JOSIPA LOVRIĆ

Arheološki muzej Zadar
Trg opatice Čike 1
HR-23000 Zadar
jlovric@amzd.hr

UDK: 7.025.3-035.3
629.5:902.034>(497.581.1Zaton)"652"

Stručni članak / Professional paper
Primljen / Received: 26.1.2021.
Prihvaćen / Accepted: 15.2.2021.

KONZERVACIJA ANTIČKOG BRODA IZ ZATONA

Sedamdesetih godina prošlog stoljeća u Arheološkom muzeju Zadar prvi put je na ovim prostorima provedena konzervacija mokrog drva. Konzervirana su dva ranohrvatska broda tipa *Condura Croatica* iz Nina otopinom polietilen-glikola. Istraživanjem antičke luke Enone (Nina) pronađeni su i izvađeni ostatci dvaju antičkih šivanih brodova tipa *serilia.* Ti su brodovi jedinstveni jer su izrađeni bez metalnih dijelova. Naime, svi dijelovi broda spojeni su šivanjem, a korišteni su samo konopci i drveni klinovi. Prvi brod konzerviran je neposredno nakon vađenja 1979. godine, a drugi je izvađen 1987. godine. Spletom okolnosti ostao je nekonzerviran dugi niz godina. Nastavljajući tradiciju, ponovno je pokrenuta konzervacija mokrog drva istom metodom. U tu svrhu izrađen je novi sustav zagrijavanja bazena toplovodnom grijalicom. U radu je opisana konzervacija broda. Dat je kratak osvrt na metodu konzervacije otopinom polietilen-glikola te je detaljno opisan sustav zagrijavanja bazena toplovodnom grijalicom.

Ključne riječi: konzervacija mokrog drva, šivani brod, *serilia*, polietilen-glikol, desalinizacija

CONSERVATION OF A ROMAN-PERIOD SHIP FROM ZATON

In the 1970s, for the first time in these parts, conservation of waterlogged wood was carried out in Archaeological Museum Zadar. Two early Croatian ships from Nin, of *Condura Croatica* type, were conserved using polyethylene glycol solution. Excavations in the Roman port of Enona (Nin) resulted in finding and salvaging of two Roman-period sewn-plank ships of *serilia* type. These ships are unique because they were built with no metal components. All of their components were sewn together and only ropes and wooden wedges were used. The first of the two ships was conserved immediately after its salvaging in 1979. The second one was salvaged in 1987 but, by a combination of circumstances, it was not conserved for a number of years. Continuing the tradition, conservation of waterlogged wood by the same method was resumed. To this end, a new tank heating system was created: a hot-water heater was used. This paper describes the conservation of the ship, briefly analyzing the conservation method based on polyethylene glycol solution. It also offers a detailed description of heating of the tank with a hot-water heater.

Key words: waterlogged wood conservation, sewn-plank ship, *serilia*, polyethylene glycol, desalinization

UVOD

Arheološko drvo može se definirati kao drvo koje ima tragove kulturnih aktivnosti i koje je sačuvano u specifičnom okruženju. To je bilo koji drveni predmet koji daje podatke o ljudskom razvoju i kulturi. Ako je takvo drvo sačuvano u morima, jezerima, rijekama ili vlažnom tlu, tada ga nazivamo arheološkim mokrim drvom. Najčešće nalaze mokrog drva čine brodovi. Najpoznatiji nalaz drvenog broda u svijetu jest brod *Wasa* koji je šezdesetih godina 20. stoljeća izvađen s morskog dna ispred stokholmske luke. To je bio jedrenjak dužine 70-ak metara, a potonuo je u 17. stoljeću, na svom prvom isplovljavanju. Konzerviran je 60-ih godina prošlog stoljeća otopinom polietilen-glikola. Iskustva stečena na vađenju i konzervaciji broda *Wase* bila su iznimno važna za daljnji razvoj konzervacije arheološkog mokrog drva. Kako je u Europi krajem šezdesetih i početkom sedamdesetih godina došlo do naglog poleta podmorskih arheoloških istraživanja, tako je i u našem podmorju pronađeno više brodova među kojima su najvažnija dva ranohrvatska broda tipa *Condura Croatica* iz Nina.[1] Njihov pronalazak potaknuo je domaće stručnjake da pokrenu vađenje i konzervaciju arheološkog mokrog drva na ovim prostorima. Djelatnici Arheološkog muzeja Zadar, okupljeni oko konzervatora Božidara Vilhara, sedamdesetih godina prošlog stoljeća uspješno su izvadili, konzervirali i rekonstruirali navedene brodove. Brodovi su izloženi u Muzeju ninskih starina. Na položaju Kremenjača kod mjesta Zatona u blizini Nina sredinom šezdesetih godina 20. stoljeća otkrivena je luka antičke Enone. Na tom su mjestu 1966. i 1982. godine pronađena dva antička šivana broda. Njihov naziv *serilia* govori da su šivani lanenom i žukovom užadi. Iako su brodovi dospjeli u mulj antičke luke sredinom 1. stoljeća poslije Krista, radiokarbonska analiza drvenih uzoraka pokazuje razliku od gotovo 300 godina od rezanja drvene građe i gradnje brodova do njihova napuštanja. Prvi brod slabije je sačuvan. Izvađen je 1979. godine i konzerviran otopinom polietilen-glikola u konzervatorskoj radionici Arheološkog muzeja Zadar, ali nije rekonstruiran. Drugi je antički brod nakon pronalaska 1982. godine očišćen, fotografiran, premjeren, pažljivo pokriven najlonskom folijom i ponovno zasut pijeskom. Naime, tada

1 Prvi brod pronađen je 1966., a drugi 1968. godine rekognosciranjem priobalnog područja Ninskog zaljeva. Položaj na kojem su pronađena oba broda vrlo je zanimljiv. To je uski prolaz na ulazu u ninsku luku koji tvore dva pješčana poluotoka. Pretpostavlja se da su brodovi tamo namjerno potopljeni da bi spriječili ulaz u luku. U brodovima je pronađena veća količina kamenja kojim su potopljeni. Prvi brod je 1969. u potpunosti istražen i stručno dokumentiran. Godine 1973. očišćen je i istražen i drugi brod. Ustanovilo se da je on sačuvan u lošijem stanju od prvog. Brodovi su 1974. godine izvađeni u komadima i prevezeni u Arheološki muzej Zadar gdje su složeni u vodom pripremljene betonske bazene. Napravljena su dva bazena. U jednom se vršio postupak desalinizacije, a u drugom postupak konzervacije. Nakon desalinizacije konzervirani su otopinom polietilen-glikola. U konzervaciji su korištena iskustva iz Švedske i Danske koja su kod nas prvi put primijenjena. Radiokarbonskom analizom (^{14}C) brodovi su datirani u drugu polovinu ili kraj 11. st. (M. Jurić, S. Oguić, B. Vilhar 1994, 44–45).

INTRODUCTION

Archaeological wood can be defined as wood exhibiting traces of cultural activities, preserved in a specific environment. It can be any wooden object that offers an insight into human development and culture. If such wood has been preserved in a sea, lake, river or humid soil, it is called archaeological waterlogged wood. Ships account for most of waterlogged wood finds. The best known find of a wooden ship in the world is the *Wasa*, a ship that was salvaged from the seabed in front of the Stockholm port in the 1960s. She was a 70-meter-long sailing ship that sank on her maiden voyage in the 17th century. It was conserved in the 1960s using polyethylene glycol solution. The experience acquired when the *Wasa* was salvaged and conserved was very important for further development of the methods of archaeological waterlogged wood conservation. As Europe saw a sudden boost in underwater archaeological excavations in the late 1960s and the early 1970s, several ships were also found on the seabed along our coast. The most important among them were the two Early Croatian ships of *Condura Croatica* type from Nin.[1] These two finds encouraged local experts to initiate salvaging and conservation of archaeological waterlogged wood in these parts. In the 1970s, the staff members of Archaeological Museum Zadar led by conservator Božidar Vilhar successfully salvaged, conserved and reconstructed the said ships. The ships are now exhibited in the Museum of Nin Antiquities. At Kremenjača site near Zaton, in the vicinity of Nin, the port of Roman town of Enona was discovered in mid-1960s. Two sewn-plank ships were found there, in 1966 and 1982. Their name, *serilia*, tells us they were sewn using flax ropes and ropes of Spanish broom. Although the ships ended up in the silt of the Roman port in the mid-1st century AD, the radiocarbon analysis of the wooden samples shows that almost 300 years elapsed between the cutting of the timber and building of the ships and their abandonment. The first ship is rather poorly preserved. It was removed from the seabed in 1979 and conserved with polyethylene glycol solution in the conservation workshop of Archaeological Museum Zadar, but it was not reconstructed. As for the second Roman-period ship, after its discovery in 1982, it was cleaned, photographed, measured, carefully covered

1 The first ship was found in 1966 and the second one in 1968, both during surveying of the coastal area of the Bay of Nin. Both ships were found on a very interesting location. It was in the narrow channel leading to the Nin port between two sand promontories. It is believed that the ships were intentionally sunken there in order to prevent access to the port. Large quantities of stones used for the sinking were found in them. The first ship was fully researched and documented in 1969. The second one was cleaned and researched in 1973. It was established that it was in worst condition than the former one. In 1974, the ships were salvaged section by section and transported to Archaeological Museum Zadar, where they were assembled in two concrete tanks filled with water. One tank was used for desalinization and the other for the conservation process. After desalinization, they were conserved using polyethylene glycol solution. Swedish and Danish experience was applied for the first time in Croatia at that occasion. A radiocarbon analysis (^{14}C) dated the ships to the second half or late 11th century AD. (M. Jurić, S. Oguić, B. Vilhar 1994, 44–45).

nije postojala mogućnost njegova vađenja i konzervacije jer se u isto vrijeme odvijala konzervacija ranije spomenutog prvog broda. Drugi antički brod izvađen je tek 1987. godine. Budući da je bio dug desetak metara, izvađen je u dijelovima. Prvo su se vadila rebra koja su u potpunosti izvađena u jednom komadu, a zatim se oštrim nožem sjekla oplata po sredini mjesta na kojem je prethodno ležalo rebro. Sva su rebra nakon vađenja bila ucrtana na poseban papir u prirodnoj veličini jer je postojala mogućnost da prilikom konzervacije dođe do određenih deformacija. Ukupno je sačuvano 27 rebara. Sva drvena građa prevezena je u konzervatorsku radionicu Arheološkog muzeja Zadar i složena u već pripremljeni bazen, koji je bio napunjen vodom kako bi se izvršio proces desalinizacije drva.[2] Nažalost, nakon vađenja drugog antičkog broda prekida se kontinuitet u konzervaciji mokrog drva u konzervatorskoj radionici Arheološkog muzeja Zadar. Tome su pridonijele mnoge objektivne okolnosti. Uhodani tim stručnjaka koji je radio na poslovima konzervacije, nije više bio na okupu. Sustav zagrijavanja bazena koji je izrađen sedamdesetih godina, djelatnici su napravili vlastitim snagama, bez primjerenih tehničkih i drugih pratećih pomagala. U to vrijeme postojao je veliki entuzijazam, ali su mogućnosti bile ograničene. Ondašnji sustav zagrijavanja bio je neupotrebljiv i nesiguran za daljnji rad. Ponovno pokretanje konzervacije mokrog drva zahtijevalo je velika financijska ulaganja, ali i okupljanje stručnjaka. Trebalo je izraditi sustav zagrijavanja bazena koji će biti učinkovit i siguran za rad. Nakon 29 godina otkako je izvađen iz mora, antički brod iz Zatona konačno je uspješno konzerviran. Da bismo pristupili postupku konzervacije mokrog drva, potrebno je razumjeti postupak razgradnje drva, uzrokovan dugim stajanjem u moru ili vodi.

SVOJSTVA MOKROG DRVA

Drvo koje se dugo nalazi u vodi ili moru ima oslabljenu strukturu koja je rezultat biološke, ali i kemijske razgradnje. Voda koja ga popunjava samo daje podršku oslabljenim stanicama i takvo drvo izgleda stabilno samo dok je mokro. Tri najvažnija gradivna sastojka drva: celuloza, hemiceluloza i lignin, prvi se otapaju u vodi. Celuloza se podvrgava postupku hidrolize i njezinom razgradnjom u staničnoj stijenki ostaje samo ligninska mreža koja podupire drvo. Tijekom duljeg razdoblja dolazi i do razgradnje lignina. Zbog propadanja celuloze i lignina povećavaju se razmaci između stanica i molekula te drvo postaje porozno i upija vodu poput spužve. Svi su oštećeni dijelovi drva, uključujući stanične šupljine i intermolekularne prostore, ispunjeni vodom. Preostala ligninska struktura drvnih stanica i apsorbirana

2 S. Glušćević 1987, 43–44.

with a nylon foil and reburied under sand. Its salvaging and conservation were not possible at the time due to the ongoing conservation of the first ship. The second Roman-period ship was salvaged only in 1987. As it was approx. ten meters long, it was removed from the seabed section by section. The frames were the first to be removed, each of them in a single piece. The planking was then cut with a sharp knife in the middle of the place where a frame once had been. After salvaging, all the frames were drawn in actual size on a special paper because there was a possibility that they suffer certain deformations during conservation. A total of 27 frames were preserved. All the wooden finds were taken to the conservation workshop of Archaeological Museum Zadar and submerged into a tank filled with water in order to undergo desalinization.[2] Unfortunately, after the second Roman-period ship had been salvaged, the waterlogged wood conservation practice in the Museum's conservation workshop was discontinued due to a number of circumstances. The well-tuned team of conservation experts disbanded. The tank heating system made in the 1970s by the Museum staff members without adequate technical and other aids had become obsolete and unsafe for use. Despite huge enthusiasm, possibilities were limited. Relaunching the waterlogged would conservation practice required substantial finances and bringing experts together again. An efficient and safe tank-heating system had to be constructed. Exactly 29 years after its removal from the seabed, the Roman-period ship from Zaton was finally successfully conserved. Discussing the waterlogged wood conservation procedure requires understanding of the process of wood decomposition caused by prolonged stay in sea or fresh water.

CHARACTERISTICS OF WATERLOGGED WOOD

If wood is submerged in fresh or sea water for a prolonged period of time, its structure becomes biologically and chemically degraded. The water that penetrates it only supports its degraded cells; such wood seems stable as long as it remains waterlogged. The three most important components of wood – cellulose, hemicellulose and lignin – are the first ones to dissolve in water. Cellulose undergoes hydrolysis; when decomposed, only the lignin network that supports wood remains in its cell walls. Lignin, too, becomes decomposed after an extended period of time. The degradation of cellulose and lignin increases the distance between cells and molecules and the wood becomes porous and starts soaking water like a sponge. All the damaged parts of the wood, including its cell cavities and intermolecular spaces, fill with water. The remaining lignin structure of wood cells and the absorbed water retain the shape of wood.[3] When waterlogged wood is exposed to sudden drying, the water

2 S. Glušćević 1987, 43–44.
3 L. D. Hamilton 1999, file 6.

voda zadržavaju oblik drva.[3] Naglim sušenjem mokrog drva dolazi do isparavanja vode, a kako mu je struktura oslabljena, nastaju značajne dimenzijske promjene. Te su promjene ireverzibilne. Svako drvo izvađeno iz vode ili mora prije procesa sušenja potrebno je stabilizirati procesom konzervacije, a do tada ga je neophodno čuvati u vlažnim uvjetima, poput bazena s vodom, da bi se izbjegle prethodno spomenute ireverzibilne promjene.

POLIETILEN-GLIKOL U KONZERVACIJI MOKROG DRVA

Konzerviranje mokrog drva otopinom polietilen-glikola jedna je od prvih i često korištenih metoda. Pogodna je za konzerviranje velikih drvenih nalaza. Konzervacija mokrog drva složen je postupak koji se provodi tako da se voda u drvenoj strukturi zamjenjuje impregnacijskim sredstvom koje će pružiti mehaničku potporu drvu i spriječiti da se uklanjanjem vode dogode dimenzijske promjene. Kao impregnacijsko sredstvo koristi se kemikalija polietilen-glikol (PEG). Polietilen-glikol je sintetska smola dobivena kondenzacijom etilen-glikola s viškom molekula etilen-oksida. Molekule PEG-a imaju vrlo veliku molekularnu masu. Polietilen-glikoli variraju po svojim svojstvima ovisno o molekularnoj masi od ljepljivih, viskoznih tekućina do krutih tvari sličnih vosku. Difuzija PEG-a u drvo spor je proces i ovisi o veličini njegovih molekula. Ovisno o stanju očuvanosti drva, odabire se određena vrsta PEG-a, optimalna za njegovu strukturu.[4] Iako polietilen-glikoli imaju neka fizikalna svojstva voska, oni se razlikuju od pravog voska činjenicom da su topljivi u vodi i raznim alkoholima (etanol, metanol, izopropanol). Prije donošenja odluke o konzerviranju drva PEG-om, važno je uzeti u obzir činjenicu da PEG pri nepovoljnim klimatskim uvjetima veže za sebe vlagu koja uzrokuje koroziju metala poput željeza, olova, bakra, bronce i aluminija. Stoga se ne preporučuje da ga se koristi kao impregnacijsko sredstvo za drvo koje je u kombinaciji s bilo kojim od navedenih metala.[5] Kako se radi o šivanom brodu bez metalnih dijelova, odlučeno je da se, s obzirom na postojeće bazene, brod konzervira otopinom polietilen-glikola. U konzervaciji je korišten polietilen-glikol velike molekularne mase, PEG 4000.

3 L. D. Hamilton 1999, file 6.
4 R. Jurić 1995, 79.
5 70-ih godina prošlog stoljeća konzervacija mokrog drva bila je u svom začetku. Tada se nije znalo da PEG veže vlagu za sebe i da zbog toga dolazi do korozije željeznih dijelova koji se nalaze u strukturi broda. Ranohrvatski brodovi u svojoj su konstrukciji imali željezne čavle. U arheološkom mokrom drvu dolazi do nakupljanja sumpornih spojeva iz bakterijski proizvedenog sumporovodika. U reakciji sumporovodika i reaktivnih vrsta željeza (željezo-oksidi i oksihidroksidi) dolazi do nastajanja pirita FeS_2 koji brzo oksidira do sumporne kiseline. Nakupljanje sumporne kiseline uzrokuje degradaciju drva. S Međunarodnim centrom za podvodnu arheologiju u Zadru pokrenuta je suradnja u sanaciji navedenih problema.

evaporates from it and, due to its degraded structure, the wood shrinks significantly. This change is irreversible. Every wooden object extracted from fresh or sea water should be stabilized by means of conservation prior to drying; until such time, it must be kept in humid conditions (such as a tank with filled with water), in order to avoid the abovementioned irreversible change.

POLYETHYLENE GLYCOL IN WATERLOGGED WOOD CONSERVATION

Conserving a waterlogged wooden object with polyethylene glycol solution is one of the oldest and frequently used methods. It is suitable for conserving large wooden finds. Waterlogged wood conservation is a complex procedure: it is based on replacing the water in the wooden structure with an impregnation agent that will support the wood mechanically and prevent it from changing its size when the water is removed. The chemical called polyethylene glycol (PEG) is used as an impregnation agent. Polyethylene glycol is a synthetic resin obtained by condensing ethylene-glycol with surplus ethylene-oxide molecules. The PEG molecules have a large molecular mass. Depending on their molecular mass, the polyethylene glycols vary by their characteristics, ranging from adhesive, viscous liquids to wax-resembling solids. The PEG's diffusion into the wood is a slow process that depends on the size of its molecules. The type of PEG to be used must be optimal for the wood's structure; it depends on the condition of the wood.[4] Although polyethylene glycols have some physical characteristics of wax, they differ from the real wax by their solubility in water and various alcohols (ethanol, methanol, isopropanol). Before deciding to conserve a wooden object by using a PEG, it is important to keep in mind that, in unfavorable climate conditions, a PEG can bind moisture that causes corrosion of the metals like iron, lead, copper, bronze and aluminum. For this reason, it is not recommended for impregnating wooden objects which are combined with any of these metals.[5] As the object in question was a sewn-plank ship with no metal components, it was decided that, given the existing tanks, a polyethylene glycol solution be used for its conservation. A polyethylene glycol with a large molecular mass (PEG 4000) was used for the conservation.

4 R. Jurić 1995, 79.
5 In the 1970s, waterlogged wood conservation was still in its initial stage. It was not known then that PEG`s bind moisture, thus causing corrosion of the iron components in the ship's structure. Early Croatian ships had iron nails in their structure. In archaeological waterlogged wood, bacteria produce hydrogen sulfide. As a result, sulfur compounds accumulate. When hydrogen sulfide reacts with the reactive types of iron (iron oxides and oxyhydroxides), pyrite (FeS_2) is created, which soon oxidizes into sulfuric acid. The accumulation of sulfuric acid causes degradation of the wood. In order to solve these problems, cooperation with International Centre for Underwater Archaeology in Zadar was established.

ODREĐIVANJE SADRŽAJA VLAGE U MOKROM DRVU

Na uzorku drva trebalo je odrediti postotak vlage, tj. odnos između suhe tvari i vode sadržane u drvu. Uzorak se uzima dok je drvo još u vodi, prije njegova tretiranja sredstvom za impregnaciju, odnosno PEG-om. Postotak vlage određuje se termogravimetrijskim postupkom. Uzorak od nekoliko grama drva odvaže se u vlažnom stanju, a potom suši u sušioniku do konstantne mase. Nakon hlađenja osušenog uzorka u eksikatoru i vaganja, postotak vlage sadržane u vlažnom uzorku izračunava se prema formuli:[6]

$$\psi = \frac{A-B}{A} \times 100\ (\%)$$

gdje je:
A = masa vlažnog uzorka
B = masa suhog uzoraka

Ovi podatci važni su pokazatelji degradacije, a ujedno su važni za daljnji konzervatorski postupak. Drvo s više vlage, odnosno manje suhe tvari, zahtijevat će veću količinu sredstva za konzerviranje od drva s manje vlage. Sadržaj vlage u antičkom brodu iz Zatona iznosio je 87,4 %.

POSTUPAK KONZERVACIJE

Konzervacija mokrog drva započinje postupkom desalinizacije. Predmeti izvađeni iz mora moraju se desalinizirati. Postupak se provodi potapanjem drva u vodovodnoj vodi koja se mijenja u pravilnim intervalima. Desalinizacija je postupak uklanjanja soli koji se provodi da bi se spriječilo pucanje i raspadanje predmeta zbog kristalizacije soli prilikom sušenja. Također, desalinizacijom se sprječava da higroskopne soli upiju vlagu pri povišenoj vlažnosti i nakon konzervacije otope impregnacijsko sredstvo. Kontrola desalinizacije provodi se mjerenjem koncentracije klorida ili mjerenjem električne vodljivosti vode u bazenu. Smatra se završenom kad je koncentracija klorida u vodi svedena na minimum ili kad je električna vodljivost vode u bazenu na razini vodovodne vode. Desalinizacija antičkog broda provedena je u postojećem betonskom bazenu neposredno nakon vađenja. Provjeravana je električna vodljivost vode u bazenu konduktometrom. Budući da se električna vodljivost vode u bazenu spustila na razinu vodovodne vode, smatralo se da je postupak desalinizacije završen. Drveni dijelovi broda temeljito su očišćeni pod mlazom vodovodne vode (Sl. 1a i 1b). Svi su dijelovi dokumentirani i skenirani 3D skenerom (Sl. 2).[7] Dijelovi broda složeni su na rešetkaste police u bazen napunjen demineraliziranom vodom (Sl. 3). Takvim slaganjem sprječava se pritisak na donje slojeve drva i osigurava bolja cirkulacija impregnacijske otopine. Budući da je volumen bazena 4000 litara, velike

6 H. Malinar 2007, 93.
7 3D skeniranje provela je firma Vectra d.o.o. iz Varaždina.

ESTABLISHING MOISTURE CONTENT IN WATERLOGGED WOOD

The percentage of moisture – the ratio between dry matter and water contained in the wood – had to be established. Sampling is done while the wood is still submerged in water, before it is treated with an impregnation agent (a PEG). The percentage of moisture is established by means of thermogravimetry. A sample of wood, with a mass of a few grams, is weighed while waterlogged and then it is dried in a kiln until it reaches a constant mass. After the dried sample is cooled in a desiccator and weighed, the percentage of the moisture content in the waterlogged sample is calculated using the following formula:[6]

$$\psi = \frac{A-B}{A} \times 100\ (\%)$$

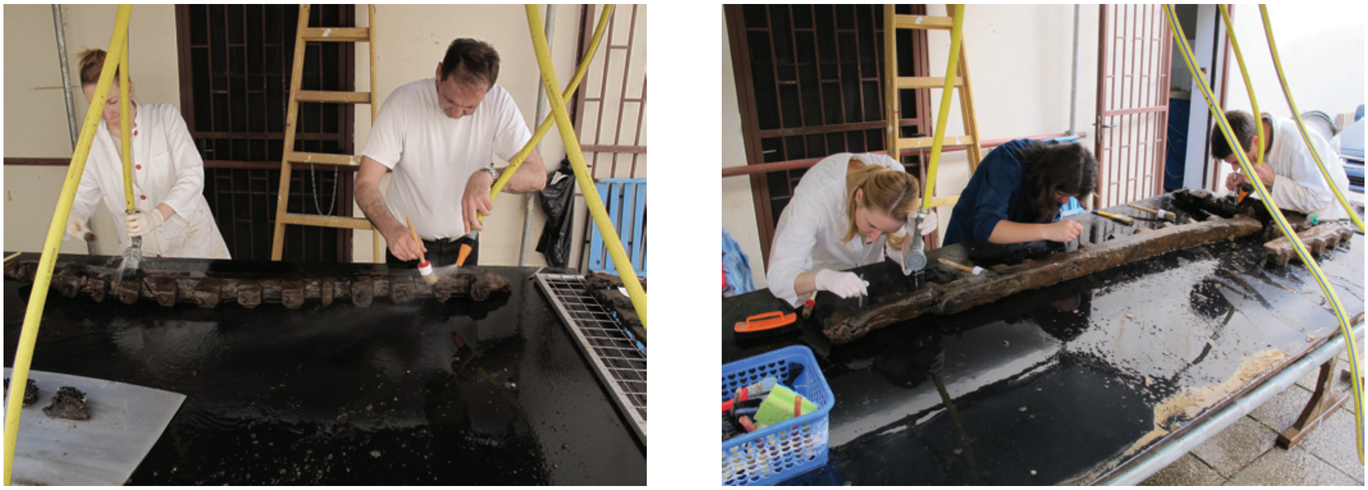
where:
A = is the mass of the waterlogged sample
B = is the mass of the dry sample

These moisture values are important indicators of degradation and are also important for further conservation procedure. Wood with more moisture (and, thus, less dry matter) will require more conserving agent than wood with less moisture. The moisture content in the Roman-period ship from Zaton was 87.4 %.

CONSERVATION PROCEDURE

Conservation of waterlogged wood begins with desalinization. Objects retrieved from seabed must be desalinized. This is done by submerging the wood into tap water, which is replaced at regular intervals. Desalinization is a process of salt removal, carried out in order to prevent breaking and disintegration of an object because of crystallization of salt during desiccation. Also, desalinization prevents hygroscopic salts from absorbing moisture at excessive humidity and dissolve the impregnation agent after the conservation. The process of desalinization is controlled by measuring chloride concentration or electrical conductivity of water in the tank. It is considered completed when the chloride concentration in water is reduced to a minimum or when the electrical conductivity of water in the tank reaches the level of tap water. The desalinization of the Roman-period ship was carried out in the existing concrete tank immediately after the salvaging. The electrical conductivity of water in the tank was controlled with a conductometer. Since the electric conductivity of water in the tank had been reduced to the tap water level, it was believed that the process of desalinization was completed. The ship's wooden parts were thoroughly hosed off with tap water (Figs. 1a and 1b). All the parts were documented

6 H. Malinar 2007, 93.



Slike 1a i 1b. Postupak čišćenja drvene građe
Figures 1a and 1b. Cleaning of wooden objects

foto / photo: **J. Lovrić**

Slika 2. 3D skeniranje drvene građe
Figure 2. 3D-scanning of wooden objects
foto / photo: **D. Romanović**

količine demineralizirane vode proizvedene su procesom reverzne osmoze.[8] Kako bi se lakše slagala drvena građa, napunjena je polovina bazena, a dio vode uliven je u dva spremnika od 1000 litara. Slaganjem drvene građe bazen se nadopunjavao vodom iz spremnika. Vodile su se bilješke o svakom naknadnom dolijevanju. Konačni volumen vode u bazenu iznosio je 3500 litara. Ukupan volumen vode u bazenu određivao je dnevnu količinu dodanog PEG-a te količinu dezinfekcijskog sredstva koje se dodalo u vodu da bi se kontrolirala biološka aktivnost. Kao dezinfekcijsko

8 Reverzna osmoza najsavršeniji je proces filtracije vode koji omogućuje odstranjivanje najsitnijih čestica iz vode. Reverznom osmozom voda prolazi kroz polupropusnu membranu pri čemu osmotski tlak uzrokuje ostavljanje soli na jednoj strani te prolaz filtrata na drugu stranu. Reverznu osmozu vode provela je firma Nirosta d.o.o. iz Osijeka.

and scanned with a 3D scanner (Fig. 2).[7] The ship's parts were placed on the latticed shelves in the tank filled with demineralized water (Fig. 3). Such arrangement prevents pressure on the lower layers of the wood and ensures better circulation of the impregnation solution. As the tank's volume is 4,000 liters, large quantities of demineralized water are made by means of reverse osmosis.[8] In order to facilitate the placing of the wooden parts, a half of the big tank was filled and some of the water was poured into two 1,000-liter tanks. While the wooden objects were being placed, the tank was being refilled with the water from the 1,000-liter tanks. Every subsequent refill was recorded. The final volume of water in the tank was 3,500 liters. The daily quantity of the added PEG and the disinfectant required to control biological activity depended on the overall volume of water in the tank. A 2-percent mixture of boric acid and borax (in 7:3 ratio) was used as disinfectant.[9] The frames were arranged individually and parts of the planking were placed in plastic-net bags. All the components of the ship were designated before placing into the tank. The conservation began with adding a 0.25 % of PEG to the overall volume of water in the tank. In equal daily portions, the concentration increased up to 30 % of PEG in the solution. Upon reaching the 30 %, the daily portions were doubled until the concentration of 80 % was reached. Then the added PEG was reduced to the initial 0.25 %, until the final concentration of 86 % was reached.

7 3D-scanning was carried out by Varaždin-based company Vectra d.o.o.
8 Reverse osmosis is the most perfect water filtration process that enables removal of even the tiniest particles from water. In reverse osmosis, water passes through a semipermeable membrane. The osmotic pressure causes the salts to stay on one side of the membrane and the filtrate to pass to the other side. Reverse osmosis of water was performed by Osijek-based company Nirosta d.o.o.
9 Boric acid, H_3BO_3, is a weak inorganic acid used as antiseptic and insecticide. Borax or disodium tetraborate, $Na_2[B_4O_5(OH)_4]\cdot 8H_2O$, is a salt of boric acid. It is also used as fungicide and insecticide.

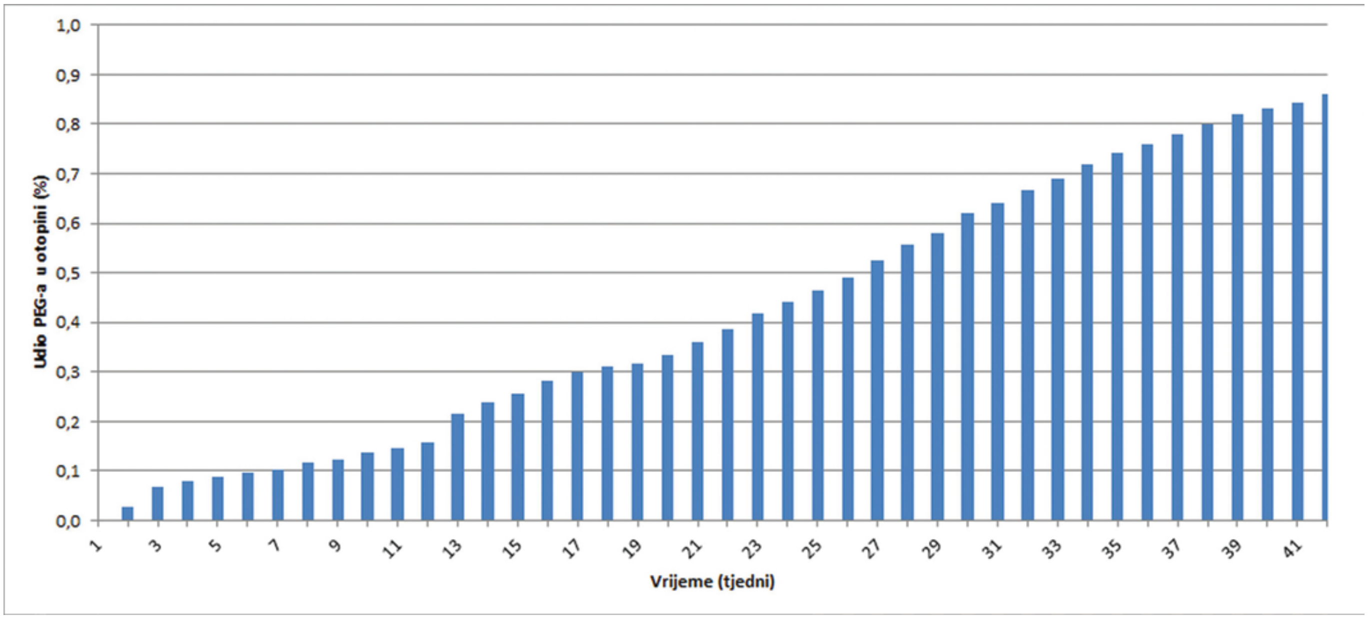
Slika 3. Slaganje drvene građe na rešetkaste police
Figure 3. Placing wooden objects on latticed shelves
foto / photo: **J. Lovrić**

Slike 4a i 4b. Završetak konzervacije i vađenje drvene građe iz bazena
Figures 4a and 4b. The end of conservation and removal of wooden objects from tank
foto / photo: **D. Romanović**

sredstvo korištena je 2-postotna smjesa borne kiseline i boraksa u omjeru 7 : 3.[9] Rebra su se slagala pojedinačno, a dijelovi oplate stavljali su se u vreće izrađene od plastične mreže. Svi su dijelovi broda složeni u bazen s odgovarajućom signaturom. Konzervacija je započela dodatkom 0,25 % PEG-a na ukupan volumen vode u bazenu. U jednakim dnevnim obrocima koncentracija se povećavala do 30 % PEG-a u otopini. Pri postignutoj koncentraciji od 30 % PEG-a u otopini, dnevni su se obroci udvostručili do postizanja koncentracije PEG-a u otopini od 80 %. Tada se dodavanje PEG-a smanjilo na početnu količinu od 0,25 % do postizanja konačne koncentracije od 86 %. Povećanjem koncentracije PEG-a iznad 40 %, otopina postaje zasićena i daljnjim dodavanjem PEG-a došlo bi do njegova taloženja na dnu bazena. Kako bi se povećala topljivost

9 Borna kiselina, H_3BO_3, slaba je anorganska kiselina koja se koristi kao antiseptik i insekticid. Boraks ili dinatrijev tetraborat, $Na_2[B_4O_5(OH)_4]{\cdot}8H_2O$, sol je borne kiseline. Također ima antifungalno i insekticidno djelovanje.

When the concentration of the PEG exceeds 40 %, the solution becomes saturated. Further adding of the PEG would result in its sedimentation at the bottom of the tank. In order to increase the solubility of polyethylene glycol, the solution must be heated up. The solution was heated up to 60 °C because the melting point of PEG 4000 is at 53–55 °C. In order to prevent evaporation of polyethylene glycol solution, a stainless steel lid was made; if necessary, it could be disassembled and removed from the tank. After the final concentration had been reached, the adding of the PEG was terminated. Throughout the conservation process, the PEG solution was sampled periodically in order to establish the percentage of the PEG in the solution. To this end, a sample of the PEG solution was weighted before and after drying at 100 °C over a 24-hour period. The ratio of the sample's mass before and after drying was used to establish the percentage of the PEG in the solution. The sample would be taken from the surface and from



Grafikon 1. Udio PEG-a u otopini tijekom procesa konzervacije
Chart 1. Share of PEG in solution during conservation process

izradila / prepared by: **J. Lovrić**

Slika 5. Uklanjanje viška PEG-a nakon vađenja iz impregnacijske otopine papirnatim ručnicima
Figure 5. Removal of excessive PEG with paper towels after removal from impregnation solution
foto / photo: **D. Romanović**

polietilen-glikola, otopinu je potrebno zagrijavati. Otopina se zagrijavala na 60 °C s obzirom na to da PEG 4000 ima talište na temperaturi od 53 – 55 °C. Kako bi se spriječilo isparavanje otopine polietilen-glikola, izrađen je poklopac od nehrđajućeg čelika koji se po potrebi mogao rastaviti i ukloniti s bazena. Nakon postizanja konačne koncentracije, dodavanje PEG-a je prekinuto. Tijekom cijelog postupka konzervacije periodički su uzimani uzorci otopine PEG-a kako bi se odredio postotak PEG-a u njoj. Određen je tako da se uzorak otopine PEG-a vagao prije i poslije sušenja

Slike 6a i 6b. Uklanjanje vidljivog PEG-a nakon sušenja drvene građe vrućim zrakom
Figures 6a and 6b. Removal of visible PEG after hot-air drying of wooden objects
foto / photo: **D. Romanović**

Slike 7a i 7b. Drvena građa nakon konzervacije
Figures 7a and 7b. Wooden objects after conservation
foto / photo: **J. Lovrić**

Slika 8. Replika dijela broda u Muzeju ninskih starina
Figure 8. Replica of ship's part in Museum of Nin Antiquities
foto / photo: **J. Lovrić**

na temperaturi od 100 °C tijekom 24 sata. Iz omjera mase uzorka poslije i prije sušenja određivao se postotak PEG-a u otopini. Uzorak se uzimao s površine i iz dubljih slojeva bazena. Dobiveni su slični rezultati što je ukazivalo na to da je otopina PEG-a bila homogena. Homogenost otopine PEG-a postizala se svakodnevnim uključivanjem cirkulacijske pumpe. Na grafikonu (Graf. 1) može se pratiti udio PEG-a u otopini tijekom procesa konzervacije. Konačna koncentracija od 86 % postignuta je nakon 42 tjedna. Nakon toga drvena građa ostala je u bazenu još dva mjeseca te je potom izvađena (Sl. 4a i 4b). Prilikom vađenja polietilen-glikol s površine drvene građe uklanjao se papirnatim ručnicima (Sl. 5). Konzervirana se građa postupno sušila prekrivena plastičnom folijom da ne bi došlo do većih deformacija. Nakon sušenja, vidljivi višak PEG-a na površini drva uklanjao se vrućim zrakom (Sl. 6a i 6b). Vrući zrak otapao je višak PEG-a koji se potom s površine drva također uklanjao papirnatim ručnicima. Konzerviranu građu broda potrebno je rekonstruirati (Sl. 7a i 7b). Budući da antički brod iz Zatona dugi niz godina nije bilo moguće konzervirati, u međuvremenu je napravljena replika dijela broda koja je izložena u Muzeju ninskih starina (Sl. 8).

the deeper layers of the tank. Similar results were obtained, which indicated that the PEG solution was homogenous. The solution's homogeneity was attained by daily activation of the circulation pump. Chart 1 shows the share of the PEG in the solution during the conservation process. The final concentration (86 %) was achieved after 42 weeks. After that, the wooden objects remained in the tank for two more months, after which period they were removed from it (Figs. 4a and 4b). When they were being removed from the tank, the polyethylene glycol was being removed from the surface of the wooden objects with paper towels (Fig. 5). The conserved objects were gradually dried under a plastic foil in order to avoid major deformations. After drying, the visible surplus of the PEG on the surface of the wood would be removed with hot air (Figs. 6a and 6b). The hot air dissolved the excessive PEG, which was then also removed from the surface of the wood with paper towels. The conserved parts of the ship require reconstruction (Figs. 7a and 7b). As conservation of the Roman-period ship from Zaton had not been possible for many years, a replica of its part was made in the meantime. It is now exhibited in the Museum of Nin Antiquities (Fig. 8).

OPIS INSTALACIJE I OPREME SUSTAVA ZA ZAGRIJAVANJE BAZENA

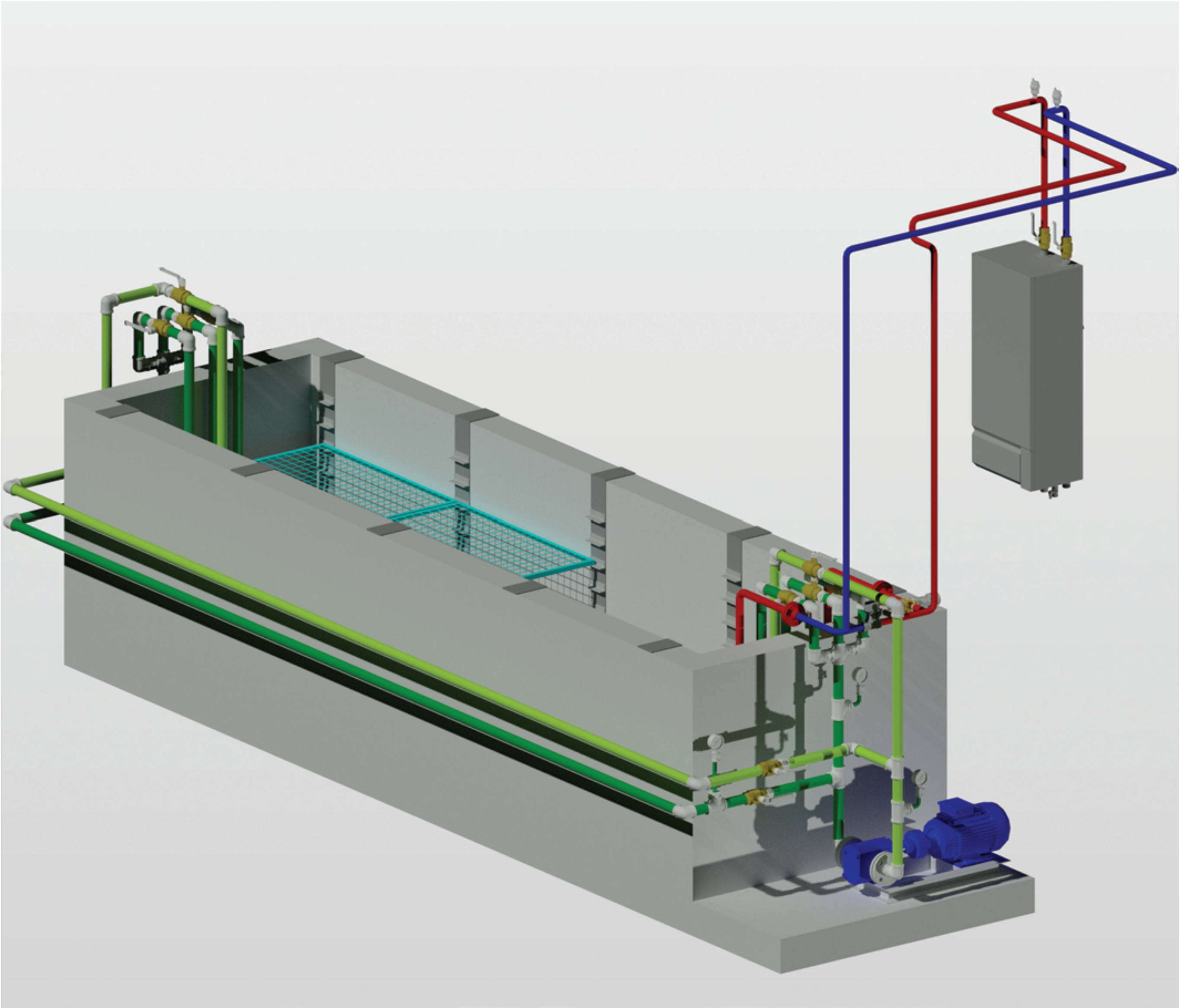
Stari sustav zagrijavanja bazena za današnje je prilike bio nepouzdan i neadekvatan, stoga se pristupilo izradi novog sustava koji će se nadograditi na već postojeći betonski bazen za konzervaciju mokrog drva. U suradnji s inženjerima i proizvođačima opreme napravljen je sustav zagrijavanja koji je omogućio da se postupak konzervacije izvodi poluautomatski, da ispunjava sve zahtjeve vezane za tehnološki postupak kao i sve zakonske odredbe vezane za zaštitu na radu i zaštitu od požara. Sustav zagrijavanja sastoji se od sljedećih komponenti:

- generatora topline (toplovodni kotao na struju)
- jedinice za zagrijavanje otopine (podna spirala izrađena od nehrđajućeg čelika)
- jedinice za regulaciju temperature (sklop regulacije bez pomoćne energije)

INSTALLING AND EQUIPPING THE TANK-HEATING SYSTEM

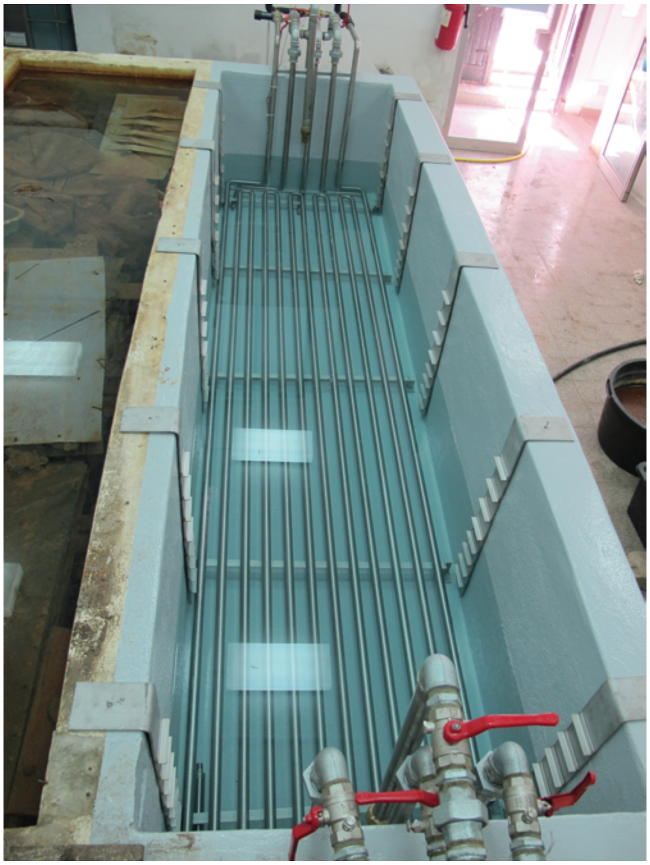
As the old tank-heating system was unreliable and inadequate according to modern standards, the development of a new one began. It was supposed to be added to the existing concrete tank for waterlogged wood. In cooperation with engineers and equipment manufacturers, a heating system was installed that enabled semiautomatic conservation process, meeting of all technological requirements for it and meeting all the legal provisions concerning safety-at-work and fire protection. This heating system consists of the following components:

- Heat generator (electric hot-water boiler)
- Solution-heating unit (floor stainless-steel spiral coil heater)
- Temperature regulation unit (regulation system without auxiliary power)



Slika 9. Projekt sustava zagrijavanja bazena
Figure 9. Tank-heating system design

crtež / drawing: **S. Lovrić**



Slike 10 i 11. Izvedeno stanje sustava zagrijavanja bazena
Figures 10 and 11. Installed tank-heating system
foto / photo: **J. Lovrić**

– jedinice za miješanje otopine (zupčasta pumpa)
– toplinske izolacije cjevovoda i pratećih grijača cjevovoda i opreme izvan bazena
– otklopno-demontažnog poklopca na gornjoj strani bazena
– odsisne ventilacije prostora (odsisni ventilator prostora s pripadajućim ventilacijskim kanalima i rešetkama).

Betonski bazen u kojem se ranije proveo postupak konzervacije, trebalo je sanirati. Sanacija je uključivala uklanjanje ostatka epoksidnog premaza ranije nanesenog na unutarnje stijenke bazena. Za potrebe sanacije u dogovoru s kemijskim inženjerima izabran je premaz koji će biti zaštita za bazen, a koji će ujedno biti i postojan na povišenim temperaturama (60 °C) tijekom cijelog procesa konzervacije. Određen je premaz Sigmaguard 720[10] koji se u određenim omjerima aplicirao na stijenke i dno bazena ukupno u tri sloja.

Nakon sanacije bazena, blizu njegova dna ugrađena je cijevna grijalica izrađena od nehrđajućeg čelika kroz koju će protjecati ogrjevna voda potrebna za grijanje cjelokupnog sadržaja bazena.

– Solution-mixing unit (gear pump)
– Thermal insulation of pipes and accompanying pipe heaters and equipment outside the tank
– Removable lid on the upper part of the tank
– Extraction ventilation (extraction ventilator with appertaining ventilation ducts and grates).

The concrete tank where conservation used to be carried out had to be repaired. The repair also included removal of the remaining old epoxy coating from the tank's inner walls. In consultation with chemical engineers, a protective coating stable at higher temperatures (60 °C) throughout the conservation process was selected. It was Sigmaguard 720,[10] which, in certain ratios, was then applied to the tank walls and base in three layers.

After the repair, a stainless-steel tubular heater was installed close to the tank's bottom. The water required for heating the entire content of the tank was supposed to flow through the heater.

Net supports that enable shifting of the level of the nets (depending on the thickness of the wooden objects being conserved) were installed on the tank's side walls. Both the nets on which archaeological waterlogged wood is placed and the net supporters are also made of stainless steel. The circulation system consists of a gear pump required for circulation of the solution, the pipeline around the tank and the pipeline inside the tank. The pump was selected in consultation with a pump manufacturer (MPD

10 Sigmaguard 720 je dvokomponentni epoksidni premaz s kemijskom otpornošću na širok spektar kemikalija i temperaturu. Ovaj premaz nabavljen je u Chromos boje i lakovi d.d. Zagreb.

10 Sigmaguard 720 is a two-component epoxy coating chemically resistant to a wide range of chemicals and temperatures. This coating was purchased at Chromos boje i lakovi d.d. Zagreb.

Na bočne stijenke bazena ugrađeni su držači mreža koji omogućavaju da se mreže mogu stavljati na različite visine, ovisno o debljini drvene građe koja se konzervira. Mreže za odlaganje arheološkog mokrog drva i sami držači također su izrađeni od nehrđajućeg čelika. Sustav cirkulacije sastoji se od zupčaste pumpe potrebne za cirkulaciju otopine, cjevovoda oko bazena i cjevovoda u samom bazenu. Pumpa je odabrana prema naputku proizvođača pumpi (MPD Daruvar) i karakteristikama otopine PEG-a.[11] Takva vrsta pumpi koristi se za transport neagresivnih, samopodmazujućih medija koji ne sadrže veću koncentraciju abrazivnih čestica. Sustav cirkulacije napravljen je tako da omogućava miješanje cijelog sadržaja bazena. Prostrujavanje bazena postignuto je postavljanjem istrujnih mlaznica uz samo dno bazena na jednoj strani, a usisavanje otopine događa se pri površini na drugoj strani bazena. Moguće je napraviti i obrnuto strujanje zatvaranjem pojedinih ventila na cjevovodima. Kako bi se spriječilo stvrdnjavanje otopine PEG-a u cjevovodima koji nisu uronjeni u bazen, postavljeni su duž cjevovoda i opreme prateći grijači (grijači kabeli). Preko pratećih grijača, cjevovoda i opreme ugrađena je cijevna toplinska izolacija koja služi za sprečavanje velikih toplinskih gubitaka te povećanje efikasnosti samih grijača.

Cirkulacijska zupčasta pumpa ima upravljanje putem daljinskog upravljača s frekventnim regulatorom brzine vrtnje. Tako se može vrlo precizno upravljati jačinom strujanja otopine kroz bazen. Zagrijavanje otopine bazena izvedeno je toplovodnim električnim kotlom snage 9 kW i pripadajućom podnom spiralom (toplovodnom grijalicom) na dnu bazena. Regulacija temperature ogrjevne vode regulira se na samom kotlu a fina regulacija temperature otopine PEG-a ventilom bez pomoćne energije čija je sonda uronjena na polovinu dubine bazena. Kao uređaj za optičku kontrolu temperature bazena ugrađen je kapilarni termometar. Kako bi se spriječilo isparavanje otopine iz bazena, ugrađen je otklopno-demontažni poklopac napravljen također od nehrđajućeg čelika.[12] Projekt sustava zagrijavanja bazena prikazan je na slici 9, a izvedeno stanje na slikama 10 i 11.

Budući da prostor u kojem su smješteni bazeni nije imao ventilaciju, bilo ju je potrebno izraditi (Sl. 12). Sustav ventilacije sastoji se od odsisnog kanalnog ventilatora, pripadajućeg prigušivača buke u kanalu, kanalnog filtera odsisnih rešetki u prostoru. Usis svježeg zraka te izbacivanje otpadnog zraka iz prostora izvedeno je putem protukišnih ventilacijskih rešetki na fasadi objekta.

Regulaciju količine odsisanog zraka u prostoru vrši regulator broja okretaja ventilatora s integriranim osjetnikom vlage koji uključuje ventilator ako vlaga poraste iznad zadane vrijednosti.

11 Ugrađena je zupčasta pumpa ZPC-3213KPSK/100L-6 s regulatorom KN700E.

12 Demontažni poklopac od nehrđajućeg čelika izradio je strojobravarski obrt M-Inox iz Svetog Ivana Zeline.

Daruvar) and based on the characteristics of the PEG solution.[11] Such pumps are used for transporting non-aggressive, self-lubricating media which do not contain any substantial quantity of abrasive particles. The circulation system was designed in such way that it enabled mixing of the entire content of the tank. Perfusion through the tank was achieved by installing jets on the very bottom of the tank on one side and suction of the solution at the surface of the tank on the other side. The streaming can be reversed by shutting certain valves on the pipelines. In order to prevent solidification of the PEG solution in the pipes which are not submerged in the tank, accompanying heaters (heating cables) were installed along the pipes and on the equipment. Thermal insulation was installed around the accompanying heaters, pipes and equipment in order to prevent substantial heat losses and increase the efficiency of the heaters.

The circulation gear pump is operated with a remote control equipped with a frequency regulator for rotational speed. This enables very accurate control of the solution's flow through the tank. The solution in the tank is heated by means of a 9kW electric hot-water boiler and an appertaining floor spiral coil heater at the bottom of the tank. The heating-water temperature is regulated on the boiler. The fine adjustment of temperature of the PEG solution is done by means of a valve with no auxiliary power (the valve's probe is immersed down to the half of the tank's depth). A capillary thermometer was installed to enable optical control of the tank temperature. A removable stainless-steel lid was installed in order to prevent evaporation of the solution in the tank.[12] The project of the tank-heating system can be seen in Figure 9 and the actual installation in Figures 10 and 11.

The room with the tanks had no ventilation system, so it had to be installed (Fig. 12). The ventilation system consists of an extraction duct ventilator, appertaining duct damper and a duct filter on the extraction grates in the room. The intake of fresh air and extraction of waste air are enabled by the rain grates on the front of the building.

The quantity of the extracted air in the room is regulated by the ventilator rotating speed regulator with an integrated moisture sensor that starts the ventilator if moisture exceeds the preset value.

CONCLUSION

Reintroducing the waterlogged wood conservation in Archaeological Museum Zadar was a major challenge. In addition to repairing the existing tank, a new, reliable, efficient and safe tank-heating system had to be designed.

11 The ZPC-3213KPSK/100L-6 gear pump with the KN700E regulator was installed.

12 The removable stainless-steel lid was made by M-Inox machine-producing company from Sveti Ivan Zelina.

ZAKLJUČAK

Ponovno pokretanje konzervacije mokrog drva u Arheološkom muzeju Zadar bio je veliki izazov. Osim postojećeg bazena koji je trebalo obnoviti, trebalo je projektirati novi sustav zagrijavanja bazena koji će biti pouzdan, učinkovit i siguran za rukovanje. Zahvaljujući dobro razrađenom projektu izrađen je sustav zagrijavanja bazena toplovodnom grijalicom koji je besprijekorno funkcionirao od početka do kraja postupka konzervacije. Postupak konzervacije zahtijevao je mnogo truda jer je trebalo okupiti i koordinirati stručnjake koji će projekt izvesti.[13] Trebalo je osigurati velika financijska sredstva za opremu bazena, nabavu velikih količina kemikalija, demineralizirane vode, dezinficijensa i energenta. Realizacija tako složenog postupka konzervacije nije bila moguća bez suradnje većeg broja djelatnika.[14] Zajedničkom suradnjom sačuvan je iznimno vrijedan nalaz antičkog šivanog broda. Slijedi rekonstrukcija brodske konstrukcije i pronalazak prikladnog prostora u kojem će se brod izložiti javnosti. Prostor bi trebao imati odgovarajuće mikroklimatske uvjete. Relativna vlažnost trebala bi biti oko 50 %, a temperatura ne bi trebala prelaziti 21 – 22 °C.[15]

Slika 12. Sustav ventilacije prostora
Figure 12. Ventilation system
foto / photo: **J. Lovrić**

Thanks to a well-prepared project, a tank-heating system based on a hot-water heater was built. It worked impeccably from the beginning to the end of the conservation. The conservation process required lots of efforts because experts for such a project had to be brought together and coordinated.[13] Also, substantial finances for the tank equipment and large quantities of chemicals, demineralized water, disinfectants and energy source had to be ensured. Accomplishing such a complex conservation procedure would not be possible with the help of a large number of staff members.[14] Their joint efforts made it possible to preserve a very valuable find of a Roman-period sewn-plank ship. The ship's structure is now to be reconstructed and an appropriate space for exhibiting it to the public is to be found. Adequate microclimate conditions in such a space should be ensured. The relative humidity should be around 50 % and the temperature should not exceed 21–22 °C.[15]

13 Projekt sustava za zagrijavanje bazena izradio je dipl. ing. strojarstva Siniša Lovrić. Grijalicu od nehrđajućeg čelika izradio je Pireko d.o.o. iz Zagreba, a police od nehrđajućeg čelika Bravarija Nauta d.o.o. iz Zadra. Cjevovode, spoj na pumpu i sanaciju bazena izveo je Elektro Vamm d.o.o iz Zadra. Prateći cijevni grijaći nabavljeni su putem Weishaupt d.o.o. iz Zagreba.

14 Zahvaljujem suradnicima: višoj kustosici Dušanki Romanović, višem kustosu Dinu Tarasu, konzervatorici-restauratorici Martini Rajzl, kućnom majstoru Mariju Duki, studentima Sari Iglić, Valentini Volf i Dinu Molnaru.

15 I. Koncani Uhač, M. Petrović, A. Sardoz 2017, 187.

13 The tank-heating system was designed by Siniša Lovrić, B. Sc. (Mech. Eng.). The stainless-steel heater was made by Zagreb-based Pireko d.o.o. company and the stainless-steel nets by Zadar-based Bravarija Nauta d.o.o. company. The pipes and the access to the pump were produced and the repair of the tank was performed by Zadar-based Elektro Vamm d.o.o company. The accompanying pipe heaters were provided by Zagreb-based Weishaupt d.o.o. company.

14 I wish to express my gratitude to Senior Curator Dušanka Romanović, Senior Curator Dino Taras, Conservator-Restorer Martina Rajzl, resident repairman Mario Duka and students Sara Iglić, Valentina Volf and Dino Molnar.

15 I. Koncani Uhač, M. Petrović, A. Sardoz 2017, 187.

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