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Determining compatness of the quality of natural stone blocks with ultrasonic technic

Določanje kompaktnosti blokov naravnega kamna z ultrazvokom

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Abstract
The company Marmor Sežana d. d., has been engaged in the excavation, processing and installation of natural stone - limestone in Slovenia and worldwide since 1947. Natural stone is produced in our quarries. Natural stone is a specific type of mineral raw material, produced in large blocks, parallelepiped shaped monoliths. An important specificity of extracting natural stone is the requirement for compactness. In Slovenia, where tectonics is strongly expressed, it is difficult to ensure compactness. Furthermore, the extraction is hampered by the increasing demand for large dimensions of natural stone blocks. Irregularities in blocks and thereby the quality has so far been determined only visually; pouring water on the block and inspecting it visually, and by banging on the block and listening to the echoes. Recently, the demands about the quality of the blocks have surfaced, as the producers are eager to ensure the best possible utilization of the material depending on the desired end product and to reduce the backlog in production processes. For this reason, only a visual inspection of the blocks is no longer sufficient.

Key words: ultrasonic examinations, natural stone, geological research

Izvleček
Družba Marmor, Sežana d. d., se že od leta 1947 ukvarja s pridobivanjem, obdelavo in vgradnjo naravnega kamna – apnenca pri nas in po celem svetu. Naravni kamen pridobivamo v svojih kamnolomih. Naravni kamen je specifična vrsta mineralne surovine, ki se pridobiva v čim večjih blokih, monolitih paralelepipedne oblike. Pomembna specifičnost pridobivanja naravnega kamna je zahteva po kompaktnosti. V Sloveniji, kjer je tektonika močno izražena, je kompaktnost težko zagotoviti. Dodatno pridobivanje otežuje tudi vedno večje povpraševanje po velikih gabaritih blokov naravnega kamna. Nepravilnosti v blokih in s tem kvaliteta so se do sedaj določale le vizualno; s polivanjem bloka z vodo in vizualnega pregleda ter z udarjanjem po bloku in poslušanjem odmeva. Na trgu se v zadnjem času pojavljajo zahteve o garanciji kvalitete prodanih blokov. Investitorji si na ta način želijo zagotoviti čim boljšo izrabo materiala glede na želene končne produkte. Zaradi tega samo vizualni pregled blokov ne zadošča več.

Ključne besede: ultrazvočne preiskave, naravni kamen, geološke raziskave

Introduction

According to past experience, the greatest difficulty in extracting natural stone are the consequences of tectonics, especially cracks and fragmentation (Vesel, 1975). Due to increasing demands for large dimensions of natural stone blocks, the knowledge about the content of the irregularities in the blocks is very important. Quality of the blocks or monoliths has so far been determined only visually, that is by pouring water on the block and inspecting it visually, and by banging on the block and listening to the echoes. The course of the irregularities (cracks) can thus be determined only superficially, however, we cannot predict how deep they actually are. Sometimes a crack occurs just a few centimeters below the surface of the block and intersects the majority of the block, but cannot be detected on the surface. This often leads to complaints or can even damage the processing machines. The demands of investors for larger slabs and for optimizing the utilization of the block, lead to the fact, that it is necessary to assess the natural stone block not only visually, but also to determine its internal structure. A more detailed inspection and determination of quality enables more rational and economical use of the material, as mistakes about cutting are often made during the preparation and processing of the block. The internal structure of the block can be determined by using ultrasonic methods. Ultrasonic devices are used for determination of defects, voids, cracks, etc. in situ in the concrete constructions, which gives us information about the homogeneity of the material. In practice, a speed measurement profile can help assesss the degree of homogeneity of a natural stone block.

Currently, we performs ultrasonic measurements of natural stone blocks in predefined profiles, on which the travel speed of waves is measured. Speed measurements of travelling waves with ultrasonic instrument and with it the determination of quality of natural stone blocks will be implemented on a limestone of the Upper Cretaceous age, known under trade names Lipica enotni, Lipica rožasti, Koprivo and Repen. Our goal is to create the categorization of natural stone bloks quality on the basis of statistical processing of a large number of measurement data. The current classification is based solely on visual inspection of each block of limestone and its dimensions, but gives no information on the internal compactness of the block. The task is also to remove damaged, cracked, and poor quality parts of the block and combine them into a larger composit block by using the polyester resin, and later on cut it on the gangsaw.

Ultrasonic examinations of natural stone

Ultrasonic devices have been in use since before the Second World War. Sound waves and echoes were used to help detect icebergs, search for sunken submarines and measure sea depth on the basis of the reflected waves. In 1929 Sokoloff proposed detecting faults in the material by using ultrasound and in 1934 he conducted the first practical experiments with ultrasonic control on metal objects. In 1931 Mulhauser patented the use of control by ultrasound and determining the relationships in the material and errors in it. Firestone (1942) patented the first impulse reverberation instrument. The terminology of »ultrasound« means high-frequency waves, which are frequencies higher than human hearing (Meola, Maio, Roberti, Carlomagno; Bray, et.al, 1992). Ultrasonic devices are now portable to allow for the implementation of in situ researches, making them less expensive. Ultrasonic examinations are useful techniques, especially when researching properties of stone such as elasticity, anisotropy, mechanical strength and condition of deterioration (Christaras, 1999). The techniques enable an assessment in relation to the sound of the stone, with which we can identify the authenticity of discontinuities or defects in materials, such as demolishing zones and voids (Bray, et al 1992: 278, Kahraman, et al., 2008). They are also useful in tracking and studying changes in basic physical and mechanical properties of stone in relation to moisture, weathering and stress (Christaras, 1999; Kahraman, et. al. 2008). The methods, where we discover irregularities in the material structure, dimensions, physical and mechanical properties, chemical analysis and voltage without damaging the material, are called non-destructive methods (NDT) and have been in use for several decades. The aim was to detect cracks and irregularities in the material in a way, that does not further damages the material and that causes no additional damage to the cracks during the investigation (Akveren 2010). Non-destructive methods are mainly used in mechanical engineering (control of steel wires, metal elements), in construction for concrete control (Trtnik, 2012), in examinations of stone elements, electrical engineering, medicine, arts, forensics. (Bodare, 2005).

Measurement techniques using ultrasonic technic on natural stone

Acoustic methods are based on generating, disseminating and reflecting mechanical sound waves in solids, where the latter depends on the density and elastic properties of the used material, the frequency of waves, and on the method of generating and receiving sound waves (Špeglič, 2013). Transmitters and receivers are piezoelectric devices that transmit and receive waves. Ultrasonic frequencies are frequencies above 20 kHz (Wiberg, 1994). Ultrasonic methods are based on the passage and reflection of ultrasonic waves, generated by transmitter and detected by receiver. Transmitters generate longitudinal, transverse waves, which spread depending on the mechanical properties of the material. Measurements of the material, through which ultrasonic impulse velocity passes, can be made in three ways: direct, semi-direct and indirect (Kahrman, et al., 2008, Meola, et al., 2005). For quality measurements the surface of the material being measured should be smooth, so that transmitters and receivers have a good contact. To ensure a good contact a gel can also be used (Meola, e soil. 2005). According to the authors Lemona and Christaras (1999), a direct method is the most satisfactory method, where the direction of waves is parallel to the transducers. If the transducers are on the opposite side of the material, the spread of the impulses will be faster and pulse velocity larger than in the indirect method. The indirect method is used for finding the depth of weathering, degree of consolidation and to detect cracks near the surface (Lemon and Christaras, 1999, Akveren 2010).

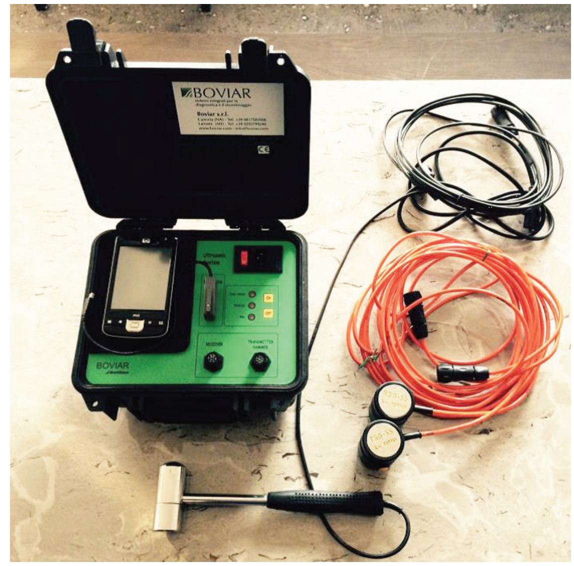


Figure 1: *Ultrasound instrument Boviar with ultrasound probe and a hammer.*

Transmitter:	
Frequency	55 kHz
Voltage	1,6 kV
Energy	0,05 J
Weight	770 g
Dimension	50 mm × 75 mm
Receiver:	
Frequency Range	1 - 70kHz
Sensitivity	1 kHz = 4 840 mV/g
Top Sensitivity	6 kHz = 30 V/g
pre-amplified Receiver	20 dB
Weight	760 g
Dimension	50 mm × 75 mm

Hammer-transmitter, with which the system is equiped, is intended for use when energy of piezoelectric transmitters TSG-55 and TSG-Hi20 is not sufficient for the examination. In such circumstances the received signal is too weak and can not be properly analyzed or it is difficult to determine the first arrival of the signal (First Break Pick). Signal by means of hammer is characterized by low frequency and high energy consumption. The device is used for a material with outstanding low wave propagation characteristics or for a material of large dimensions.

There are some known examples of ultrasound examinations from the past, for example on architectural ornamental stone in the case of reconstruction of stone elements, or examination of stone monuments and decorative panels, on which the irregularities as a result of weathering or due to inadequate installation technology were observed.

Ultrasonic measurements on natural stone blocks

Since the deposits of natural stone in the Karst (Slovenia) are subject to strong local tectonics, they generally contain a lot of interruption surfaces. This is also reflected in compactnes and maximum dimensions of the blocks, which include a number of irregularities. For a proper classification of blocks regarding the quality of both external surfaces and interior of the blocks, we carried out several in-situ measurements and then compared the data with the actual state of the panels that were gained by sawing the blocks. Doing so we obtained the first information that give us a rough estimate on the applicability of the method, however, in order to make the categorization, more measurements need to be performed and more data, that will be statistically representative, need to be obtained.

Measurements of the speed of ultrasonic waves passing through the material were carried out on the sample. We used a pulsed ultrasound at a frequency of 55 kHz. The sound that arises from the piezoelectric transducer does not originate from a point, but from practically the entire surface of the element. Round converters are sometimes also called cylinder sources, as the sound in front of transmiter expands in the shape of a cylinder. (Medvešček).

According to the scientific literature and practical experience the rule applies, that the defects in the material which are larger than ½ of wavelength can be detected. Resolution and sensitivity are also important for detecting defects.

Sensitivity is the ability to detect small defects and usually increases with increasing the frequency (decrease in wavelength). Resolution is the ability of the system to detect errors that are packed closely together in the material or that are in the vicinity of the surface. Resolution also increases with the frequency.

By increasing the frequency the opposite effect can also be achieved. If our observed material is not completely homogeneous, we will get reflections at high frequencies due to grain size of the material and the microscopic irregularities. In this way the maximum depth that can be achieved will be reduced, because as a result of reflection the wave power declines rapidly. (Medvešček).

The first part of the research was carried out in the laboratory on previously selected samples, where we sought to discover differences in sound pressure measurement with a pulse unit. The results are shown in the Table 2.

To perform in situ measurements we used the Boviar instrument and a computer program DataSonic by Boviar S.r.l. company. The program calculates on the basis of measurements that are conducted with the help of the following equation.

Among the most important characteristics of sound are speed c, frequency f and wavelength λ. Wavelength is proportional to the speed

Figure 2: *Opening of slabs on a gangsaw.*

Table 1: *Transitions of transverse and shear waves through certain stones by Dobrin (1976). a- value is set to* 50 Hz *frequency. α- and Q values are shown in the table below*

Material	cp (m/s)	cS (m/s)	αP 105 (1/m)	Q
Granite	5000–6000	2500–3300	0.21–0.38	9800–15000
Granodiorite	4780	3100		
Diorite	5780	3060	0.21	12900
Gabbro	6450	3420		
Basalt	5400–6400	2700–3500	0.41(5500)	6900
Dunite	6800–8640	3500–4400		
Gniess	3500–7500			
Marble	3700–7000			
Sandstone	1400–4300		0.71(4300)–1.77(4000)	2200–5100
Limestone	5900–6100	2800–3100	0.37 (6000)	7100
Anhydrite	4100			
Shale	2100–3400		0.68(3300)–2.32(2150)	3100–7100

of the wave and inversely proportional to the frequency, as shown in the following equation

$$\lambda = \frac{c}{f} \tag{1}$$

The speed of passage of ultrasonic waves ($\boldsymbol{c_i}$) from the transmitter to the receiver is calculated according to the equation, l is the length of the measured profile and t is the time of passage of longitudinal waves

$$c_i = \frac{l}{t} \left(\frac{km}{s}\right) \tag{2}$$

With the help of a large number of measurements, we have calculated the mean value that will determine the quality of the block

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i = \frac{1}{n} \cdot (x_1 + \ldots + x_n) \tag{3}$$

The standard deviation can be calculated as σ (sigma), that is as a deviation of the total population or its random variable, or as s, that is as deviation of each sample of the statistical population. The formulas for the two deviations differ.

$$\bar{s}_x = \sqrt{\frac{\sum_{i=1}^{N} (x_i - \bar{x})^2}{N-1}} \tag{4}$$

where x_i is the i-th unit in the statistical population, the arithmetic mean of the population and N is the number of all units

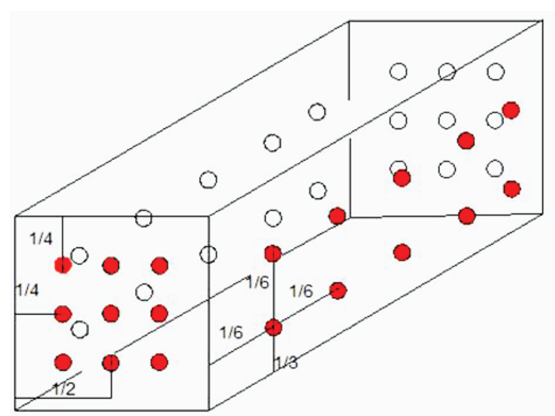
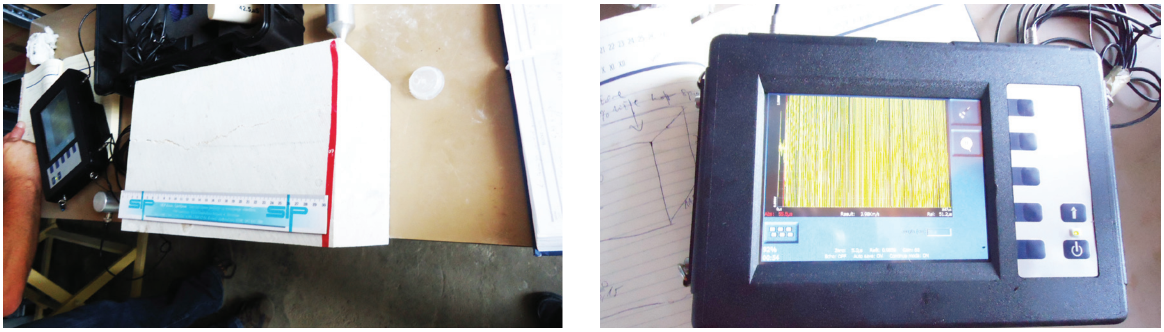


Figure 3: *Setting up profiles of ultrasonic measurement on natural stone block.*

The measurements were carried out on blocks of large dimensions. Thus, we tested the real possibility of using this method on blocks of natural stone - limestone. The figure below shows the placement of measuring profiles on a glued block and an overview of obtained panels, as well as a comparison with the results of measurements on the block from which the panels were cut.



a b

Figure 4: *Display of measurements on the laboratory specimen. An example of a crack in the middle of the block (a) and the measured velocity of ultrasonic waves of* 3.98 km/s *(b).*

Profiles for measuring the block were determined by width in three lines, namely at 1/6 of the distance of width and height; lengthwise in two lines at an interval of 1/6 of the length, and heightwise in two lines at an interval of 1/3 of the height. Density of the profiles depends on the dimensions of the blocks and on the results of the measurements. In the event that there are significant deviations, the profiles must be condensed. On the basis of the profiles' density, it is possible to follow a crack, which is located in the block.

Block in Figure 5 was characterized by an average speed of sound pressure of 4.572 km/s. 24 profiles were measured. Measurements were carried out both with the probe and with a hammer. Both measurements gave similar results. The block is composed of three pieces that are 45 cm thick, meaning we are dealing with a composed block. The speed was very low for a limestone, but we cut the block in panels 4 cm thick. The surfaces between smaller blocks were filled with polyester resin. Therefore, the block did not open during multi-blade sawing.

a b c

Figure 5: *Measurement of the composed block (a, b) and review of the panels after cutting the block (c).*

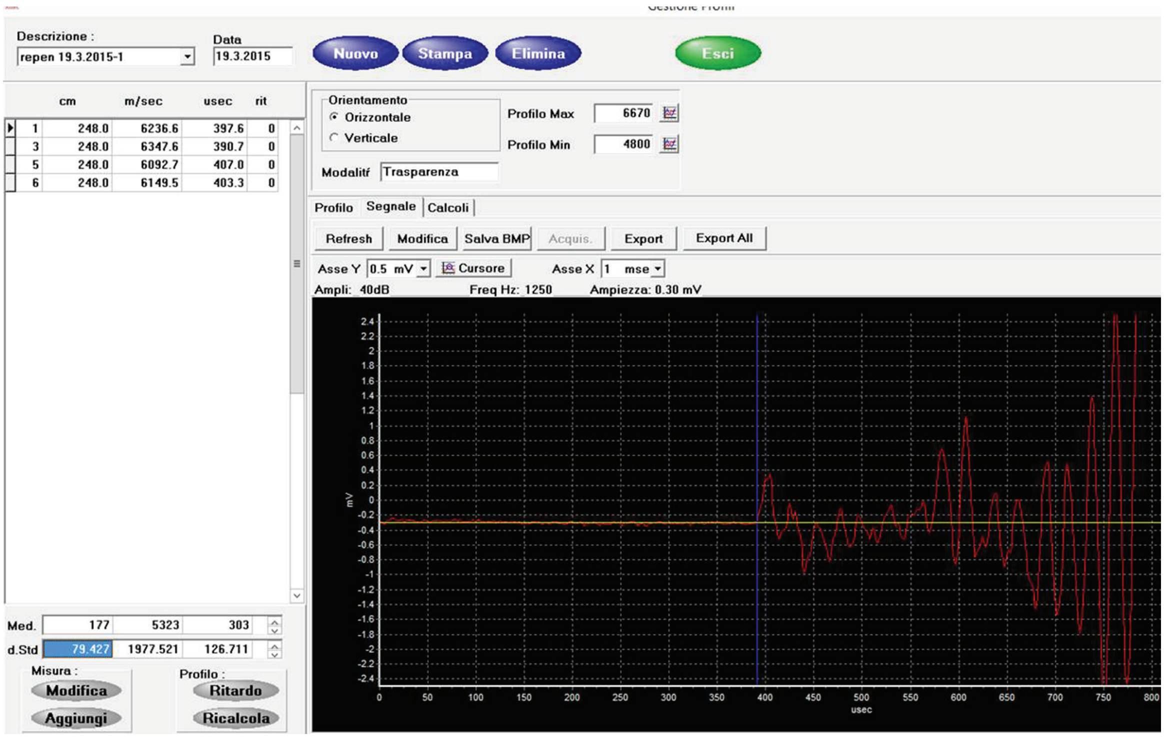


Figure 6: *Display of data processing with DataSonic computer programme.*

In 2015 we made about 10,100 m^2 of differently thick stone panels with the multi-blade saw, which amounts to 68 blocks. By using ultrasonic measurement of blocks, there has been no breakage of the block on the table so far. Despite some very risky blocks, we have successfully cut and classified them. With the use of measurements certain blocks were also cleaned and we came to the conclusion, that the blocks can also be glued together to fill-up the cutting table. By using ultrasound, we examined whether the surfaces were well lubricated with resin.

In Table 2 the data from previous examinations using ultrasound on different types of natural stone are collected. The natural stone »Lipica rožasti« is characterized by an average passing speed of ultrasonic waves of 5.60 km/s, and the maximum measured speed reached 6.44 km/s. In the »Lipica enotni« we measured an average speed of 5.90 km/s and a maximum speed of 6.45 km/s. For »Repen« an average speed of 6.11 km/s and a maximum speed of 6.60 km/s were measured. All types of stone held up while on the saw and did not open. So far we have made more than 120 measurements of natural stone blocks and thus obtained a large amount of data for making a classifications of natural stone blocks. The aim of the present study was achieved with a good estimate of the blocks and the completion of a technological process, as since we have been using the measurements not one block has opened during the cutting.

Table 3 shows the proposal for categorization of natural stone blocks on the basis of preliminary measurements of average velocity of transition of ultrasonic waves. The categorization was made on the basis of the performed measurements and the review of panels after processing the blocks.

For inspection of natural stone blocks we spent 12–15 min on average. The process includes visual and ultrasonic inspection and also gives a more accurate assessment of the quality of the block and reduces the risk of errors.

Table 2: *The results of previous research on the blocks of natural stone*

Block	Type of material	Block dimension			Mesured profile			Max. Velocity
		Length	Width	Height	Velocity by the length	Velocity by the width	Average velocity	
		(cm)	(cm)	(cm)	(km/s)	(km/s)	(km/s)	(km/s)
1	rožasti	285	141	103	2.61	3.50	3.08	-
8	rožasti	300	114	100	6.25	5.90	6.07	-
9	rožasti	259	175	160	5.89	6.28	6.09	-
16	rožasti	260	112	152	6,21	4.55	5.38	6.37
17	rožasti	262	139	158	5.92	4.33	5.12	6.17
18	rožasti	277	122	107	6.25	5.23	5.74	6.40
11	rožasti	303	157	112	6.13	6.05	6.09	6.22
3	enotni	236	98	144	6.11	6.05	5.42	6.12
4	enotni	122	150	90	6.18	5.94	6.06	6.20
10	enotni	142	138	100	6.14	6.20	6.17	6.17
19	enotni	262	118	107	5.7	6.22	5.96	6.45
12	repen	172	173	129	5.99	5.95	5.97	6.08
5	repen	308/240	141	100	6.11	5.16	5.63	6.60
7	repen	175	110	111	7.31	6.22	6.76	7.50
6	repen	315	128	79	6.05	6.08	6.06	6.06
13	repen	200	148	87	6.14	6.16	6.15	6.22

Table 3: *An example of categorization of the natural stone blocks*

Category	Velocity (km/s)	Explanation of quality
I.	≥ 6.00	High-quality natural stone block suitable for any thickness, without reinforcement
II.	5.00 ÷ 5.99	Natural stone block, which contains a small veins and changes in the structure, suitable for any thickness without reinforcement
III.	4.00 ÷ 4.99	Natural stone block with bigger cracks, holes, veins, suitable for slabs thicknesses greater than 3 cm
IV.	3.00 ÷ 3.99	Poor quality natural stone block, more irregularities in the structure, and contains a lot of cracks, suitable for slabs thicknesses greater than 4 cm
V.	≤ 2.99	Poor quality natural stone block unsuitable for slabs

Conclusions

To date, there have been many research conducted with various geophysical and other methods, implemented on plates and monuments, but an ultrasound examination of blocks of natural stone – limestone in order to determine their quality or qualification is yet to be done in practice. Relying solely on visual inspection for determining the quality of the blocks is not reliable. Due to deadlines for installing and economical processing of materials, it is necessary to wisely choose the quality of the material for processing and using natural stone blocks.

In reviewing the material we found the following. Many of the pieces need to be sawn through, because of the discontinuities, faults or irregu-

lar shapes. For this reason we started manufacturing smaller blocks that are 30–60 cm thick, in order to improve the efficiency of material and improve the material processing prices. For such blocks to be able to supplement the space on a multileaf saw, they were glued together with polyester resin and then cut into panels. Ultrasound examination also gives us an overview of the glued block, as it enables an assessment of whether the contacts between surfaces of the blocks are well filled with resin. The differences in measured speeds are mainly due to defects in materials and different structures of materials, as well as possible errors in performing measurements. The categorization needs to be supplemented with intermediate categories in the future, as in determining the quality of natural stone blocks the shape also plays an important role.
In the future it will also be necessary to add a tomography of blocks, on the basis of measurements, and thus get a picture of where in the materials hazardous areas that need special attention lie.

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