms

The photo (Fig.6) confirms that there is a stain on the wall below the windows, on the right side, (Fig.6a) and IR thermography shows that there is active moisture (Fig.6b). The moisture area is colder and appears as a darker area on the thermogram. On the other, left wall, (Fig.7) the stain is not visible, (Fig.7a), but the thermogram shows that there is moisture (Fig.7b).

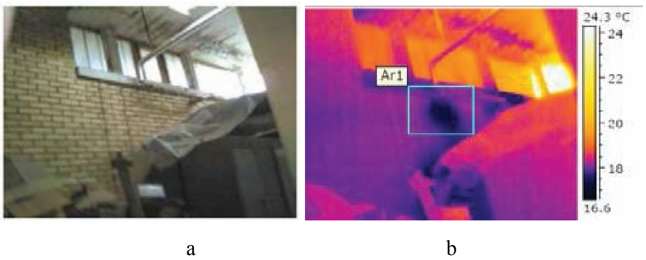


Figure 6. The stain and moisture area below the windows on the right

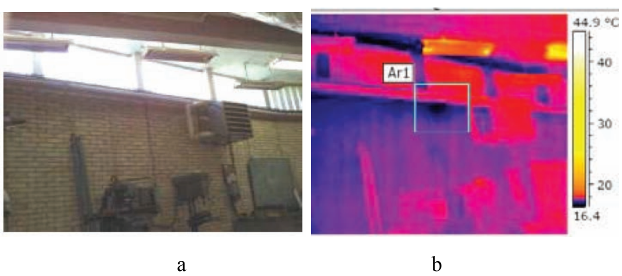


Figure 7. The wall below the windows without a stain, but with captured moisture (Ar1).

The presence of moisture is found in several places in the floor of the depot (Fig.8), on the ceiling and the walls (Figures 9 and 10b). The thermogram 9b next to the line tool has the area limited by isotherms. The diagram in Fig.9c shows that the temperature difference along the line tool is more than 1ºC (1.3ºC). The similar temperature distribution is on the line tool, Fig.10.

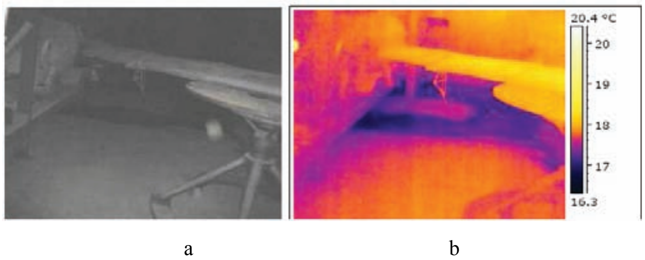


Figure 8. Moisture is found in several places in the floor of the depot

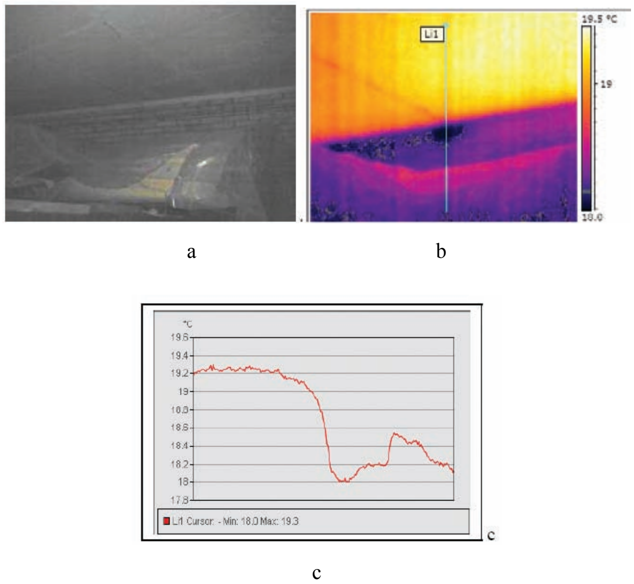


Figure 9. a - Photo record, b - thermogram and c - temperature diagram of moisture in the upper wall part.

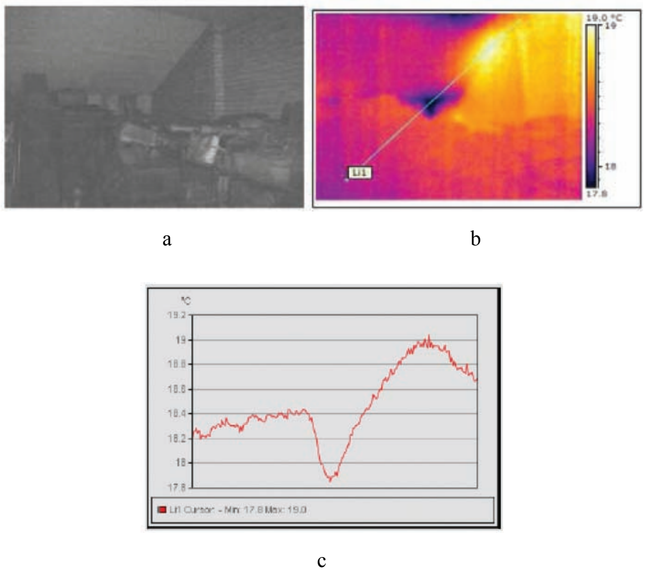


Figure10. Documentation for the detected moisture in the farthest right corner of the depot.

The interpretation of moisture measurements with thermography on surfaces can be very difficult due to several overlapping effects: emissivity changes due to composition, heat transfer through wet sections of the specimen, cooling through air flow or reflected spurious radiation sources. These effects can be reduced by selectively measuring the reflection in two wavelength windows, one on the absorption band of water and another in the reference band and then combining the results in a moisture index image.

As it can be seen in Figures 1-10, passive thermography can locate moisture in the museum depot and the galleries. The sources of moisture in the Aeronautical Museum are condensation on metal and concrete cold spots as well as moisture having gained access through the capillary action at various openings in the exterior walls. The damage in the building from condensation includes mould growth, brick spawning, metal parts fastener corrosion and reduced insulation values.

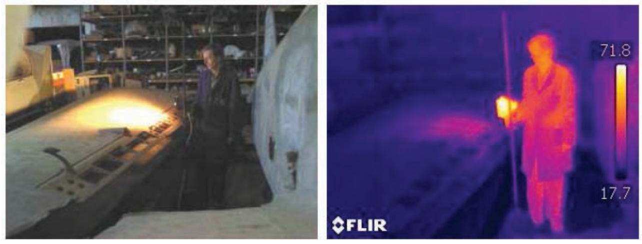
Corrosion detection

Corrosion of metal objects is caused by variable temperature conditions and the presence of moisture in the air, on the depot and galleries walls, floors and ceilings [12]. These conditions are very harmful and can lead to complete destruction of important exhibits. Among other exhibits stored in the depot, a great loss occurs on the G50 aircraft. The visual inspection shows some aircraft parts damaged by corrosion. The conservation of this aircraft is needed urgently.

The research that has been carried out in the museum building belongs to passive thermography. The *passive* approach tests materials and structures which naturally have different temperature than the ambient one, while in the case of the *active* approach, an external stimulus is necessary to induce relevant thermal contrasts. The active approach includes several methods that, besides an IR camera, require a heat source by which the thermal energy flux can be added to the investigated object (thermal wave, lock in, pulse phase thermography, etc). Heating is typically performed by using IR lamps, delivering about 2000 Wm^{-2}, for 60-300 s. A thermogram sequence must contain: the initial image, taken just before heating, the image of the maximum temperature taken at the end of heating and the image at the optimum observation time, for the most relevant class of defects.

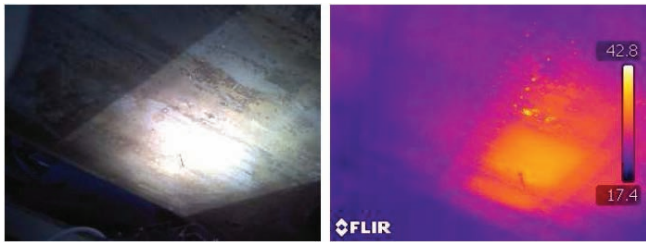
The thermographic inspection of the G50 aircraft was performed by the step heating technique. The increase of the surface temperature was monitored during the application of stepped heating. Some parts of the aircraft were continuously heated at low power. The variations of the surface temperature with time are related to the specimen features. This technique of step heating is sometimes referred to as time-resolved infrared radiometry. The time-resolved part means the temperature is monitored as it evolves during and after the heating process. Step heating finds various applications such as for coating thickness evaluation (including multilayered coatings, integrity of the coating-substrate bond, determination or evaluation of composite structures, characterization of airframe and hidden corrosion among others. Figures 11 and 12 show some parts of the aircraft thermographic inspection. The thermogram recorded the maximum temperature differences at the end of heating. The corroded parts have different temperatures compared to non corroded ones, because they have a porous structure and the corrosion products have different temperature conductivity and capacity in relation to the non corroded parts.

The recorded thermograms indicated the corrosion damage in many parts that were examined in detail by radiography and the XRD method. Fig.13 represents a radiogram of the aircraft landing gear. The composition of the corrosion products was analyzed by the method of diffraction of X-rays (XRD) and is presented in Fig.14 [4,17,18].



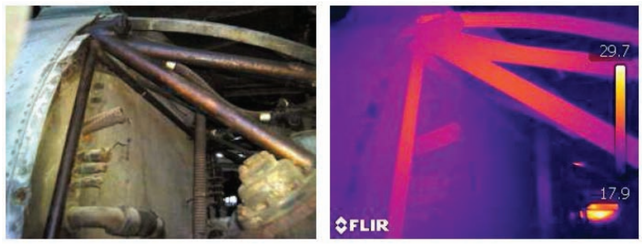
a b

c d



e f

Figure 11. Thermographic inspection of the F50 aircraft; a, b - aircraft wing, c, d - side part of the aircraft and e, f - bottom side of the aircraft



a b

Figure 12. a - Photo and b - thermogram of a metal tube

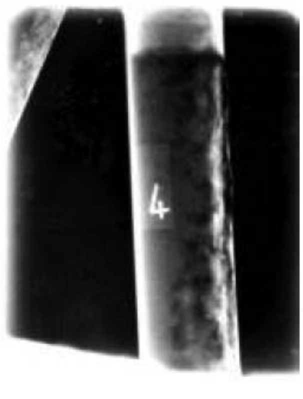


Figure 13. Radiogram of the F50 aircraft landing gear

The sample base is aluminium, Al (JCPDS 4-0787). Crystal hydroxide aluminium, gibsit, $Al(OH)_3$, (Al_2O_3 $3H_2O$ (JCPDS 70-2038) is detected in the corrosion products. The composition of the aluminium corrosion products analyzed by the method of XRD is presented in

Table 1. The corroded specimen of the G50 was taken and examined in a laboratory.

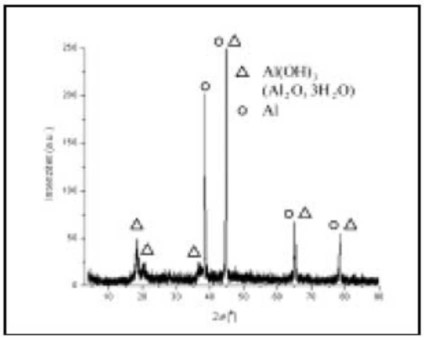


Figure 14. The composition of the F50 aircraft corrosion products analyzed by XRD

Table 1. Aluminium corrosion products (Fiat 50 aircraft)

	d (A)	2(θ°)	I/I_{max} (%)	Al *hkl*	$Al(OH)_3$ *hkl*
1	4.8128	18.420	13.67		002
2	4.3102	20.590	5.47		200
3	3.1763	28.070	3.91		
4	2.4568	36.545	3.91		021
5	2.3347	38.530	70.31	111	
6	2.0236	44.750	100.00	200	023
7	1.4942	62.065	3.91		133
8	1.4321	65.080	22.66	220	600
9	1.3385	70.270	3.91		333
10	1.2203	78.280	16.41	311	622

CONCLUSION

The thermographic inspections focused on the moisture mapping of the Aeronautical Museum building, especially its depot and galleries, are analyzed in this paper. The results confirm that thermography is a useful tool in the rapid determination of moisture intrusions, building envelope failures, building air pressures, and air flows. These parameters are important factors to consider when evaluating indoor environmental quality.

The thermographic inspection shows that the thermal insulation of the Aeronautical Museum building is not good and that moisture is detected in the museum depot. The recorded thermograms indicate a need for a detailed examination of the metal artefacts where the corrosion is in progress.

Acknowledgments

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Termografsko ispitivanje vlage u depou i galerijama vazduhoplovnog muzeja

U radu su prikazani rezultati ispitivanja vlage u depou i galerijama Vazduhoplovnog muzeja u Beogradu. Promenjiva temperatura i vlaga su glavni uzročnici za pojavu korozije u istorijskim zdanjima i na muzejskim eksponatima. Glavni cilj ispitivanja je određivanje navedenih uslova u muzeju, gde se čuvaju i izlažu veoma značajni metalni eksponati, uključujući i jedini sačuvani primerak aviona Fiat G50, metodom pasivne IC termografije. Analizirane su prednosti

termografije za brzo i precizno određivanje prisustva vlage u zidovima, tavanicama i podovima muzeja. Aktivna IC termografioja je korišćena za određivanje složene strukture i karakterizacija skrivenih korozionih oštećenja u delovima aviona Fiat G50. Snimljeni termogrami su ukazali da postoje koroziona oštećenja na više mesta, koja su detaljnije ispitana radiografijom I XRD metodom.

Ključne reči: **termografija, IC termografija, vlaga, korozija, ispitivanje, muzej, muzejski eksponati.**

Термографическое испытание влаги в складе и в галереях музея авиации в Белграде

В данной работе представлены результаты испытания влаги в складе и в галереях Музея авиации в Белграде. Переменная температура и влажность являются основными причинами коррозии в исторических зданиях и на экспонатах в музее. Основная цель этих тестов заключается в определении условий в музее, с использованием пассивной инфракрасной термографии, там где хранятся и выставляются значительные металлические артефакты, в том числе и единственный сохранившийся экземпляр самолёта Fiat G50. Здесь проанализированы преимущества термографии для быстрого и точного определения наличия влаги в стенах, потолках и полах музея. Активная инфракрасная термография была использована для определения сложной структуры и характеристик скрытых коррозионных повреждений в частях самолета Fiat G50. Записанные термограммы показали, что существуют коррозионные повреждения в нескольких местах, которые в дальнейшем рассматриваются методом рентгенографии и РСА.

Ключевые слова: **термография, инфракрасная термография, влага, коррозия, испытания, музей, музейные артефакты.**

Les essais thermo graphiques sur l'humidité dans le dépôt et dans les galeries du Musée de l'aviation

Dans ce papier on a présenté les résultats des tests sur l'humidité dans le dépôt et dans les galerie du Musée de l'aviation à Belgrade. La température variable et l'humidité sont les causes principales de l'apparition de corrosion dans les bâtiments historiques et sur les objets exposés dans les musées. Le but principal de ces recherches était la détermination des conditions citées dans ce musée où l'on garde et expose les objets en métal très importants, y compris le seul exemplaire existent de l'avion Fiat G50, par la méthode de la thermographie passive infra rouge. On a analysé les avantage de cette méthode pour la détermination rapide et précise de la présence de l'humidité dans les murs, les plafonds et les planchers du musée. La thermographie infra rouge a été utilisée pour la détermination chez la structure complexe et pour la caractérisation des endommagements corrosifs cachés chez les pièces de l'avion Fiat G50. On a enregistré les thermo grammes qui ont démontré l'existence des endommagements corrosifs à plusieurs endroits et qui ont été ensuite examinés par la radiographie et par la méthode XRD.

Mots clés: **thermographie, thermographie infra rouge, humidité, corrosion, recherches, musée, objets exposés.**