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An Empirical Modeling and Evaluation Approach for the Safe use of Industrial Electric Detonators in the Hazards of Radio Frequency Radiation

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The major causes of radio frequency radiation hazards are the transmitting antennas of radio, TV, radar, cell phones, wireless data acquisition systems and global positioning systems in the new age of communication technology using various modulation schemes such as amplitude modulation (AM), frequency modulation (FM) etc. The transmitting antennas of these communication devices generate electromagnetic fields (EMFs). Under such conditions, electric detonator wires work as receiving antenna and pickup sufficient energy from electromagnetic fields to initiate an accidental explosion. There have been several instances of accidental firing of detonators by radio frequency pickup. In this study an attempt has been made to minimize such explosions and to provide a basis for the assessment and simulation of the radio frequency radiation hazard parameters associated with industrial electric detonators. This research examines the radiated powers of various frequency bands to determine the safe distance from transmitting antenna. Two empirical relationships for the estimation of minimum safe distance (MSD) have been suggested based on mathematical simulation. Using these relations desired MSDs have been calculated for the relevant frequency bands. The values obtained have been compared with the experimental values available that demonstrated strong agreement between them. The average percentage deviations of calculated MSDs from suggested relations are found between 0.096% and 10.718%, with regression coefficient $0.970 \leq R \leq 1$. This reflects the soundness of the proposed empirical relations. The blasting engineers, detonator designers and researchers may use these relations as a handy tool to prevent undesired explosions by maintaining minimum safe distance in radio frequency prone hazardous areas.

Keywords: Blasting caps, Electromagnetic radiation, Empirical relations, Mathematical modeling, Transmitter power

Introduction

Explosive materials and explosive devices are inherently dangerous products. Safety of its manufacturers, users, environment and general public is the challenge for peer researchers. Several accidents have been investigated in which explosive blasting is initiated by radio frequency radiation. To avoid such explosions electric detonators are made in such a way that they are either EMF resistant or placed to operate outside the effective area of radio frequency hazards.

To look into the more details of electric detonators the study of different phases of its historical evolution is required. The development of an electric method of explosive blasting has a long history of late 18th to early 19th centuries.[1] Worldwide blast of a demolition gunpowder charge by an electrical method for the first time ever was implemented in 1811 by P L Schilling.[2] He developed a special charcoal fuse and power supply along with an insulated electrical wire for underground and underwater blasting operations. However, the first patent for ignition of the gunpowder charges by electric spark using mixture of fulminate and gunpowder was received in 1830 by Moses Show. In Russia the electric blasting technique was mastered for military and public uses in the years 1840–46. Alfred Nobel in 1864–67 developed first commercial fulminating detonator using mercury. The first electrical detonator with a resistance bridge was developed by D M Andrievskii in 1865 where as the first patent of electric delay detonator was received by American inventor G J Smith in 1895.

In 1940, the use of penthrite as a main detonator was begun in the USA. This led to the strengthening of electrical detonator in terms of initiating impulse power, safety and reliability of its practical applications. During 1956–1980 different types of electrical detonators were developed. For example, in 1956 heat resistant electrical detonators and in 1966–68 delay electrical detonators were developed in USSR; in 1976–77 an Australian company developed the first sample of an electronic detonator using capacitor as delay element and an electronic chip; in 1988 a domestic wireless microwave radio electrical detonator was developed.

The subject of radiation frequency risk associated with electric detonators is sensitive and critical to life

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safety. Modern radio and radar transmitters emit electromagnetic radiation of high intensity that is harmful to ordnance, attendant workers and associated equipment. Premature actuation of electric detonators increases with the developing powerful antennas of communication systems. Characterization of the radio frequency sensitivity and other details of electrically initiated blasting devices are enumerated in various standards, manual, guides and handbooks. IEEE Std C95.4[(3)] offers an overview of electromagnetic radiation phenomena that may pose a possible threat to the transport, storage or use by industrial or military personnel of electrical blasting caps. In this standard, the horizontal dipole model has been taken into account for determining the standoff distances from transmitters. Time to time different safety guides[4,5], standards[6,7] and manuals[8,9] have been adopted and practiced for safety against radio frequency radiation hazards. Galuga and Bray[10] have studied the electromagnetic susceptibility of commercial electric detonators when exposed to plane wave radiation to access the feasibility of inducing sufficient current to cause its explosion. Wagh *et al.*[11] have focused their research on the application of electrical detonators for magnetic flux compression generator uses which require synchronization of two occurrences with precise time delay of tens of microsecond and jitter within a few microsecond. Apart from electric detonators now a day’s electronic detonators are becoming very popular due to its precise delay time and many other attractive technical features.[12] The computer simulation and calculation of the mono-static radar cross section (RCS) of the electric hot-wire detonator with its casing and lead wires provide the biggest RCS contribution, ranging from –16 and –22 DBsm in the 3–10 GHz frequency range.[13] Fousson *et al.*[14] have developed a high safety, high reliability two-stage electric detonator that consists of only secondary high explosive. Electromagnetic (EM) modeling to determine the electromagnetic characteristics of hot-wire detonators in modern EM radiation is done by Lambrecht *et al.*[15] The following sections cover the details of radiation hazards along with transmitter power for different frequency bands.

Radio Frequency Radiation Hazards

Different modulating schemes such as AM, FM, frequency shift keying (FSK), phase shift keying (PSK) etc. and TVs, RADARs, mobile phones base stations are the main sources of strong EMFs. With the distance from the transmitting antenna, the strength of EM fields declines. The detonators exposed under the strong electromagnetic field in certain circumstances pickup this radiation energy and led to the accidental explosion of ammunitions. The standard method of firing an electric detonator is to add electrical energy to the firing line connected to the detonator from a blasting machine, power line or other sources of electrical power. The unshielded leg wires or circuit wires can serve as an antenna similar to that on a radio or TV receiver when the detonator wires are exposed in a strong EM fields. In the circuit wiring, the radio frequency (RF) field generates an electrical current that flows through the electrical detonator linked to it. In some situations, ample RF power may be induced in the wires to fire the electrical detonator, depending on the strength of the RF field and the antenna configuration created by the detonator wires and its orientation. By maintaining safe operating distances[16] from the transmitting antenna accidental firing of detonators can be minimized.

Sources of Radio Frequency Hazards

In the era of information technology, transmitting antenna needs more input power for long distance reliable communication of data. The power fed to the transmitting antenna is considered as main source of radio frequency in the space and transmitted in the form of signal. The received power P_R (Watt) by an antenna placed at a distance R (meter) from the transmitting antenna is given by Friis[17] as $P_R = P_T G_T G_R c^2/(4\pi R f)^2$, where P_T, G_T , G_R, c, and f are, respectively, the power (in Watt) fed to the transmitting antenna, gain of transmitting antenna, gain of receiving antenna, speed of light (3×10^8 m/s) and frequency (Hz) of the transmitted signal. The radio frequencies of commercial AM broadcast transmitters (0.535 to 1.605 MHz) are theoretically the most dangerous.[17] This is because high power and low frequency are combined to ensure the lead wires have no loss of RF energy. It is unlikely that high-frequency FM and TV transmitters would create a dangerous situation, as they are generally mounted on top of high towers and the strength of EM wave is significantly reduced at ground level. The cell radio and other wireless products must be identified as a possible threat and should therefore not be put directly in the blasting zone. There is little risk that RF energy sources such as microwave relays will ever be a realistic problem. However all directional RF sources of high-gain antennas, such as fixed and mobile marine radar, should be taken into account to greatly increase the effective radiated power. In surrounding of high power radar installations, blasting should be avoided. RF antennas used in underground mining activities could pose a dangerous condition and they can only be allowed after proper assessment and testing as per IS/IEC 60079–0.[(18,19)]

Mobile Telephony

In the explosive industry, installations of cell phone towers and mobile handsets have raised concern about such personnel communication devices and installations operating near electrical blasting circuits. The average height of the mobile phone tower is typically 33.50 m to 36.60 m and operates with a maximum efficient radiated power of 500 W. In this case, the resulting safe distance to the blasting circuits should be appropriate as the vertical angle between the radiator and the ground is very sharp when rolling off the RF antenna output. Battery powered hand held mobile phones are low power devices and their specific absorption rate (SAR) is maintained below recommended safe levels for human tissue. It may be possible that portable mobile phones brought very close to the detonator leg wire. Therefore, mobile phones with output less than 1 W should be kept at least about 2.50 m from a blasting circuit. The battery charging jack of a mobile phone may also come into touch with a detonator's leg wire. The consequence is in any event, a potentially dangerous situation.

Hand held RF Sources

Low power hand held RF sources such as keyless entry systems, remote control, garage door openers etc., poses several concerns relating to the safe use of blasting circuits or electro-explosive equipment in the vicinity. For such devices of power less than or equal to 2 W a safe distance of 1.50 m must be maintained.[16]

RF Receiving Antenna

In AM radio broadcasting and mobile operation, the radio frequencies are picked up by lead-wire layout of detonator and work as receiving antenna. The receiving antennas of the type dipole circuit can play a very sensitive role in RF pickup. The wavelengths of radio frequency radiations are approximately given by $\lambda\ (feet) = 1000/f(MHz)$. The loop circuit is also sensitive pickup circuit usually encountered in blasting operations besides the dipole antenna.[16] The larger loop area pickups greater RF current and it is highest when placed parallel to the plane of the transmitter antenna.

Military RF Installations

The number of military RF source transmitters is becoming very high, covering frequencies from kilohertz to high power outputs of thousands of megahertz. Military radars can affect the particular type of blasting operations conducted during the investigation and manufacture of offshore oil and gas resources, the removal of fixed or mobile offshore oil or gas drilling rigs and manufacturing platforms, etc. The safe distance from an electrically initiated blasting operation from this sort of radar is 4830 m.[16]

Methods of Modeling and Assessment

The calculation of MSDs from potential hazardous zone of radio frequency transmitter to electric detonators is needed to prevent explosions that may take place during its operation by induced electromagnetic field. Attempts[8,16,20] have been made to access the potential hazardous zones as the function of frequency and electric field strength. The most dangerous frequencies are between 2 MHz and 80 MHz for electric field strength of 0.5 V/m.[20] The safety distances in meter are reported[16,20] as $5.5fP^{0.5}$, $10.95P^{0.5}$ and $876f^{-1}P^{0.5}$ for frequency range $0.01 \leq f < 2\ MHz$, $2.0 \leq f < 80.0\ MHz$ and $80.0 \leq f < 10^5 MHz$, respectively, where 'P' is the equivalent isotropic radiated power (EIRP) in Watt and 'f' is the frequency in MHz. The distance in meter between the antenna and the point at which the electric field is measured is also given by $D = \sqrt{30P}/E$, where 'P' is equivalent isotropic radiated power in Watt and E is the electric field strength in Volt/meter.

It has been observed that in previous research works various attempts have been made to calculate MSDs of commercial electronic detonators form the radio frequency source based on experimental findings. Conducting experiments are not possible without expensive instruments, specialized manpower and also very time consuming. The distances are expressed for limited range of frequencies and EIRP. One can find very difficult to know such distances for different frequency ranges and EIRPs. It therefore calls for the creation of relationships which could be used at any given value of radiated power for the measurement of MSD. In the present work, an attempt has been made to express the MSD (or D) in terms of transmitted antenna power (P). The experimental values[16] of transmitted power and minimum safe distance (D) are simulated and results are analyzed. Based on mathematical

Table 1—Numerical values of constants for different radio frequency transmitters

S. Nos.	Transmitter types	K_1	K_2	K_3	K_4	K_5
1.	AM broadcast (0.535 to 1.705 MHz)	-1.0×10^{-8}	0.010	213.7	—	—
2.	Up to 50MHz (Excluding AM Broadcast)	—	—	—	24.12	0.5
3.	Medium Frequency (1.7 to 3.4 MHz)	-7.0×10^{-6}	0.113	22.30	—	—
4.	High Frequency (28 to 29.7 MHz)	—	—	—	14.30	0.499
5.	VHF (35 to36 MHz) Public, (42 to 44 MHz) Public use, (50 to 54 MHz)	—	—	—	11.20	0.499
6.	VHF (144-148 MHz) Amateur, (150.8-161.6 MHz)	—	—	—	3.669	0.499
7.	UHF (450- 470 MHz) Public Use Mobile phones Above 800 MHz	—	—	—	2.435	0.495
8.	Channel 2 to 6	—	—	—	68.60	0.216
9.	FM Radio	—	—	—	55.70	0.216
10.	Channel 7 to 13	—	—	—	41.97	0.216

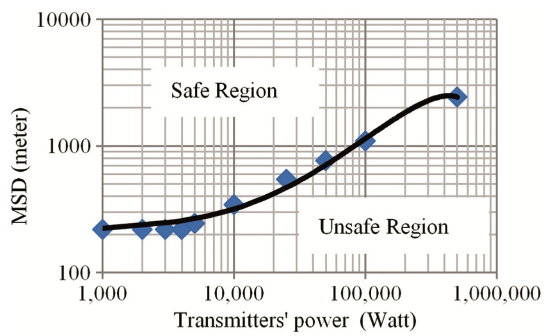

Fig. 1 — AM Broadcast transmitters (0.535 – 1.705 MHz).

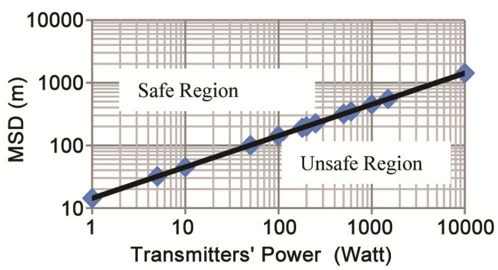

Fig. 2 — HF Amateur transmitters (28.0–29.7 MHz)

simulations, the following two empirical relations have been proposed:

$$D = K_1 P^2 + K_2 P + K_3 \quad \ldots (1)$$

$$D = K_4 P^{K_5} \quad \ldots (2)$$

where D, is MSD in meter; P, is transmitter power in Watt; K_1, K_2,K_3, K_4 and K_5 are the constants. The values of constants are listed in Table 1. These relations give very precise and accurate calculation of MSDs for various transmitter powers without having experimental setup. Having the values of transmitter power a simple technician can easily calculate the MSD and prevent explosions that may take place without proper knowledge.

The transmitted powers by various antennas working on different frequencies were studied and simulated for the calculation of MSDs. Two of them are shown in Figs 1 & 2. Proposed Eqs (1) & (2) are the mathematical representation of Fig. 1 and Fig. 2, respectively. This research will be very helpful to avoid fatal accidents caused by detonating devices and explosives.

Table 2— AM broadcast transmitters of frequencies 0.535 to 1.705 MHz

Transmitter power (W)	Min. distance (m) (experimental[16])	Min. distance (m) (theoretical)	ǀ % Deviation ǀ
1,000	219.456	223.69	1.929316
2,000	219.456	233.66	6.472368
3,000	219.456	243.61	11.00631
4,000	219.456	253.54	15.53113
5,000	243.840	263.45	8.042159
10,000	344.424	312.7	9.21074
25,000	545.592	457.45	16.1553
50,000	762.000	688.7	9.619423
100,000	1097.280	1113.7	1.496428
500,000	2438.400	2713.7	11.29019
		Average % deviation =	9.075336

Table 3—Transmitters up to 50 MHz (Excluding AM Broadcast)

Transmitter power (W)	Min. distance (m) (experimental[16])	Min. distance (m) (theoretical)	ǀ% Deviation ǀ
100	240.792	241.2	0.169441
200	341.376	341.1083112	0.078415
500	539.496	539.3395962	0.028991
1,000	762	762.7413716	0.097293
1,500	935.736	934.1635831	0.168041
5,000	1703.832	1705.541556	0.100336
50,000	5394.96	5393.395962	0.028991
500,000	17038.32	17055.41556	0.100336
		Average % deviation =	0.096480

Results and Discussion

Using proposed Eqs (1) & (2), the values of MSDs of different transmitters' power have been calculated and listed in Tables 3–5 along with the available experimental values. The calculated values are in good

Table 4 — Recommended distance of mobile transmitters and cellular telephones

Medium Frequency (1.7 to 3.4 MHz) Fixed, Mobile and Maritime

Transmitter power (W)	Min. distance (m) (experimental[16])	Min. distance (m) (theoretical)	% Deviation
1	4.572	22.412993	390.222944
5	10.058	22.864825	127.3297375
10	14.021	23.4293	67.10149062
50	31.09	27.9325	10.15599871
100	43.891	33.53	23.60620628
180	58.826	42.4132	27.90058818
200	62.179	44.62	28.23943775
250	69.494	50.1125	27.88945808
500	28.146	77.05	173.7511547
600	107.594	87.58	18.601409
1,000	138.684	128.3	7.487525598
1,500	169.774	176.05	3.696679115
		Average % deviation =	69.93663984

High Frequency (28 to 29.7 MHz) Amateur

Transmitter power (W)	Min. distance (m) (experimental[16])	Min. distance (m) (theoretical))	% Deviation
1	14.326	14.3	0.181488203
5	32.004	31.92435045	0.248873736
10	45.11	45.11656611	0.014555784
50	100.889	100.7214733	0.166050544
100	142.646	142.3429747	0.212431697
180	191.11	190.860922	0.130332258
200	201.473	201.1638808	0.153429596
250	225.247	224.8578748	0.172754865
500	318.516	317.7767138	0.232103308
600	348.996	348.0434872	0.272929429
1,000	450.494	449.0927432	0.311048932
1,500	551.668	549.8010637	0.338416639
10,000	1424.33	1416.889681	0.522373242
		Average % deviation =	0.227445249

VHF (35 to36 MHz) Public, (42 to 44 MHz) Public use, (50 to 54 MHz) Amateur

Transmitter power (W)	Min. distance (m) Experimental[16])	Min. distance (m) (theoretical)	% Deviation
1	11.278	11.22	0.514275581
5	24.994	25.04833651	0.217398202
10	35.357	35.39915187	0.119217904
50	78.943	79.02761749	0.10718808
100	111.557	111.6844878	0.114280437
180	149.657	149.7524157	0.063756283
200	157.886	157.8362757	0.031493801
250	176.479	176.426948	0.029494751
500	249.326	249.3324985	0.002606444
600	273.406	273.0802746	0.119136163
1,000	352.654	352.3650755	0.081928618
1,500	431.902	431.3823731	0.120311308
10,000	1115.263	1111.713442	0.318270922
		Average % deviation =	0.141489115

(Contd.)

Table 4 — Recommended distance of mobile transmitters and cellular telephones—(Contd.)

VHF(144–148 MHz) AMATEUR, (150.8–161.6 MHz)

Transmitter power (W)	Min. distance (m) (experimental[16])	Min. distance (m) (theoretical)	% Deviation
1	3.658	3.669	0.300710771
5	8.23	8.190939986	0.474605274
10	11.582	11.57571196	0.054291459
50	25.908	25.84245353	0.252997046
100	36.576	36.52142476	0.149210513
180	49.073	48.96984076	0.210215878
200	51.816	51.6133062	0.39117995
250	57.912	57.69255544	0.378927611
500	81.686	81.53306035	0.187228715
600	89.611	89.29871011	0.348495039
1,000	115.519	115.225264	0.254275073
1,500	141.427	141.0643428	0.2564271
10,000	365.15	363.5362406	0.441944247
		Average % deviation =	0.284654514

UHF(450 to 470 MHz) Public Use Mobile Telephones above 800 MHz

Transmitter power (W)	Min. distance (m) Experimental[16])	Min. distance (m) (theoretical)	% Deviation
1	2.438	2.435	0.123051682
5	5.486	5.401185806	1.546011554
10	7.62	7.612003259	0.104944108
50	16.764	16.88453551	0.719013997
100	23.774	23.79572633	0.091386936
180	31.6992	31.83162835	0.417765593
200	33.528	33.535811	0.023296949
250	37.49	37.45236695	0.100381571
500	53.035	52.78239807	0.476292881
600	57.912	57.76753478	0.249456451
1,000	74.676	74.38732911	0.386564483
1,500	91.44	90.92098641	0.567600163
10,000	236.22	232.5406947	1.557575694
		Average % deviation =	0.489487851

good agreement with the available experimental values. We have also calculated the average percentage deviation of MSDs obtained from proposed Eqs (1) and (2) using the relation, Percentage deviation = [|Experimental value − Calculated Value|/ Experimental value] × 100. In the case of Eq. (1), the average percentage deviation (APD) has been estimated as 9.07% and 69.93% for AM broadcast transmitters (0.535–1.705 MHz) and medium frequencies (1.7–3.4 MHz), respectively. However, in the case of Eq. (2) the average percentage deviations have been estimated to be 0.09%, 0.22%, 0.14%, 0.28%, 0.48%, 10.71%, 10.53% and 10.59%, respectively, for the transmitters up to 50 MHz (excluding AM broadcast), high frequency (28 to 29.7 MHz) amateur, VHF (35 to 36 MHz) public (42 to 44 MHz) public use - (50 to 54 MHz), VHF (144–148

Table 5—Transmitter power and minimum safe distance for VHF TV and FM broadcasting

Channel 2 to 6

Transmitter power (W)	Min. distance (m) (experimental[16])	Min. distance (m) (theoretical)	|% Deviation |
100	249.936	185.4915438	25.78438
500	249.936	262.6041812	5.06857
1,000	249.936	305.0170495	22.03806
10,000	441.96	501.5614113	13.4857
100,000	786.384	824.7534021	4.87922
316,000	1051.56	1057.441926	0.559352
1,000,000	1402.08	1356.201173	3.272198
10,000,000	2496.312	2230.09886	10.66426
		Average % deviation =	10.71897

FM Radio

Transmitter power (W)	Min. distance (m) Experimental[16])	Min. distance (m) (theoretical)	|% Deviation |
100	203.302	150.6104809	25.91786
500	203.302	213.2223454	4.87961
1,000	203.302	247.659616	21.81858
10,000	362.712	407.2444695	12.27764
100,000	644.652	669.6612901	3.879502
316,000	859.536	858.5935172	0.10965
1,000,000	1149.096	1101.17209	4.170575
10,000,000	2039.112	1810.736246	11.19977
		Average % deviation =	10.53165

Channel 7 to 13

Transmitter power (W)	Min. distance (m) (experimental[16])	Min. distance (m) (theoretical)	|% Deviation |
100	153.01	113.4851325	25.83156
500	153.01	160.6632286	5.001783
1,000	153.01	186.611743	21.96049
10,000	271.882	306.8590733	12.8648
100,000	483.108	504.5903832	4.446704
316,000	649.224	646.9509859	0.350112
1,000,000	859.536	829.734158	3.467201
10,000,000	1530.096	1364.391387	10.82969
		Average % deviation =	10.59404

MHz) amateur- (150.8–161.6 MHz), UHF (450–470 MHz) public use mobile phones above 800 MHz, channel 2 to 6, FM radio and channel 7 to 13. In most of the cases the average percentage deviations are around 10% or below, which show that the calculated values are very close to the experimental values. The regression coefficient (R) of proposed relations is 1 in most of the cases. The values of R and APD give us guarantee for the precise and accurate calculation of MSD using proposed relations. The key benefit of the current models is the simplicity of the formulas, which require no experimental data other than radio frequency transmitter power.

The proposed equations may be used to draw boundary lines separating safe and unsafe regions. For each band considered in this research a separate logarithmic curve can be plotted. These curves can be used for estimating MSDs to ensure safe use of commercial electric detonators. However, in case of a particular radiated power for which safe distance is lying between two minor gridlines, the determination of exact distance is very difficult. To avoid such critical situations the proposed equations are developed. These equations give the exact value of MSD.

Conclusions

The primary necessity for the operation of the explosive industry is the protection of workers, customers, the public and the environment in the manufacture, transport, storage, handling and use of explosive materials. Electric detonators play a very important role in the safe use of explosives. In the age of communication technology, high power radio frequency transmitters induce an undesired electric current in electric detonators that may results in disastrous explosion. Prevention of such explosions is the need of the hour and it can be achieved by assessment of hazards associated with the electric detonators operating under the influence of radio frequency radiators. This research aims to contribute in the reduction of explosions caused by induced electromagnetic current in USA make commercial electric detonators. The proposed relations have been used for the calculation of MSDs from the radio frequency radiation sources.

Their APDs lie between 0.096% and 10.71% and having regression coefficient $0.970 \leq R \leq 1$. This gives us enough confidence that the calculated values of MSDs are very precise and accurate. Therefore, proposed relations can be used as an alternative tool in place of big bank of experimental data given in different safety guide lines. It can contribute to the significant reduction of fatal accidents caused by pick up of radio frequency energy by commercial electric detonators.

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