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# CONCRETE-SURFACE DESTRUCTION BY POWERFUL MICROWAVE-RADIATION PULSES

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*The destruction of the surface layer of concrete by a powerful microwave-radiation pulse is studied. The conditions for the occurrence of shear and spall fractures in concrete at a given depth are found. The range of electrodynamic parameters within which microwave radiation is the most effective for disintegration of concrete is found. The requirements for a microwave generator that permit one to study experimentally the force action of electromagnetic radiation on concrete are formulated.*

**Introduction.** Powerful microwave generators of centimeter and millimeter wavelength range have recently found broad applications in various fields of science and engineering. At present, they are successfully used for radio-frequency plasma heating in thermonuclear installations with magnetic confinement, plasma diagnostics, pumping of gas lasers, and low-temperature plasma generation in various technological processes. In the near future, the development of microwave engineering is expected to ensure the creation of high-resolution Doppler radars and drivers for a new generation of high-gradient accelerators and the solution of problems of long-range communications in space.

In addition, we consider the possibility of using powerful pulse microwave-radiation fluxes for various technological purposes. In particular, in our opinion, they are promising in the solution of an important ecological problem of atomic energetics, namely, clearing and "rehabilitation" of structures contaminated by radioactive waste. This method is based on two processes: 1) spalling on a free surface under the action of a shock wave generated upon local heating of the surface layer of a solid by high-power microwave radiation; 2) brittle fracture of the near-surface layer upon shear deformation because of the strong anisotropy of the stress state. The doubtless advantages of the method of clearing with the use of high-power pulse microwave-radiation fluxes are long-range control of the process, which ensures the absence of direct contact of the staff with radioactive waste, relative safety of the electromagnetic radiation used in the technology, and, finally, the possibility of designing a mobile installation.

In connection with the above-said, the determination of the characteristic microwave-radiation parameters that ensure the destruction of the surface layer of concrete (constructional material used at nuclear stations) is of interest. This work deals with this problem and is focused on simulating these processes. Since we failed to find reliable literature data on the electromagnetic properties of the concrete exposed to microwave radiation, we performed a series of experiments on the measurement of the absorption energy of millimeter waves in concrete specimens of different thickness.

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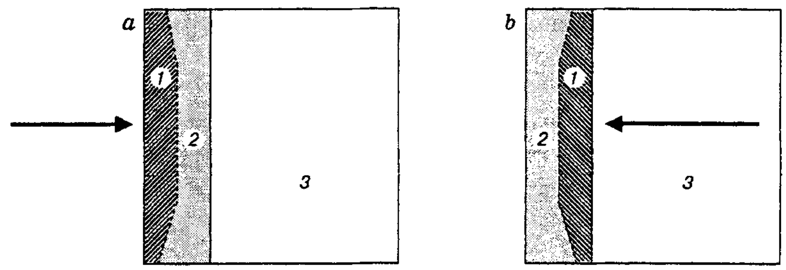


Fig. 1. Irradiation scheme for a layer of a concrete block in the experiments on destruction of its surface layer for pulse supply from the outside (a) and from the side of the concrete block (b): 1) destruction region: 2) higher-conduction region; 3) concrete block; the arrow shows the direction of microwave-radiation flux.

Russian Academy of Sciences, an energy of the order of 100 J in 4-mm radiation pulses of approximately microsecond duration has already been reached at an ELMI installation (the electron sheet and millimeter radiation) [1]. Below, it is shown that this level is sufficient for concrete-destruction experiments.

**Analytical Model of Energy Absorption.** In determining the conditions for destruction of a flat concrete layer by powerful microwave-radiation fluxes, the creation of a high-density absorbed microwave energy zone in this layer, which is necessary for the onset of spalling or shear fracture of the surface, apparently, is of primary importance. For intense microwave-radiation energy absorption, this region should possess a higher conduction; this can be achieved, in particular, by saturation of the surface of concrete by salt solutions of water (the amount of water absorbed by concrete can exceed 10% of its mass [2]).

Below, two variants of pulse microwave-radiation supply to a thick concrete block are considered: 1) the radiation is incident on a layer with intense absorption of electromagnetic energy from the side where there is a surface to be cleared (Fig. 1a); 2) the radiation arrives at the absorbing layer from the side adjacent to the basic volume of concrete (Fig. 1b).

We estimate the values of the density of electromagnetic-field electric losses upon normal incidence of a flat electromagnetic wave with amplitude $E_0$ and frequency $\omega$ on the flat interface of two homogeneous media. The boundary is perpendicular to the $z$ axis and intersects it at the point $z = 0$. The half-space $z < 0$ is filled with a medium, whose dielectric permeability $\varepsilon_0$ has only the real part; the conduction of the medium is negligible. In the half-space $z > 0$, the medium has a complex dielectric permeability $\varepsilon_1 = \varepsilon_1' + i\varepsilon_1''$, where $\varepsilon_1'' = 4\pi\sigma_1/\omega$ ($\sigma_1$ is the conduction of the medium). It is known that the complex coefficient $\theta$ of electromagnetic-wave passage from the first to the second medium over an electric field is determined by the expression

$$\theta = \frac{2}{1 + \sqrt{\varepsilon_1/\varepsilon_0}} = \frac{2}{1 + \sqrt{|\varepsilon_1|/\varepsilon_0}\,\exp(i\delta/2)}, \tag{1}$$

where $\varepsilon_1 = |\varepsilon_1|\exp(i\delta)$ [$\tan\delta = 4\pi\sigma_1/(\omega\varepsilon_1)$] is dielectric permeability (see [3]).

The density distribution of the power of electric losses of an electromagnetic wave in a conducting medium ($z > 0$) can be presented in the form

$$W = \sigma_1|E_1|^2 = \frac{4\sigma_1 \exp(-2kz\varepsilon_1' \sin(\delta/2)/\sqrt{\cos\delta})}{1 + \varepsilon_1'/(\varepsilon_0\cos\delta) + 2\sqrt{\varepsilon_1'}\cos(\delta/2)/(\varepsilon_0\cos\delta)}|E_0|^2$$

with the maximum value

$$W_{\max} = \frac{\omega\varepsilon_0}{\pi}\,\frac{\beta^2\tan\delta}{1 + \beta^2/\cos\delta + 2\beta\cos(\delta/2)/\cos\delta}|E_0|^2$$

($\beta = \sqrt{\varepsilon_1'/\varepsilon_0}$) occurring at the interface of the media.

The dielectric-permeability values of the components of a concrete mixture in the broad range of frequencies $10^2$–$10^7$ Hz lie in the interval $\varepsilon = 4$–$15$ [4]; for moisture-saturated rocks, these are greater than for dry rocks and, therefore, one can consider that $\beta > 1$. In the case $\beta \gg 1$, we have $W_{\max} \approx (\omega\varepsilon_0/\pi)|E_0|^2\sin\delta$.

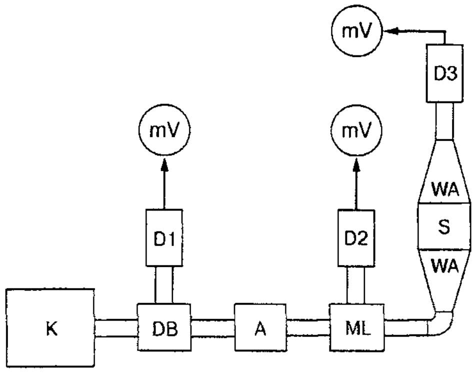


Fig. 2

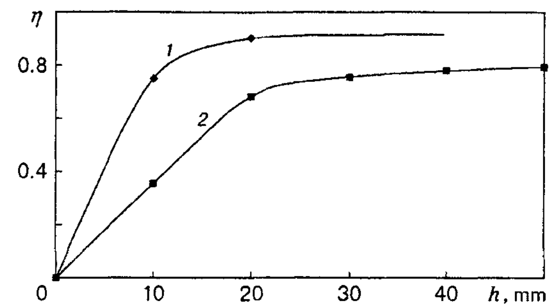


Fig. 3

Fig. 2. Layout of the stand for microwave-radiation absorption measurement in concrete specimens of different thickness: klystron (K), directed brancher (DB), attenuator (A), measuring line (ML), waveguide adapter (WA), which ensures a transition from 4 or 8 mm to 3 cm, specimen (S), microwave-radiation detectors (D1, D2, and D3), and millivoltmeters (mV).

Fig. 3. The absorption coefficient of microwave-radiation energy vs. the thickness of a concrete specimen for $\lambda = 4$ (curve 1) and 8 mm (curve 2).

Taking into account that the electromagnetic-wave amplitude $E_0$ in a medium with dielectric permeability $\varepsilon_0$ is related to the field amplitude at the generator exit $E_{\rm ex}$ by a relation similar to (1), namely, by $\theta = 2/(1+\sqrt{\varepsilon_0})$, we obtain

$$W_{\max} \approx \frac{\omega}{\pi}\,\varepsilon_0 \sin\delta \frac{4}{(1+\sqrt{\varepsilon_0})^2}\,|E_{\rm ex}|^2 \approx \frac{16\sigma_1}{\sqrt{(\varepsilon_1')^2 + (4\pi\sigma/\omega_1)^2}}\,|E_{\rm ex}|^2 \sim W_{\rm ex}\,\frac{2\pi\sin\delta}{\lambda}, \tag{2}$$

where $W_{\rm ex}$ is the microwave-radiation density at the generator exit and $\lambda$ is the electromagnetic-radiation wavelength.

It follows from (2) that to obtain large values of the specific energy release and, hence, large mechanical stresses in the fractured region, the values of the conduction and dielectric permeability of the material should satisfy the condition $\sin\delta \to 1$ in this region.

Since adequate data on the conductivity and dielectric permeability of concrete (there are only the conductivity data for rocks in its composition [4]) are lacking, the absorption coefficient of electromagnetic energy in concrete of different thickness on the 4- and 8-mm wavelengths was measured.

**Absorption Measurement in Concrete.** The electromagnetic-wave absorption coefficient in concrete was measured on an installation whose layout is shown in Fig. 2. The microwave radiation with a wavelength of 4 or 8 mm was generated by the klystron and entered a 3-cm waveguide through the system of waveguides, the attenuator, and the horns, where the specimen to be exposed was placed. The dependence of the electromagnetic-radiation attenuation on the specimen thickness was found.

Figure 3 shows experimental dependences of the energy absorption coefficient $\eta$ on the thickness $h$ of a specimen made from 200-grade concrete. The measurements were performed 2 weeks after the specimens were fabricated. The electromagnetic-field penetration depth was approximately 10 mm for electromagnetic radiation with a wavelength of 4 mm at a reflection coefficient of about 10% and about 20 mm for electromagnetic radiation with a wavelength of 8 mm at a reflection coefficient of a little greater than 20%. Similar measurements were performed for the two main components of concrete, namely, sand and cement (in the dry state). For both components, the reflection coefficient was 20–25%, and the characteristic energy-absorption depth was approximately 40 mm, almost irrespective of the wavelength.

**Estimates of the Energy Necessary for Concrete Destruction.** Using the measured conduction of concrete, one can determine the conditions under which the concrete exposed to microwave irradiation begins to fracture. The simplest estimates show that at irradiation pulses of approximately microsecond duration, the energy redistribution will involve only the cement particles that are in close proximity to the pores owing to thermal conduction and, apparently, the main mechanism of its redistribution is gas-dynamic.

At the first stage, one can estimate the specific energy necessary for shear fracture to emerge in concrete in a quasistatic approximation. In accordance with [5], the thermoelasticity relations have the form

$$\hat{\varepsilon}_{ij} = \frac{1}{9K}\,\delta_{ij}\hat{\sigma}_{ll} + \frac{1}{2\mu}\Big(\hat{\sigma}_{ij} - \frac{1}{3}\,\delta_{ij}\hat{\sigma}_{ll}\Big) + \frac{1}{3}\,\alpha(T - T_0)\,\delta_{ij}.$$

Here $\hat{\sigma}_{ij}$ and $\hat{\varepsilon}_{ij}$ are the stress and strain tensors, respectively, $\delta_{ij}$ is the Kronecker symbol, $K$ and $\mu$ are the moduli of volumetric compression and shear, respectively, $\alpha$ is the volumetric coefficient of thermal expansion, $T$ is the temperature, $T_0$ is the initial temperature, and $\hat{\sigma}_{ll}$ is the sum of the diagonal elements of the stress tensor. For the conditions of uniaxial compression–extension in the principal axes, one of which (with index 1) is perpendicular to the concrete surfaces, the tensors have a diagonal form and $\hat{\varepsilon}_{22} = \hat{\varepsilon}_{33} = 0$. In addition, we have $\hat{\sigma}_{11} = 0$. Therefore, using the relation between the elastic moduli, where $K/\mu = 2(1+\nu)/(3(1-2\nu))$, where $\nu$ is the Poisson ratio, we obtain

$$\hat{\varepsilon}_{22} = \frac{1}{3}\Big\{\frac{1}{2K}\,\frac{1-\nu}{1-2\nu}\,\hat{\sigma}_{ll} + \alpha(T - T_0)\Big\} = 0. \tag{3}$$

We assume that the destruction of concrete occurs when the limiting level of shear stresses is reached according to the Mises condition

$$J = \sqrt{1.5 \sum_{i=1,2,3} (\hat{\sigma}_{ii} + P)^2} \leqslant Y,$$

where $P = -\hat{\sigma}_{ll}/3$ is the pressure.

With allowance for $J = 3/(2|\hat{\sigma}_{11} + P|) = |\hat{\sigma}_{ll}|/2$, to estimate the limiting value of the internal-energy density from (3), we obtain

$$w_q = C(T - T_0) = \frac{1-\nu}{1-2\nu}\,\frac{CY}{K\alpha},$$

where $C$ is the specific heat. For example, for $K = 13$ GPa, $\nu = 0.2$, $C = 0.84 \cdot 10^{-3}$ kJ/(g · K), $\alpha = 4 \cdot 10^{-5}$ K$^{-1}$ [6], and $Y = 0.02$ GPa (200-grade concrete), we obtain $w_q = 43$ J/g.

Thus, being heated slowly, concrete disintegrates in supplying an energy greater than 43 J/g because of the strong asymmetry of the stress state, namely, because it cannot expand along the directions parallel to the surface of concrete.

The energy release in the conducting area leads to an increase in the temperatures of concrete and a salt solution by approximately 10 K [$C_{H_2O} = 4.2 \cdot 10^{-3}$ kJ/(g · K)] and an increase in conduction by 20–25%. Since the error of determining the conduction itself is not smaller (20–25%), the absorption-induced temperature variation may be ignored.

**Destruction Simulation.** Upon intense energy release, the concrete can be destroyed when the expansion (spalling fracture) appears. The possibility of implementing its process is analyzed with the use of a one-dimensional program complex "Volna-RS"; the basic algorithms are described in [7]. The elastoplastic properties of substances and material destruction were simulated according to the approach expounded in [8].

The optimization conditions for concrete destruction were calculated for different variants of energy release. A flat concrete layer whose left boundary was assumed to be free was considered (the boundary condition $P = 0$). The right boundary was assumed to be a rigid wall. In addition, the layer thickness was chosen sufficient to ignore the right boundary.

The energy release was described with the use of the dependence

$$\frac{dW}{dt} = W_0 f(z)\varphi(t),$$

Here

$$\varphi(t) = \begin{cases} 1, & 0 \leqslant t \leqslant t_u, \\ 0, & t > t_u; \end{cases} \qquad f(z) = \begin{cases} \exp\Big(-\dfrac{z-d}{L}\Big), & z \geqslant d, \\ 0, & z < d; \end{cases}$$

TABLE 1

| Energy-release parameter | | | | | Bedding depth of the destruction zone, cm | |
|---|---|---|---|---|---|---|
| $d$, cm | $t_u$, $\mu$sec | $L$, cm | $Q_0$, J/cm$^2$ | $W_{max}$, J/g | for compression | for expansion |
| 0 | 0.1 | 1.2 | 22.1 | 8.2 | — | — |
| 0 | 0.1 | 1.2 | 23.0 | 8.5 | — | 1.95 |
| 0 | 1 | 1.2 | 25.4 | 9.4 | — | — |
| 0 | 1 | 1.2 | 31.7 | 11.7 | — | 1.31 |
| 0 | 1 | 1.2 | 127.0 | 47.0 | 0–0.26 | 2.01 |
| 2 | 1 | 1.2 | 25.4 | 9.4 | — | — |
| 2 | 1 | 1.2 | 31.7 | 11.7 | — | 1.55–1.56 |
| 2 | 1 | 1.2 | 127.0 | 47.0 | 2.0–2.23 | 0.17–0.57 |
| 0 | 10 | 1.2 | 63.4 | 23.5 | — | — |
| 0 | 10 | 1.2 | 79.2 | 29.3 | — | 2.2 |
| 2 | 10 | 1.2 | 127.0 | 47.0 | 2.0–2.38 | 0.7–2.0 |
| 0 | 100 | 1.2 | 79.2 | 29.3 | — | — |
| 0 | 100 | 1.2 | 119.0 | 44.0 | 0–0.12 | — |
| 0 | 100 | 1.2 | 793.0 | 294.0 | 0–2.6 | 5 |
| 0 | 1000 | 1.2 | 317.0 | 117.0 | 0–1.3 | — |

**Note.** $Q_0$ is the specific energy released in concrete, and $W_{max}$ is the maximum value of the specific energy release in concrete. The line denotes the absence of destruction.

$L = 1.2$ cm is the characteristic length of reduction, which corresponds to the experimental data obtained for a 4-mm radiation, and $d$ is the concrete depth at which the energy begins to release. In the calculations, the energy-release duration $t_u$ and the quantities $d$ and $W_0$ were varied.

The equation of state of concrete was set in the form $P = c_{0,f}^2(\rho - \rho_{0,f}) + (\gamma - 1)\rho W$, where $c_{0,f} = 2.4$ and $\gamma = 1.3$. The initial density of concrete coincided with the "crystalline" density and amounted to $\rho_{0,f} = 2.25$ g/cm$^3$.

The dynamic values of the strength characteristics of continuous concrete were assumed to coincide with their static values indicated above. It was assumed that the shear strength $Y$ is constant and is equal to $Y = 0.02$ GPa, and the critical tensile (spall) strength is $\sigma_{cr} = -0.003$ GPa [6].

The strength of concrete decreased abruptly upon shear fracture. Here the shear strength was specified as a function of pressure:

$$Y = Y_0 + \beta P \frac{A - Y_0}{A - Y_0 + \beta P}.$$

Here $Y_0 = 0$, $A = 0.002$ GPa, and $\beta = 1$. The value of $Y$ decreased to zero in the absence of pressure and was restored to a value equal to 0.1 of the strength limit of continuous concrete as this value increased. It was assumed that concrete cannot resist expansion ($\sigma_{cr} = 0$). The concrete destroyed upon expansion did not possess either shear strength or tensile strength.

The calculation results obtained, which show the state of the concrete exposed to pulse microwave radiation, are given in Table 1. In addition, Fig. 4 shows the results of numerical calculations in the form of stress profiles $\hat{\sigma}_{11}(z)$ at various moments of time $t$, which illustrate wave propagation in a concrete block and its destruction.

It follows from Table 1 that the minimum value of $Q_0$ at which spall fracture begins for the type of concrete considered is $Q_{01} = 25$–$30$ J/cm$^2$ ($W_{max} \approx 10$ J/g) for the exposure time $t_u = 0.1$–$1.0$ $\mu$sec.

With increase in the exposure-pulse duration, the minimum value of the energy incident on the layer area that is necessary for spalling increases to $Q_{01} \approx 80$ J/cm$^2$ for $t_u = 10$ $\mu$sec. At $t_u = 100$ $\mu$sec, this

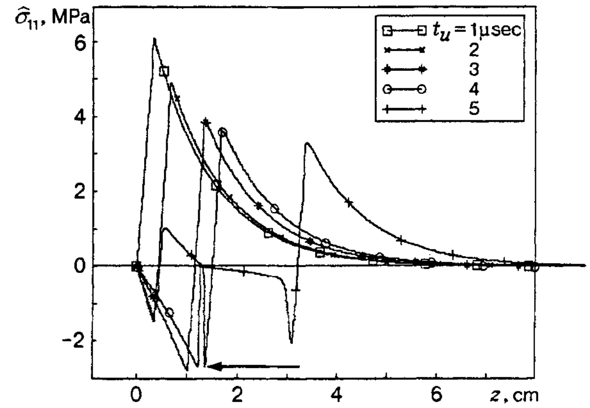


Fig. 4

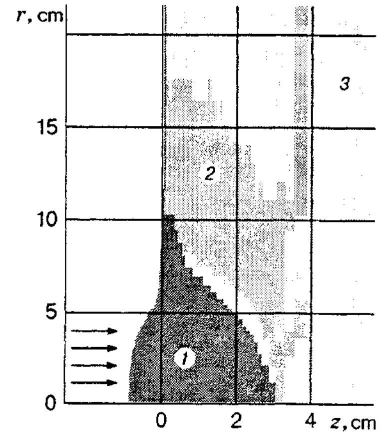


Fig. 5

Fig. 4. Stress profiles at various moments of time ($Q_0 = 31.7$ J/cm$^2$ and $t_u = 1$ $\mu$sec); the arrow denotes the point of destruction.

Fig. 5. Concrete-destruction zones after its surface was exposed to a 4-mm Gaussian radiation beam of radius $r_b = 5$ cm ($Q_0 = 120$ J/cm$^2$ and $t_u = 100$ $\mu$sec): 1) shear-fracture zone; 2) spall-fracture zone; 3) concrete block; arrows show the direction of microwave-radiation flux.

magnitude becomes greater than $Q_{02} \approx 130$ J/cm$^2$, which corresponds to the shear-fracture boundary. A further increase in pulse duration should not, apparently, cause spall fracture of continuous concrete.

The critical values of the specific energy necessary for shear fracture are the same for any values of $t_u$ and equal $Q_{02} \approx 130$ J/cm$^2$. Here the maximum energy absorbed per unit mass of concrete is equal to $W_{\max} \approx 47$ J/g, which is in good agreement with the above estimates in the quasistatic approximation.

The shear-fracture zone is supplemented, from the outside, by the spall-fracture zone. With increase in $Q_0$, the amount of a substance destroyed in shear grows; as a result, the shear-fracture zone moves 5 cm from the boundary of the energy-release zone for $Q_0 \approx 270$ J/cm$^2$.

In displacing the energy-release region deeply in concrete, the critical values of the energy release $Q_{01}$ and $Q_{02}$ are preserved, because only the level of stresses is of importance and the wave damping is insignificant. Here the destruction region becomes enlarged, since fracture occurs also near the surface of concrete outside the energy-release zone.

Significant pulse durations are of great interest. In this case, it is expedient to consider a two-dimensional picture of variation of the stressed sites in concrete because of the possible unloading in directions parallel to the free surface. Figure 5 shows calculations of the destruction dynamics of concrete irradiated by a Gaussian microwave-radiation beam with a 5-cm width at half-height, which were performed according to the two-dimensional program SPRUT [8]. The calculations support the main results of one-dimensional simulation and the efficiency of application of microwave radiation to destruction of the surface of concrete.

It is noteworthy that because of the absence of information on the strength of concrete in dynamic processes, the strength values that refer to the static loading conditions were used in the calculations both for large and small ($t_u \leqslant 1$ $\mu$sec) pulse durations. In real conditions, owing to the fact that the strength limit of concrete increases at high deformation rates, the values of $Q_{01}$ and $Q_{02}$ can change (increase). Here the possible errors increase with decrease in the pulse duration.

**Conclusions. Requirements for Microwave Sources.** The calculations have shown that destruction of the surface of concrete exposed to high-power microwave radiation can occur owing to shear and tensile deformations. For tensile deformation, the specific energy release upon pulse microwave irradiation should be equal to 10, 30, and 300 J/g for $t_u \approx 1$, 10, and 100 $\mu$sec, respectively. The specific electromagnetic-radiation energy release necessary for shear-induced destruction of concrete should amount to approximately 50 J/g.

This value depends weakly on the pulse duration, the exposure geometry, and the shape of the energy-release zone. The boundary of the destruction zone is determined by the boundary of the conducting layer and the exposure geometry and can be adjusted in accordance with specifications.

Based on the data obtained, one can formulate some requirements for microwave generators as applied to concrete-surface destruction experiments. The microwave-radiation power necessary for shear fracture can be estimated from formula (2), where the specific absorbed energy is determined by the quasistatic limit $w_q$:

$$\frac{w_q}{t_u} = W_{\text{ex}} \frac{2\pi \sin \delta}{\rho\lambda}.$$

Therefore, the density of the generator-supplied power should be of the order of $W_{\text{ex}} \approx \rho\lambda/(2\pi \sin \delta)(w_q/t_u) \approx 100\,\lambda/(2\pi t_u)$ [W/cm$^2$]. Here, on the surface to be destroyed, the energy per unit area should be of the order of $100\,\lambda/(2\pi)$ [J/cm$^2$]. These are quite attainable magnitudes for modern mobile microwave generators.

Shock-wave destruction with the formation of spalls requires substantially smaller energy expenditures but much more powerful installations. In particular, for a pulse-radiation duration of 1–10 $\mu$sec, the energy should be of the order of kilojoules, and the power should be of the order of several gigawatts.

The microwave-radiation energy sufficient for destruction experiments of concrete upon short-term exposure can be reached with the use of a 4-MJ sheet electron beam, which has already been generated by a U-2 accelerator [9].

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