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IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems

Sponsor

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The Institute of Electrical and Electronics Engineers, Inc.

Foreword

(This Foreword is not a part of IEEE Std 142-1972, Recommended Practice for Grounding of Industrial and Commercial Power Systems.)

This standard is a revision of IEEE Std 142-1956, Grounding of Industrial Power Systems. The subjects covered by this standard are divided into four parts corresponding to the four sections.

Section 1 covers the problems of system grounding, that is, connection to ground of the neutral, of the corner of the delta, or of the mid-tap of one phase. The advantages and disadvantages of grounded versus ungrounded systems are discussed. Information is given on how to ground the system, where the system should be grounded, and how to select equipment for the grounding of the neutral circuits.

Section 2 deals with the problems of connecting the frames and enclosures of electric apparatus such as motors, switchgear, transformers, buses, cables, conduits, building frames, portable equipment, etc to a ground system. It also outlines the fundamentals of making the interconnection or ground conductor system between electric equipments and the ground rods, water pipes, etc.

Section 3 deals with the problems of static electricity — how it is generated, what processes may produce it, how it is measured, and what should be done to prevent its generation or to drain the static charges to earth to prevent sparking. The methods of protecting structures against the effects of lightning are also covered; since the system for protecting structures against lightning consists entirely of conductors to earth, it is considered within the scope of this standard to discuss the general aspects of the problem.

Section 4 deals with the problems of obtaining a low-resistance connection to the earth. The use of ground rods, connections to water pipes, etc are discussed.

Looking at the problem from an overall standpoint, the grounding of the system would in most cases be done by making a metallic connection direct or through an impedance between transformer or generator neutrals and the building grounding system that is described in Section 2. The grounding system described in Section 2 in turn is connected to earth through the system of ground rods and water pipes described in Section 4.

The protective systems discussed for static and lightning protection in Section 3 would likewise be connected to the ground rods and water pipe system as outlined in Section 4.

The major revisions are contained in Sections 1 and 2 with only minor changes in Sections 3 and 4. Section 2 has been changed to emphasize the practical aspects of equipment grounding.

This publication was reviewed and approved by the Industrial and Commercial Power Systems Committee of the Industry Applications Society of the IEEE. This revision was prepared by the Industrial and Commercial Power Systems Committee's Power Systems Grounding Subcommittee, which had the following membership:

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4. Connection to Earth

4.1 Resistance to Earth.

4.1.1 *Recommended Acceptable Values.* The most elaborate grounding system that can be designed may prove to be inadequate unless the connection of the system to the earth is adequate and has a low resistance. It follows, therefore, that the earth connection is one of the most important parts of the whole grounding system. It is also the most difficult part to design and to obtain.

The perfect connection to earth should have zero resistance, but this is impossible to obtain. Ground resistance of less than 1 Ω can be obtained, although this low a resistance may not be necessary in many cases. Since the desired resistance varies inversely with the fault current to ground, the larger the fault current, the lower must be the resistance.

For larger substations and generating stations, the earth resistance should not exceed 1 Ω. For smaller substations and for industrial plants in general, a resistance of less than 5 Ω should be obtained if practicable. The NEC states that the maximum resistance shall not exceed 25 Ω.

4.1.2 *Resistivity of Soils.* It is recommended that the resistivity of the earth at the desired location of the connection be investigated. The resistivity of soils varies with the depth from the surface, with the moisture content, and with the temperature of the soil. Presence of surface water does not necessarily indicate low resistivity. Representative values of resistivity for general types of soils are shown in Table 7. The effects of moisture and temperature are shown in Tables 8 and 9.

4.1.3 *Calculation of Resistance to Earth.* Resistance to earth may be calculated and/or measured. Calculation has been simplified to a great extent by the formulas given in Ref 1. These formulas appear in Table 10.

4.1.4 *Current-Loading Capacity.* One factor which should not be overlooked in designing a grounding system is the current-loading capacity of a connection to earth. The temperature and moisture conditions immediately surrounding the electrode have a direct effect on the resistivity of this section of the grounding circuit. Currents passing from the electrode into the earth will have a definite effect on these two factors. Therefore, the current-loading capacity of a connection must be analyzed from the standpoint of the nature of the grounding circuit and the types of loading which it can normally be expected to carry.

Table 7
Resistivity of Different Soils

Soil	Resistance in Ohms 5/8-in (15.88-mm) by 5-ft (1.52-m) Rods			Resistivity ρ Ω/cm^3 (MΩ/m^3)		
Fills	Average	Minimum	Maximum	Average	Minimum	Maximum
Ashes, cinders, brine waste	14	3.5	41	2370	590	7000
Clay, shale, gumbo, loam	24	2	98	4060	340	16 300
Same, with varying proportions of sands and gravel	93	6	800	15 800	1020	135 000
Gravel, sand, stones, with little clay or loam	554	35	2700	94 000	59 000	458 000

Table 8
Effect of Moisture Content on
Resistivity of Soil

Moisture Content Percent by Weight	Resistivity, Ω/cm³ (MΩ/m³) Top Soil	Sandy Loam
0	>1000 x 10⁶	>1000 x 10⁶
2.5	250 000	150 000
5	165 000	43 000
10	53 000	18 500
15	19 000	10 500
20	12 000	6300
30	6400	4200

Table 9
Effect of Temperature on
Resistivity of Soil*

Temperature °C	°F	Resistivity Ω/cm³ (MΩ/m³)
20	68	7200
10	50	9900
0 (water)	32	13 800
0 (ice)	32	30 000
−5	23	79 000
−15	14	330 000

*Sandy loam, 15.2 percent moisture.

Currents of low magnitude, even if of long duration, will result in relatively little heating. The effect of heat conduction and the movement of moisture due to capillary action will maintain, in most cases, the resistivity of the earth at the electrode to a value close to that considered desirable.

Where the earth must dissipate high currents for short durations, no appreciable amount of heat can be dissipated by the normal process of thermal conductivity. The permissible current density for a given temperature rise is inversely proportional to the square root of the soil resistivity. The effective resistance of the earth connection would therefore depend on the number of such situations which could occur in succession before stable conditions in the earth were reestablished.

Ground currents of high magnitude and long duration are unusual, but could occur as the result of ground faults that are not cleared promptly. If ground currents of this type are anticipated, the system must cover a relatively large area in order to keep the current density in the earth to a low value [2].

4.1.5 *Soil Treatment.* Soil resistivity may be reduced anywhere from 15 to 90 percent, depending upon the kind and texture of the soil, by chemical treatment. There are a number of chemicals suitable for this purpose, including sodium chloride, magnesium sulfate, copper sulfate, and calcium chloride. Common salt and magnesium sulfate are most commonly used.

Chemicals are generally applied by placing them in the circular trench around the electrode in such a manner as to prevent direct contact with the electrode. While the effects of treatment will not become apparent for a considerable period, they may be accelerated by saturating the area with water. Also, such treatment is not permanent and must be renewed periodically, depending on the nature of the chemical treatment and the characteristics of the soil.

4.2 Ground Electrodes.

4.2.1 *Existing Electrodes.* Basically, all ground electrodes may be divided into two groups. The first group comprises underground metallic piping systems, metal building frameworks, well casings, steel piling, and other underground metal structures installed for purposes other than grounding. The second group comprises made electrodes specifically designed for grounding purposes.

The NEC states that continuous underground water or gas piping systems generally have a resistance to earth of less than 3 Ω and that metal building frames, local metallic underground piping systems, metal well casings, and the like have in general a resistance to earth of substantially less than 25 Ω. For safety grounding and for small distribution systems where the ground currents are of relatively low magnitude, such electrodes are usually preferred because they are economical in first cost. However, before reliance can be placed on any electrodes of this group, it is

Table 10
Formulas for Calculation of Resistances to Ground*†

	Hemisphere radius a	$R = \frac{\rho}{2\pi a}$
	One ground rod length L, radius a	$R = \frac{\rho}{2\pi L}\left(\ln \frac{4L}{a} - 1\right)$
	Two ground rods $s > L$; spacing s	$R = \frac{\rho}{4\pi L}\left(\ln \frac{4L}{a} - 1\right) + \frac{\rho}{4\pi s}\left(1 - \frac{L^2}{3s^8} + \frac{2\,L^4}{5\,s^4} \cdots\right)$
	Two ground rods $s < L$; spacing s	$R = \frac{\rho}{4\pi L}\left(\ln \frac{4L}{a} + \ln \frac{4L}{s} - 2 + \frac{s}{2L} - \frac{s^2}{16L^2} + \frac{s^4}{512L^4} \cdots\right)$
	Buried horizontal wire length 2 L, depth $s/2$	$R = \frac{\rho}{4\pi L}\left(\ln \frac{4L}{a} + \ln \frac{4L}{s} - 2 + \frac{s}{2L} - \frac{s^2}{16L^2} + \frac{s^4}{512L^4} \cdots\right)$
	Right-angle turn of wire length of arm L, depth $s/2$	$R = \frac{\rho}{4\pi L}\left(\ln \frac{2L}{a} + \ln \frac{2L}{s} - 0.2373 + 0.2146 \frac{s}{L} + 0.1035 \frac{s^4}{L^2} - 0.0424 \frac{s^4}{L^4} \cdots\right)$
	Three-point star length of arm L, depth $s/2$	$R = \frac{\rho}{6\pi L}\left(\ln \frac{2L}{a} + \ln \frac{2L}{s} + 1.071 - 0.209 \frac{s}{L} + 0.238 \frac{s^3}{L^8} - 0.054 \frac{s^4}{L^4} \cdots\right)$
	Four-point star length of arm L, depth $s/2$	$R = \frac{\rho}{8\pi L}\left(\ln \frac{2L}{a} + \ln \frac{2L}{s} + 2.912 - 1.071 \frac{s}{L} + 0.645 \frac{s^2}{L^8} - 0.145 \frac{s^4}{L^4} \cdots\right)$
	Six-point star length of arm L, depth $s/2$	$R = \frac{\rho}{12\pi L}\left(\ln \frac{2L}{a} + \ln \frac{2L}{s} + 6.851 - 3.128 \frac{s}{L} + 1.758 \frac{s^2}{L^3} - 0.490 \frac{s^4}{L^4} \cdots\right)$
	Eight-point star length of arm L, depth $s/2$	$R = \frac{\rho}{16\pi L}\left(\ln \frac{2L}{a} + \ln \frac{2L}{s} + 10.98 - 5.51 \frac{s}{L} + 3.26 \frac{s^3}{L^3} - 1.17 \frac{s^4}{L^4} \cdots\right)$
	Ring of wire diameter of ring D, diameter of wire d, depth $s/2$	$R = \frac{\rho}{2\pi^2 D}\left(\ln \frac{8D}{d} + \ln \frac{4D}{s}\right)$
	Buried horizontal strip length $2L$, section a by b, depth $s/2$, $b < a/8$	$R = \frac{\rho}{4\pi L}\left(\ln \frac{4L}{a} + \frac{a^2 - \pi ab}{2(a+b)^2} + \ln \frac{4L}{s} - 1 + \frac{s}{2L} - \frac{s^2}{16L^2} + \frac{s^4}{512L^4} \cdots\right)$
	Buried horizontal round plate radius a, depth $s/2$	$R = \frac{\rho}{8a} + \frac{\rho}{4\pi s}\left(1 - \frac{7}{12}\frac{a^2}{s^2} + \frac{33}{40}\frac{a^4}{s^4} \cdots\right)$
	Buried vertical round plate radius a, depth $s/2$	$R = \frac{\rho}{8a} + \frac{\rho}{4\pi s}\left(1 + \frac{7}{24}\frac{a^2}{s^2} + \frac{99}{320}\frac{a^4}{s^4} \cdots\right)$

*See Ref 1.
†Approximate formulas including effects of images. Dimensions must be in centimeters to give resistance in ohms.
ρ = resistivity of earth in ohms per cm^3 ($M\Omega/m^3$).

essential that their resistance to earth be measured to insure that some unforeseen discontinuity has not seriously affected their suitability. Also, care should be exercised to insure that all parts which might become disconnected are effectively bonded together.

4.2.2 *Made Electrodes.* Made electrodes may be subdivided into driven electrodes, buried strips or cables, grids, buried plates, and counterpoises. The type selected will depend upon the type of soil encountered and the available depth. Driven electrodes are generally more satisfactory and economical where bedrock is 10 ft (3 m) or more below the surface, while grids, buried strips, or cables are preferred for lesser depths. Grids are frequently used for substations or generating stations to provide equipotential areas throughout the entire station where hazards to life and property would justify the higher cost. They also require the least amount of buried material per ohm of ground conductance. Buried plates have not been used extensively in recent years because of the higher cost as compared to rods or strips. Also, when used in small numbers, they are the least reliable type of made electrode. The counterpoise is a form of buried cable electrode used to ground transmission line towers and structures.

When multiple electrodes are used, spacings of less than 10 ft (3 m) do not provide the most economical use of materials.

In selecting the number and size of grounding terminals, their current discharge limitations must be recognized. If these are exceeded, the earth around the electrode may be exploded by steam generation, or may be dried out to the extent of becoming nonconductive.

4.2.3 *Driven Rod or Pipe.* Driven electrodes may be either rods or pipes, although rods are generally more economical. Where soil conditions permit, a few deep rods are usually more satisfactory than a multiplicity of short rods since the volume of soil affected increases directly with the length of electrode below the surface, and the soil resistivity generally decreases with depth due to the increased moisture content. A number of design charts for determination of optimum ground rod dimensions and spacings for a given installation are given in Ref 3.

4.2.4 *Concrete-Encased Rods or Wires.* Concrete below ground level is a semiconducting medium of about 30-$\Omega \cdot$m resistivity at 20°C, or somewhat lower than average earth resistivity. Consequently, in earth of average or higher resistivity, the encasement of rod or wire electrodes in concrete develops lower resistance than a similar electrode directly in earth. This results from reduction of the resistance of the material closest to the primary electrode, in much the same manner as does chemical treatment of the earth near the electrode. While it is seldom justifiable to excavate or drill holes for placement of concrete for this purpose, the widespread use of steel reinforcing bars in concrete foundations and footings provides a ready-made supply of grounding electrodes at structures utilizing this construction. It is necessary only to bring out an adequate electrical connection from a main reinforcing bar of each such footing for attachment to the building ground bus or structural steel. Each such "footing electrode" has a resistance equal to or lower than a drive rod of equal depth. The large number of such footings inherent to buildings will provide a net ground resistance considerably lower than normally provided by other made electrode methods. Test results and design data for determination of ground resistance of single and multiple concrete-encased footing electrodes are given in Ref 4.

Steel rods in concrete in (irregular) excavations in rock or very rocky soil have been found greatly superior to other types of made electrodes. The principles involved in this electrode type are those which provide grounds for the majority of the steel towers of high-voltage transmission lines.

4.2.5 *Buried Strip, Wire, and Cable.* Where bedrock is near the surface, or where sand is encountered, the soil is apt to be very dry and of high resistivity, and it is necessary to have an earthing connection of considerable extent. Under such conditions, buried metal strips, wires, or cables offer the most economical solution. Since the effectiveness of this type of electrode for lightning discharges is a function of its inductance, the use of a number of well-spaced shorter strips in parallel is preferable to one or more long strips. The depth at which the strips are buried is not critical. Tests by the National Bureau of Standards [5] show that the decrease in resistance from the minimum depth for cultivation to the maximum practicable — about 18 to 36 in (0.5 to 1 m) — is only about 5 percent, based on uniform soil resistivity. Similarly, the effect of conductor size is extremely small.

4.2.6 *Grid Systems.* Grid systems usually extend over the entire station yard and may extend some distance beyond the boundary fence. They consist of conductors buried a minimum of 6 in (152.4 mm) in the ground or stone fill and forming a network of squares. The size of the squares will vary with the voltage class of the station but cable spacings of 10 to 12 ft (3.1 to 3.7 m) are commonly used. All cable crossings should be securely bonded and the system connected to the normal ground system as well as to all equipment and structural steel work. In rock ground where driven grounds are impractical, it is sometimes more economical and desirable to use a grid system in place of buried strips in which case the cables are usually buried at a depth of 1 to 2 ft (0.3 to 0.6 m). The basic characteristics and design elements for extensive grid systems are given in Ref 6.

4.2.7 *Plates.* The preferred practice with plate electrodes is to bury them on edge since a minimum of excavation is required and it is possible to obtain better contact with the soil when backfilling. There appears to be little difference between the effective resistance of horizontal and vertical plates. For commonly used plates of 10 to 20 ft^2 (0.9 to 1.9 m^2), the optimum burial depth is 5 to 8 ft (1.5 to 2.4 m).

4.3 Methods and Techniques of Construction.

4.3.1 *Choice of Rods.* Ground rods are manufactured in diameters of ⅜, ½, ⅝, ¾, and 1 in (9.53, 12.7, 15.88, 19.05, and 25.4 mm) and in lengths from 5 to 40 ft (1.5 to 12.2 m). For most applications, the diameters of ½, ⅝, and ¾ in (12.7, 15.88, and 19.05 mm), in lengths of 8, 10, 12, and 16 ft (2.44, 3.05, 3.66, and 4.88 m) are satisfactory. The NEC specifies that rods of steel or iron shall be at least ⅝ in (15.88 mm) in diameter and that rods of nonferrous materials shall not be less than ½ in (12.7 mm) in diameter. Copper-clad steel, one of the most common types of rod, permits driving to considerable depth without destruction of the rod itself, while the copper coat makes possible direct copper-to-copper connection between the ground wire and the rod. In addition to the copper-clad steel, galvanized steel rods are available. For ease of driving the rods, some rods are available in sections; after they are driven, the rods are connected by the couplings into a continuous conductor. A removable stud will take the driving blows and avoid damage to the threads of the joint.

The effect of the rod diameter on the resistance of the connection to earth is small. The diameter of the ground rod is determined mainly by the mechanical rigidity required for driving. It is advantageous to select the smallest diameter rod which meets the driving requirements. Average soil conditions will permit the use of the ½-in (12.7-mm) rod; the ⅝-in (15.88 mm) rod can be driven in nearly all types of soil, and the ¾-in (19.05-mm)-diameter rod may be reserved for exceptionally hard driving conditions or for deep driven rods.

For ordinary soil condition, the 10-ft (3-m) length of rod has become fairly well established as a minimum standard length to meet the code requirement of a minimum of 8 buried feet (2.4 buried meters).

4.3.2 *Methods of Driving Rods.* Sledging requires a minimum of driving equipment, but may require considerable time per foot of rod. A modification of the sledging process, consisting of a chuck and sliding hammer, permits the work to be carried on at a level convenient to the workman without a ladder or auxiliary platform. An additional advantage is that the blow is delivered to the rod at a point not far from the ground line, thus permitting rods to be driven to greater depths than would be possible by hand sledging. If rods are to be driven on a comparatively large scale, it is desirable to provide power driving equipment. Electric, pneumatic, and gasoline driven hammers are available, the first two requiring sources of power. Regardless of the type of driving tool used, precautions should be taken to prevent "mushrooming" of the head.

4.3.3 *Locating Water Main (New Construction).* Prior to new construction, analysis of the soil condition and location of the grounding point may permit locating a water pipe nearby. This would eliminate a long grounding line (to a distant water main) with its inherently high inductance. The economic advantage of such an arrangement should not be overlooked.

4.3.4 *Connecting to Electrodes.* Connections to electrodes are usually made in two principal manners. The first of these methods involves the use of mechanical (bolted) fittings, which are readily available, simple to install, disconnectable for measurements of resistance to earth, and have a long history of satisfactory usage. Although corrosion has sometimes presented a problem, treatment of the joint as an ordinary electrical connection in a corrosive element eliminates most of the problems in this respect. Mechanical connections should, if at all possible, be accessible for inspection and servicing.

The second method, a thermit process of connecting to the electrode, has increased in usage in recent years because of the savings in time and costs when many connections must be made. This method provides a permanent connection, eliminates contact resistance, is relatively corrosion free, and permits the use of smaller cable because of the 450°C maximum temperature limitation as compared to the maximum of 250°C usually permitted for mechanical connections. It does, however, have certain inherent limitations. It requires separate disconnecting means, such as aboveground bolted joints, for measurements of resistance to earth. It also requires the use of a certain amount of training, and it cannot be used in the presence of volatile or explosive mixtures, or where the gaseous products of the operation would interfere with nearby operations.

A third method that utilities are presently experimenting with involves the use of a copper or copper-alloy connector which is squeezed onto both ground rod and cable simultaneously by a hydraulic press. This method is economical, presents most of the advantages of the thermit process, and eliminates most of the objections to that process.

Other methods of joining, such as brazing or welding, are satisfactory if properly done.

4.3.5 *Joining to Underground Piping Systems.* Joining to pipe presents several problems. Clamp-type fittings are relatively expensive, since they must obviously accommodate large pipe in addition to the relatively small conductor. Welding or brazing to the pipe will cause localized stress, which may impair the function of the pipe, particularly if it contains fluid under high pressure. A typical welded connection to water pipe is shown in Fig 21.

4.3.6 *Joining to Structural Steel.* Bolted fittings lend themselves best to structural steel that can be field drilled but not welded. These are available in a number of shapes and sizes to accommodate the range of conductors. Material for the clamps, or protective finishes applied to the clamps, should be chosen so as to be satisfactory, from the corrosion standpoint, to both the grounding wire and the steel or iron. Brazing and the thermit process are also used in connecting to structural steel, but should be restricted to applications which will not affect the structural properties of the steel.

4.3.7 *Preparing the Joint.* It is important that the surface of any connection be cleaned of any insulating medium, such as insulation, grease, paint or dirt, before making the connection.

4.4 Measurement of Resistance to Earth

4.4.1 *Need for Measurement.* In any formula for the determination of the resistance to earth there are many indeterminate factors, and too much reliance should not be placed upon the calculated results. The only

Fig 21
Typical Method of Grounding to Large Ungrounded Water Pipe Using Welding Method

certain way is to measure the resistance after the system has been completed. A desirable refinement would be to measure the resistance of each electrode during installation.

4.4.2 *Methods for Measuring.* The principles used in the measurement of resistance to earth are essentially the same as those used for measuring other types of electrical resistances. The various methods available all make use of two auxiliary electrodes in addition to the one under test and may be grouped into the following three general classes:

(1) The three-point method, in which the resistance to earth of the electrode under test and the auxiliary electrodes are measured two at a time in series. This method is suitable for measuring the resistance to earth of isolated ground electrodes or small grounding installations. It is not suitable for the measurement of low-resistance installation.

(2) The fall-of-potential method, which involves passing a known alternating current through the electrode under test and one of the auxiliary electrodes, and measuring the potential drop between the former electrodes and a secondary auxiliary electrode set at various distances between the two fixed electrodes. This method may be subject to considerable error if stray ground currents are present, or if pipes or other conductors are buried near the test electrode.

(3) The ratio method, which involves measurements of the ratio of the resistance to earth of an auxiliary test electrode to the series resistance to earth of the electrode under test and a second auxiliary electrode. Multiplying this ratio by the series resistance gives the effective resistance of the ground electrodes. This method is more satisfactory than triangulation methods, since ratios of test electrode resistance to the resistance of the electrode under test may be as high as 300:1.

A more complete treatment of the details of these three methods may be found in Ref 9.

Commercially available portable testing instruments provide the most convenient and satisfactory means for measuring the resistance of connections to earth. Instruments used for measuring insulation resistance are not suitable, however, because they cannot measure sufficiently low resistance values. Precision in measurements of resistance to earth is difficult to obtain and is usually not required. Measurements in the order of 1, 10, or 100 Ω are generally indicative of the adequacy of the connection.

It is desirable, in measuring the resistance of the completed system, to allow some time to elapse before measurements are made, so that the earth around the electrodes will be consolidated.

4.4.3 *Periodic Testing.* Test should be made periodically after the original installation and test, so that it can be determined whether the resistance is remaining constant or is increasing. If later tests show that the resistance is increasing to an undesirable value, steps should be taken to reduce the resistance either by additional electrodes, by increasing the moisture content, or by chemical treatment.

4.4.4 *Cathodic Protection.* Any discussion of cathodic protection is beyond the scope of this standard. For information, see Refs 7 and 8.

4.5 Standards References. The following standards publication was used as a reference in preparing this standard and is useful in the interpretation of its meaning:

ANSI C1-1971, National Electrical Code (NFPA 70-1971)[11, 12]

4.6 References

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[11] American National Standards Institute
1430 Broadway
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60 Battermarch Street
Boston, Mass. 02110

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