Ultra-High Voltage Transmission

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IV. OVERHEAD LINES AND SUBSTATIONS

Ultra-high voltage transmission

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[Plates 14 and 15]

Prospects for ultra-high voltage (1000 kV and above) a.c. power transmission are discussed, and the problems involved in developing and constructing this u.h.v. transmission are reviewed. Research above 1000 kV is concerned with minimizing the impact of u.h.v. lines on the immediate environment, particularly radio and audible noise emission due to wet-weather corona effects, and electrostatic induction phenomena near the lines. The paper reviews the design constraints now envisaged to avoid these problems, as well as insulation requirements that may be necessary. No specific technical limitations through 1500 kV have yet been encountered, although the formation of power corridors with limited public access may be necessary above 1500 kV.

1. Introduction

In the United States ultra-high voltage (u.h.v.) transmission is generally defined as transmission of electrical energy at a.c. voltages exceeding 1000 kV phase-to-phase. There now seems little question whether transmission above 1000 kV will become a reality in the United States and in Europe – the only questions are when and in what form? This paper will discuss primarily the situation and research programme applying to u.h.v. transmission problems in North America; Forrest (1972), Paris (1972), Gary, Claude & Magnien (1966), and others have presented the perspective in Britain and on the continent.

One major incentive for adoption of u.h.v. transmission in the United States comes about as a direct result of the present energy crisis. As a result of rapid electric growth combined with environmental restrictions on the use of domestic coal resources, the United States is now facing an energy shortage of major proportions, forcing it to convert to nuclear generation of electric power as quickly as possible. About 60 % of all large thermal generation now being committed in the United States is nuclear (Seaborg 1973). Location of nuclear plants presents a major problem, and they may be far from population centres. The difficulties of siting nuclear plants has fostered the concept of 'nuclear parks', having total capacities of 4000 to 20000 MW or more located in a single complex, sharing cooling water, fuel processing, and other facilities. Carrying electrical power from such complexes will exceed the capacity of present transmission lines in the United States, and can force transmission voltages into the u.h.v. range to attain the needed capability.

Another factor encouraging the utilization of u.h.v. transmission is an inability to obtain land for transmission right-of-way construction. This necessitates increases in transmission voltage to maximize the power that can be carried over existing rights-of-way.

Adoption of u.h.v. transmission is also encouraged by the growing necessity for strong transmission ties between regions. One can broadly classify United States electric power production and consumption into six regions with 1971 average generating capacities of 39000 MW per region. To tie one region to another in order to take advantage of time and seasonal diversities of peak loads and to limit the installation of extra generation in each region, regional tie lines of 6000 MW or more have interesting economic possibilities as the generation capacity in each region continues to grow. This is approximately the surge impedance loading of one 1100 kV a.c. line.

Still another factor is the growth in generator unit sizes. Concentration of generation in a few very large machines permits economies of scale. However, in case of failure or unscheduled outage of such a machine, the resulting power deficiency must be made up by transmission from other plants; and hence, the larger the generation, the greater must be the transmission capability that is associated with it. The close relation between generator unit sizes and maximum transmission voltages is reproduced in figure 1 from a previous paper (Anderson, Zaffanella, Juette & Kawai 1971). From this curve, 1200 kV transmission should appear about 1980 when largest generator sizes reach 2000 MW.

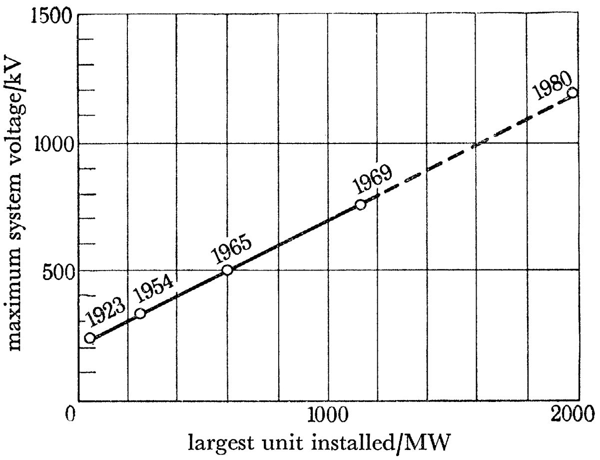


Figure 1. Relation between highest transmission voltages and largest generator unit sizes.

2. Project UHV

To obtain advanced research and design data on u.h.v. a.c. transmission for the United States network, the Electric Research Council through its Edison Electric Institute members and the Bonneville Power Administration has funded a 7-year research effort at 'Project UHV' (Anderson & Schamberger 1970; Anderson, Doyle & O'Brien 1972). Now in the final year of its present contract, the objectives of this project are to investigate the electrical and environmental design problems for 1000 to 1500 kV transmission and to supply a comprehensive design book to the industry at the end of 1973. Located in the Housatonic Valley, south of Pittsfield, Massachusetts, Project UHV has been a focal point for much of the American work (figure 2, plate 14). It is staffed by 14 engineers and technicians, and they in turn draw additional assistance on a subcontract basis from other technical organizations as required.

A key component at Project UHV is a 1500 kV (870 kV to ground) single-phase 33 MVA 2550 kV BIL auto-transformer (figure 3, plate 14). This power transformer supplies power to either an overhead test line (figure 4, plate 14), u.h.v. and e.h.v. corona-testing cages (figure 5, plate 14), or a u.h.v. insulator pollution testing chamber (figure 6, plate 14) at 3-phase equivalent voltages ranging from 750 to 1500 kV according to the setting of a voltage regulating transformer. It is protected from excessive switching and lightning overvoltages by an adjacent 900 kV free-standing surge arrester. A 5000 kV 250 kJ outdoor all-weather surge generator and a large test tower were also constructed for impulse and switching surge tests on long insulators and air gaps (figure 7, plate 14).

The transformer and overhead test line (figure 3) have been operating single-phase for the past 7 years of research to evaluate corona problems before converting to a final 3-phase system. This has proved to be a productive decision, since it saved a large amount of money, greatly simplified the changing of conductor configurations, permitted more precise calibration techniques, avoided the confusion of data that frequently occurs when 3-phases are simultaneously interacting with one another at different gradients, and permitted direct comparison of line and corona cage test results. It is a relatively simple matter to convert single-phase results to equivalent 3-phase performance once the various corona effect equations and curves have been obtained, although it is obvious that the results must eventually be evaluated on an experimental 3-phase system as a final check. Requirements for expansion to 3-phase 1500 kV transmission are now being examined to complete the research programme.

More details of this research facility have been described by Anderson, Doyle & O'Brien (1972). General Electric contributed extensively to this project by its construction of Project EHV – from which the present facility derives – and also constructed the 5000 kV surge generator used for the insulation tests.

3. Partial results of Project EHV research

(a) *Corona effects*

The four most significant corona effects on a u.h.v. line are audible noise (a.n.) emission from conductor water drops, radio noise (r.n.) emission, corona losses, and wet-weather television interference (t.v.i.). Some corona induced vibration has also been noted under certain conditions. Reduction of these four major corona effects to acceptable values will require bundles of six or more conductors per phase, (primarily for audible noise reduction) at diameters and

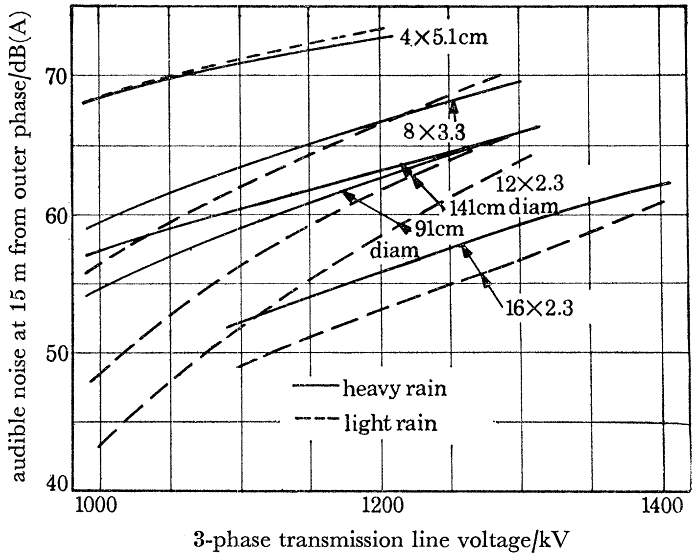


Figure 8. Audible noise at 15 m from u.h.v. transmission lines computed using u.h.v. test line results.

voltages shown in figure 8 if the bundles are symmetrical. A very significant advance in study of corona effects occurred with the demonstration by Balderston, Schamberger, Juette & Zaffanella (1972) that corona testing cages (figure 5) correlate well with the same corona effects on an overhead test line. Since these cages are smaller and much easier to string than an overhead line, provide more careful control of fields, operate at a lower voltage, and permit the injection of artificial rain, the demonstration of this correspondence has greatly speeded-up u.h.v. corona research. The primary function of an overhead test line then becomes one of calibrating the corona testing cages where work can be done with much higher efficiency.

(i) *Audible noise (a.n.)*

Audible noise emission from u.h.v. lines is most noticeable in light rain, fog, snow, or after rain but before the water drops have had time to evaporate. Noise in light rain or after rain can sometimes equal or exceed the noise in heavy rain if conductor gradients are high enough. The noise has two components, a random noise from the individual corona streamers and a hum created by field-induced motion of space charge (figure 9). Maximum sound pressure levels at the edge of the right-of-way are now under study. Comber & Zaffanella (1973) have been able to obtain substantial reductions in audible noise emission (up to 6 dB) by arranging the conductors asymmetrically within the bundle (figure 10). By compacting the conductors closer together on the underside of the bundle and separating them more on the upper side of the bundle, the gradients on the undersurfaces of each conductor where the water drops cling are better equalized and the water drop corona noise is reduced. Asymmetry can also be introduced by changing conductor diameters within the bundle or by not making the bundle circular. It is becoming increasingly clear that an insistence on symmetry in u.h.v. bundles may exact a substantial noise and economic penalty. Audible noise only reduces about 3 dB with each doubling of the width of a single-circuit right-of-way, so purchasing additional land can be an expensive method of reducing this problem.

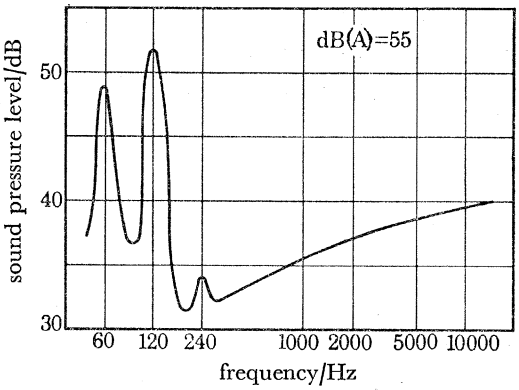


FIGURE 9. Audible noise spectrum from an eight-conductor u.h.v. line – taken at 1/10 octave bandwidth – dB above 20 μPa (0.0002 μbar).

(ii) *Radio noise (r.n.)*

Given present American environmental preferences, it appears likely that if audible noise criteria are met for u.h.v. lines, radio noise performance will also be satisfactory. This will also hold if asymmetrical bundles are used, provided it is the wet-conductor radio noise that is of primary concern. Figure 11 provides an example of radio noise values for different numbers and sizes of conductors. These curves apply for rain conditions. For fair weather noise on aged conductors, the lack of corona sources can reduce these values 17 to 20 dB, and the noise level can in addition vary by as much as ± 6 dB because of seasonal changes in quantity and type of noise sources that attach to the conductor.

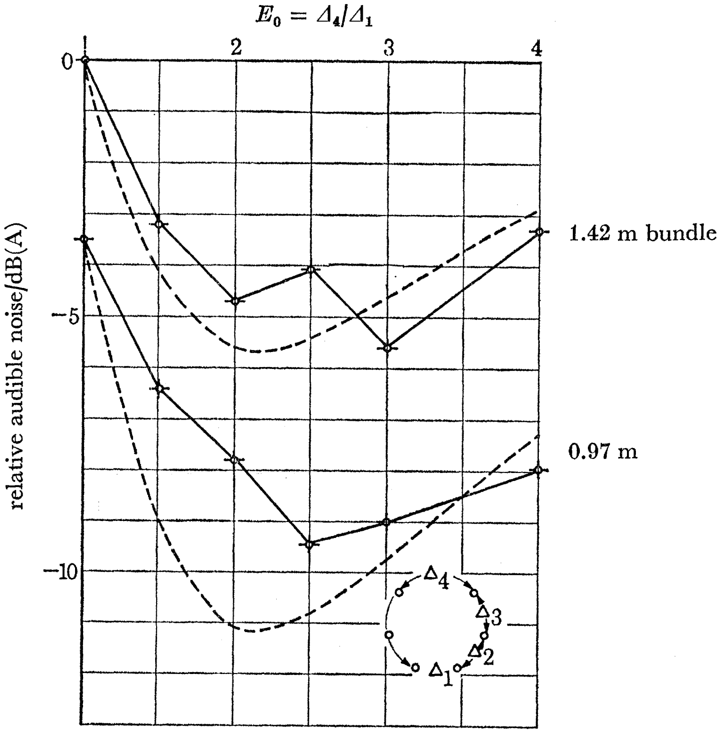


FIGURE 10. Measured (—) and computed (----) relative audible noise performance of a six conductor (6 × 4.57 cm diam) bundle with varying degrees of asymmetry, E_0.

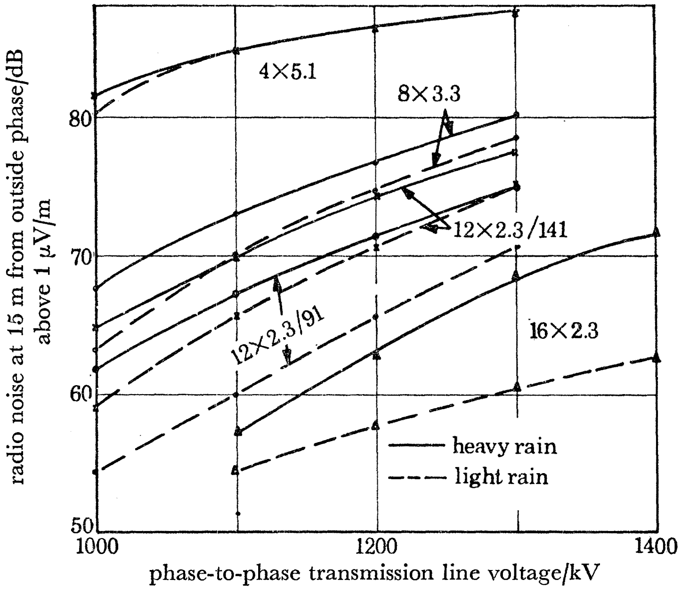


FIGURE 11. Radio noise (1 MHz, 5 kHz bandwidth) at 15 m from u.h.v. transmission lines computed using u.h.v. test line results.

(iii) *Corona loss*

Corona losses in rain on u.h.v. lines are shown in figure 12. These corona losses can vary widely with the weather pattern. For a case where rainfall covers 160 km of an 1100 kV u.h.v. line, the corona loss can be about 60 MW, depending on distribution of the rain. Since such a line has a surge impedance load of about 6000 MW, this is comparable to a loss of 1 % of surge impedance load. In general, the corona losses on e.h.v. and u.h.v. lines represent a penalty in two ways – the extra generation capacity that must be supplied to make up this loss during times of peak load, and the additional fuel that must be supplied whenever the loss occurs. The efficiencies of u.h.v. transmission lines are comparable or superior to existing e.h.v. lines in the same situation.

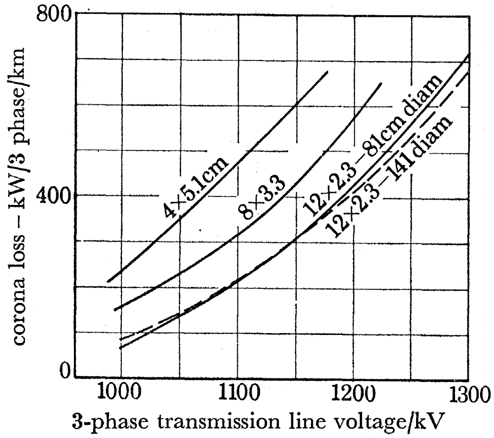


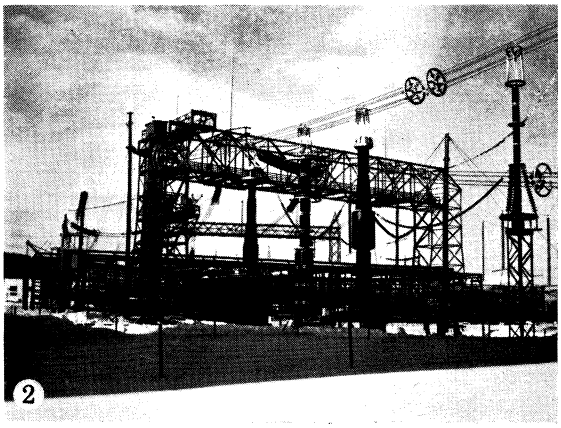
FIGURE 12. Corona loss average in rain on u.h.v. transmission computed using u.h.v. test line results.

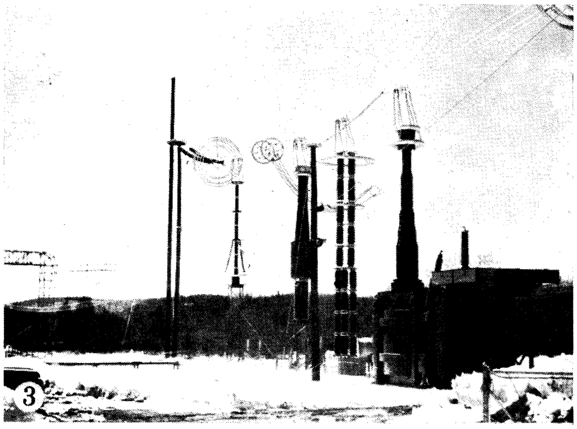
(iv) *Television interference (t.v.i.)*

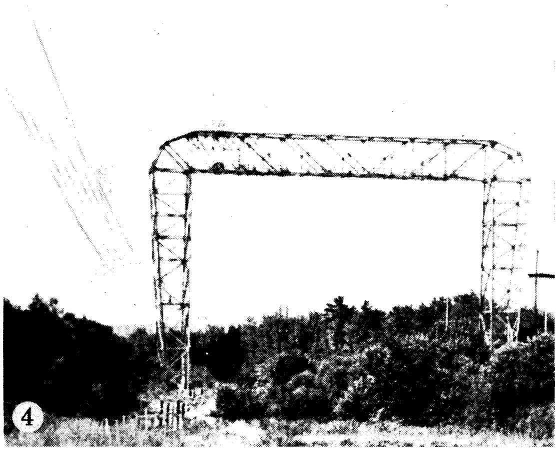
Measurements on American experimental u.h.v. lines thus far show that television interference cause by conductor corona will not be a significant problem, except perhaps in unusual circumstances. Juette (1971) made an extensive investigation of this subject at Project UHV. Figure 13, plate 15, shows the pattern of television interference that can be created by positive and negative corona in the vicinity of an experimental u.h.v. line in strong wet-weather corona. The positive polarity corona pulses on the upper part of the screen are stronger but more infrequent than the band of negative polarity Trichel discharge signals on the lower part of the screen. T.v. interference should only be noticed in very weak t.v. signal areas where high-gain directional antennas must be employed that are pointed toward a u.h.v. transmission line because of the location of stations beyond it. Little interference is likely in areas of even moderate signal strength.

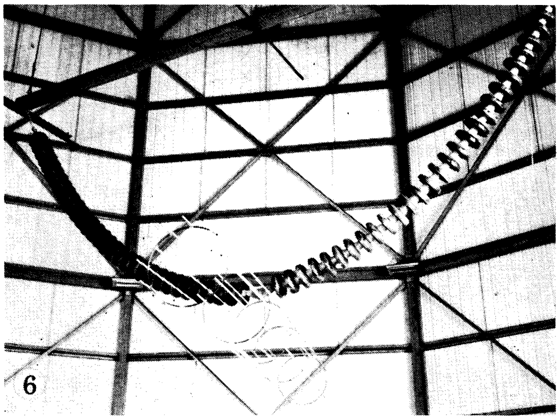
(v) *Corona-induced vibration*

Occasional instances of corona-induced vibration have been observed and the mechanism has been modelled in the laboratory. Four coincident conditions are required: rain, a certain range of conductor gradients, a favourable natural frequency of vibration, and a low initial amplitude of vibration (at high vibration amplitudes, the water drops are shaken too rapidly from the conductor and the vibration decreases). Peak-to-peak amplitudes can reach 2 cm with a natural frequency in the vicinity of 5 Hz. As the conductor with water drops on its under-









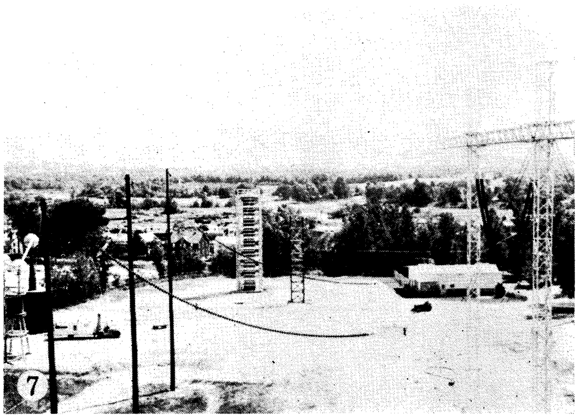


FIGURE 2. A view of Project UHV – a 1000 to 1500 kV transmission research project in Pittsfield, Massachusetts.

FIGURE 3. A single-phase $1500/\sqrt{3}$ kV 2500 kV BIL autotransformer and its associated 900 kV surge arrester and measuring devices.

FIGURE 4. A single 1300 kV 400 m bundle suspended for corona tests (16 subconductors 2.3 cm diameter with a bundle diameter of 1.4 m).

FIGURE 5. A corona testing cage for tests on bundles up to 1500 kV and 2 m bundle diameter.

FIGURE 6. U.h.v. insulators suspended for pollution-testing in a fog chamber (chamber is 26 m high and 26 m in diameter).

FIGURE 7. Outdoor surge generator and insulator – air gap testing tower.

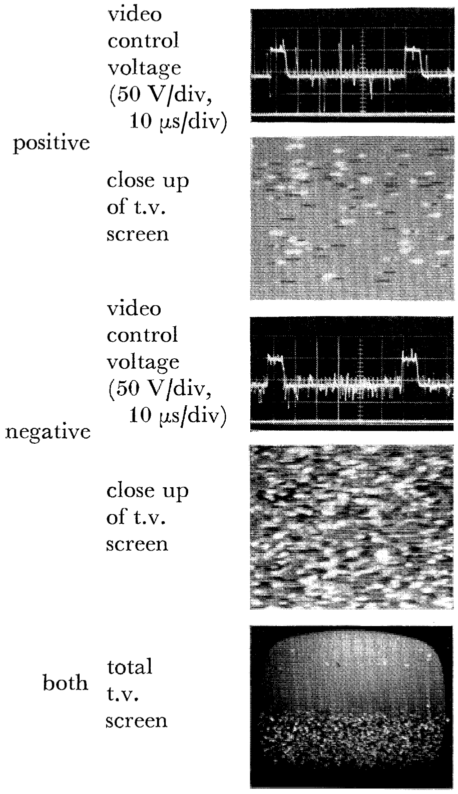


FIGURE 13. Pattern of television interference in a very weak t.v. signal area caused by wet-weather corona on an experimental u.h.v. line. Upper pattern – positive discharges, lower pattern – negative discharges.

surface reaches the bottom of its trajectory, it is undergoing maximum deceleration. This deceleration causes the water drops to elongate beyond the elongation created on them by the electric field, making them better corona points. The extra corona bursts caused by these points then – by rocket action – impart upward momentum to the conductor. Some of the droplets may actually be ejected from the conductor surface. As the conductor then reaches the upper part of its path it again decelerates and the water drops tend to flatten against the undersurface, reducing their capability as corona producing points. This unbalanced corona action can sustain the vibration. However, it does not, at this time, appear to have consequences as severe as those created by wind-induced vibration, sub-conductor oscillation, or galloping of the entire bundle.

(*b*) *Electrostatic effects*

Electrostatic fields from u.h.v. transmission lines set strong constraints on the geometry and costs of u.h.v. transmission. Prominent among these are the electric fields at the surface of the earth at mid-span beneath these lines. Figure 14 provides an example of the magnitudes of these fields for standard horizontal line configuration arrangements. For a 525 kV line, maximum earth gradients reach about 8 kV r.m.s./m; for a 765 kV line, about 10 kV/m; and for an 1100 kV line they reach about 14.0 kV r.m.s./m, if existing technologies are simply extended.

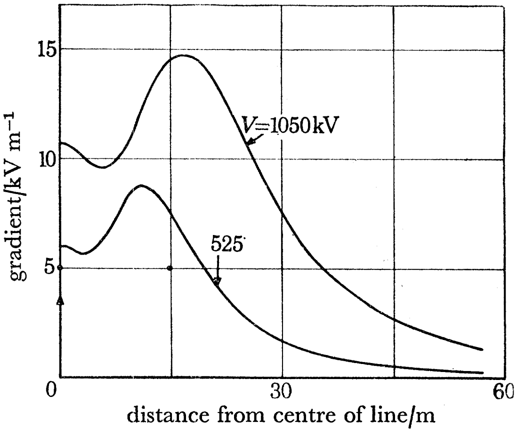


FIGURE 14. Comparison of electric fields at the surface of the earth under 525 and 1050 kV lines.

From a random sample of 20 people, the threshold of perception of these fields is about 15 kV/m – although this varies widely with weather conditions, type of clothing, and physiology. Above this value one senses a tingling of the skin, body hairs move, and weeds and grasses sometimes create microsparks to the legs. A gradient of 15 kV/m can also induce a charging current of about 5 mA from a large truck through a short-circuit path to ground, and a charging current in excess of this value could be unsafe in some circumstances. The maximum earth surface gradients under u.h.v. lines (without restriction of access to the right of way) must undergo careful study in the next few years, because these studies of electric fields will have a direct bearing on the upper limits of u.h.v. transmission. An I.E.E.E. Working Group (1971) has been actively studying this problem.

(*c*) *Insulation requirements for u.h.v. transmission*

Insulation research for u.h.v. transmission has been very extensive during the past 10 years, and the results are distributed through the references in this paper. U.h.v. insulation will – as for lower voltage insulation – be subjected to three types of electrical stress: lightning overvoltages, transients created by switching or short-time system transitions of state, and the steady power-frequency voltages. Lightning transient voltages and insulation requirements to withstand them are sufficiently well known for most design purposes, and consequently little attention has been paid to them from the research point of view. The switching surge and power frequency voltage insulation requirements are undergoing the most investigation, summarized briefly as follows:

(i) *Switching surge effects*

Figure 15 presents typical flashover characteristics of long insulator strings and u.h.v. tower air gaps as a function of gap length. These curves are influenced by wave shape, width of the tower leg, meteorological conditions, and other factors for which correction curves have been developed and described in the literature by Kachler, LaForest & Zaffanella (1970, 1971 *a*, *b*), Annestrand, LaForest & Zaffanella (1971), Dillard & Hileman (1970), Barnes & Thoren (1970), and others. The work of Barnes & Thoren (1970) describes an additional u.h.v. research activity funded in the United States by a joint venture of American Electric Power, A.S.E.A., and the Ohio Brass Company.

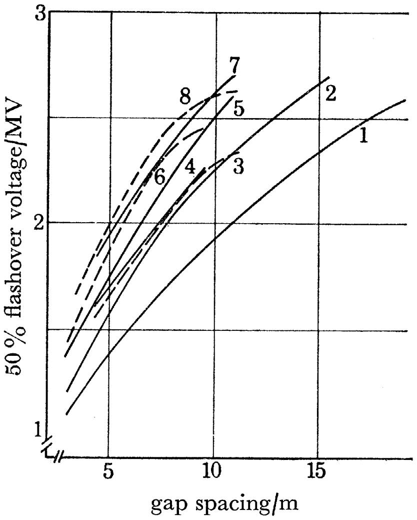


FIGURE 15. Switching surge flashover characteristics of air gaps and insulator strings for u.h.v. transmission: 1, rod–plane; 2, conductor–plane; 3, conductor–tower (centre phase V strings, tower width 1.2 m); 4, conductor–tower (outer phase); 5, vertical rod–rod; 6, horizontal rod–rod; 7, conductor-to-conductor; 8, conductor-to-tower leg.

From curves such as figure 15, it become obvious that switching surge voltages on u.h.v. systems must be suppressed to the lowest practical value to prevent the dimensions of the tower air gaps and insulators from reaching very large proportions. Figure 16 (reproduced from Anderson *et al.* 1971) shows rough dimensions of these gaps as a function of maximum system voltage and the maximum design switching surge amplitude in per unit of crest phase-to-ground system voltage. For 1100 kV and 1.6 per unit switching surges, tower air-gap dimensions can reach 6 m – which is not a formidable figure. Equivalent phase-to-phase flashover voltages against gap length are presented in figure 17, based on recent work by Boyd, Rohlfs & Zaffanella (1973). This work shows the strong dependence of the relative values of negative voltage on the flashover strength between u.h.v. buses.

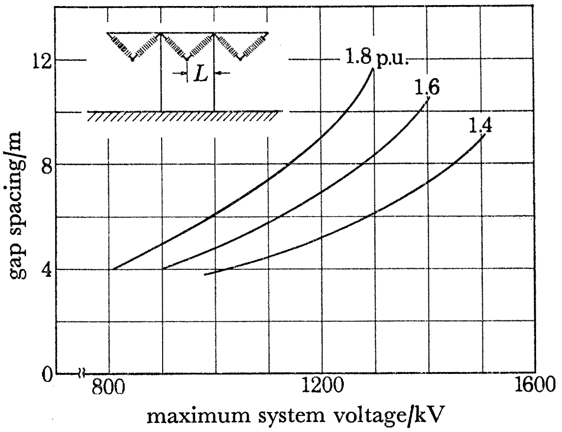


FIGURE 16. Approximate u.h.v. tower air gap spacings as a function of system voltage and per unit maximum switching surge design amplitudes.

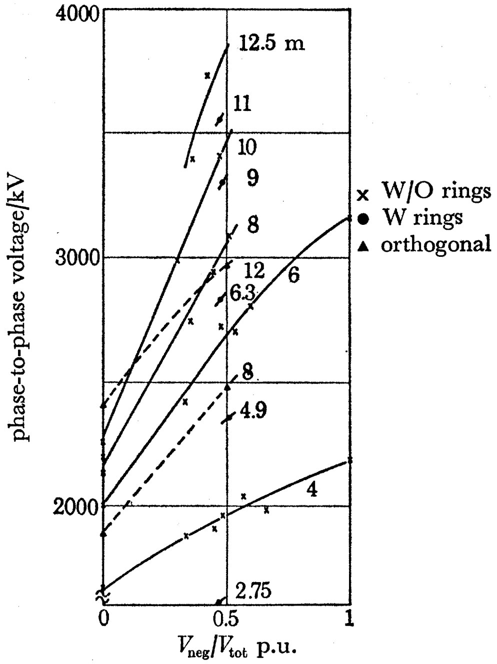


FIGURE 17. Phase-to-phase flashover voltages for u.h.v. stations with percentage negative voltage on one phase as a parameter.

(ii) *Power frequency flashovers of u.h.v. insulation*

On American 500 kV transmission systems there have been far more flashover problems at standard operating voltages than during switching operations – in fact, the latter are very uncommon. These power-frequency flashovers have been initiated by fog, dew, or a misty rain wetting light pollution layers on the insulator surfaces. When these same flashover conditions are duplicated on the much longer u.h.v. strings, Kawai & Milone (1969) have observed a pronounced nonlinearity in insulation strength with length. By use of large fog-type insulator units – with long leakage distances – the axial length of the insulator strings will be somewhat but not greatly in excess of that length necessary to withstand switching surges. In areas of heavy pollution, insulators with a semi-conducting glaze can be employed to avoid pollution flashover. However, it should be apparent that encroachment of pollution along u.h.v. transmission rights-of-way should be vigorously resisted since it could interrupt large power transfers. Design tables are now being prepared for different voltage levels and degrees of pollution to cover u.h.v. systems from 1000 to 1500 kV.

(*d*) *Mechanical vibration of u.h.v. bundle conductors*

Corona vibration of u.h.v. conductors in rain has already been mentioned. The other vibration problems of u.h.v. transmission lines will be the same ones occasionally appearing on e.h.v. systems – aeolian vibration, subconductor oscillation, and galloping. There appears to be nothing unique about u.h.v. lines in this respect, and the problems will be treated in the same way and with about the same effectiveness in both cases. However, the additional complexity of a u.h.v. bundle makes an evaluation of subconductor oscillation more difficult, and extensive research is now being done in many countries to examine this basic problem.

(*e*) *U.h.v. system characteristics*

The characteristics of u.h.v. systems are still in the formative stage. Table 1 presents a conceptual list of some line values, recognizing that many of the constraints on u.h.v. system design will be subjective ones – defined by national preference for acceptable values of radio and audible noise, electric field effects at midspan, preferred circuit-breaker characteristics, manufacturing limitations, and national power policies. Figure 18 provides a comparison of 500, 765, and 1100 kV transmission structures – assuming standard waist-type construction. The increase in height with voltage is governed by the necessity to keep midspan fields at the surface of the earth at 14 kV/m or less. A reduction in phase spacing for the 1100 kV structure in figure 18

TABLE 1. CONCEPTUAL ELECTRICAL AND GEOMETRICAL CHARACTERISTICS OF AN 1100 kV U.H.V. TRANSMISSION LINE

bundle conductor: (6) 50 mm diameter conductors arranged in an asymmetrical bundle with 92 cm bundle diameter
surge impedance: 200 Ω
surge impedance loading: 6000 MW
length of insulator strings: 9.4 m/string in V-arrangement
air gap: bundle to tower leg: 7.5 m
minimum phase-to-phase spacing: 17.5 m
midspan clearance to ground: 16.7 m
audible noise in light rain at edge of right-of-way: 60 dB (A)
height of towers: 57 m
span length: 500 m

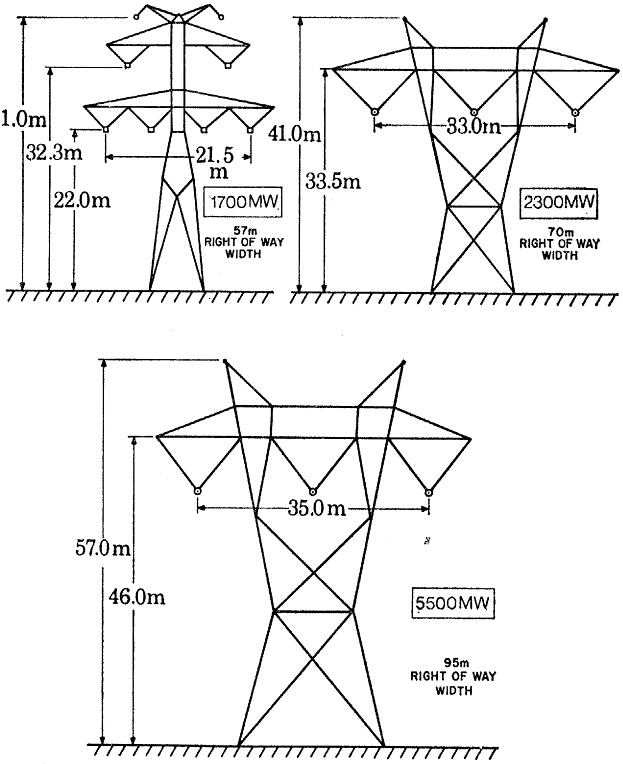


FIGURE 18. Comparison of double circuit 500, single circuit 765 and single circuit 1100 kV transmission structures assuming standard waist-type construction.

below that shown is largely an economic question. Phases moved closer together increase the electric gradients on the conductor surfaces – these fields increase the radio and audible noise, necessitating larger conductor diameters to reduce these gradients. The larger conductors weigh more and require more tower steel to hold them up, thereby increasing the cost. In addition, smaller phase spacing is contingent on use of more expensive u.h.v. circuit-breakers than can hold switching surges to the lower values that the decreased tower air gaps will require. The choice of transmission line dimensions is – as usual – dominated by economics.

4. FUTURE DIRECTIONS

Barring international debacles, the growth of u.h.v. a.c. transmission seems inevitable. In early form, it will be similar to present 765 kV transmission lines with somewhat larger towers, more subconductors per phase, longer insulators, greater ground clearances, and higher current capabilities. There will be little about it that one can categorize as unique except its size and energy capability. But what of the more distant future as population and economic pressures force a re-examination of the constraints around the problem? The design of u.h.v. transmission is largely constrained by rules that are political, economic, and environmental in nature – engineering creativity must operate within this framework and this tends to limit change greatly. Innovations in u.h.v. transmission are not likely to be dramatic unless the rules of the game are changed. One of the most significant changes would be to limit access to the transmission right of way by protective fencing. Towers of existing design would then disappear and transmission could be brought close to the ground – becoming 'overground' transmission rather than overhead transmission. Supporting structures could take more aesthetic form such as the constant gradient arch of figure 19. There are an infinite number of paths with a constant electrical gradient from a horizontal conductor to a ground plane, and some of these paths form arch-like structures that would be mechanically strong and have a kV/m gradient sufficiently low to avoid creepage flashover under the worst overvoltages. By coating these arches with a high resistance coating, the gradient could be kept constant along its surface over a

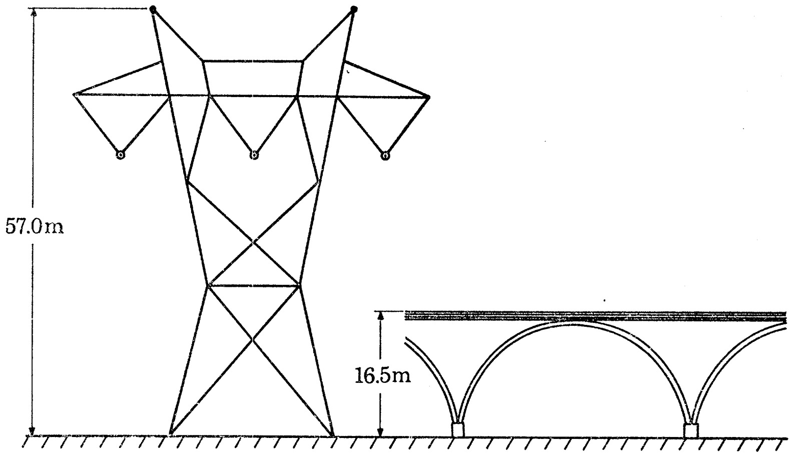


FIGURE 19. Comparison of range of options for u.h.v. transmission from standard waist-type construction to a constant-gradient arch with limited right-of-way access.

frequency range from 60 Hz to the fastest lightning transients. It would be important to maintain the lightning flashover strength of these arches higher than the mid-span air gap to ground to avoid damaging the arch from power arcs initiating by lightning. If no overhead shield wires are employed, lightning flashovers to ground would have to be cleared with special single-pole reclosing circuits, although the surge impedance of a system of this type is sufficiently low and its insulation strength sufficiently high to absorb about half the lightning strokes that contact it without flashover. Many other forms of overground transmission are possible, including gas-insulated cable. It is obvious that the sizes of u.h.v. transmission structures encourage a thorough technical and economic exploration of the advantages of gas-insulated substations for u.h.v. transmission.

Figure 19 shows the approximate range of options from conventional 1100 kV overhead construction to a constant-gradient arch design, with enough clearance to permit limited access and right-of-way maintenance under the conductors.

5. Conclusions

1. Much basic design information for 1000 to 1500 kV u.h.v. a.c. transmission is now available, although more studies are needed in all areas – particularly audible noise, electrostatic effects, contamination and mechanical vibration.
2. In the United States, u.h.v. conductor diameters will be established by audible noise emission limitations rather than radio noise or current capability. Midspan clearances to ground and possibly line geometry will be established by the need to minimize the electric field at the surface of the earth.
3. U.h.v. 1100 kV a.c. transmission structures need be only moderately wider than existing 765 kV structures, but may have to be significantly higher to reduce the earth surface gradients at midspan.
4. Substantial reductions in audible noise have been found for light rain and fog conditions by utilizing an asymmetrical bundle conductor configuration.
5. Above 1500 kV, rights-of-way may have to have limited access so that transmission line heights can be reduced to acceptable values.

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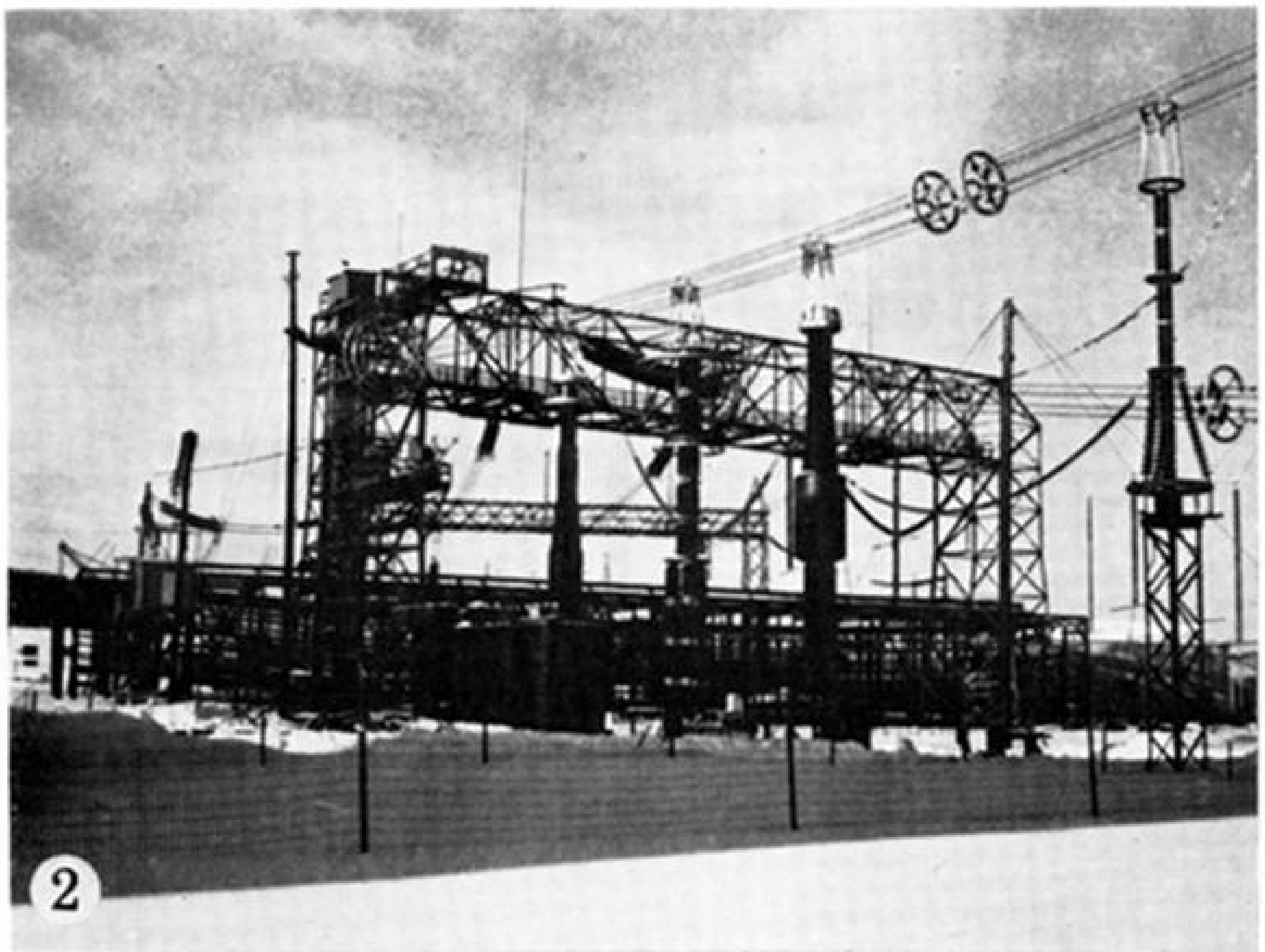
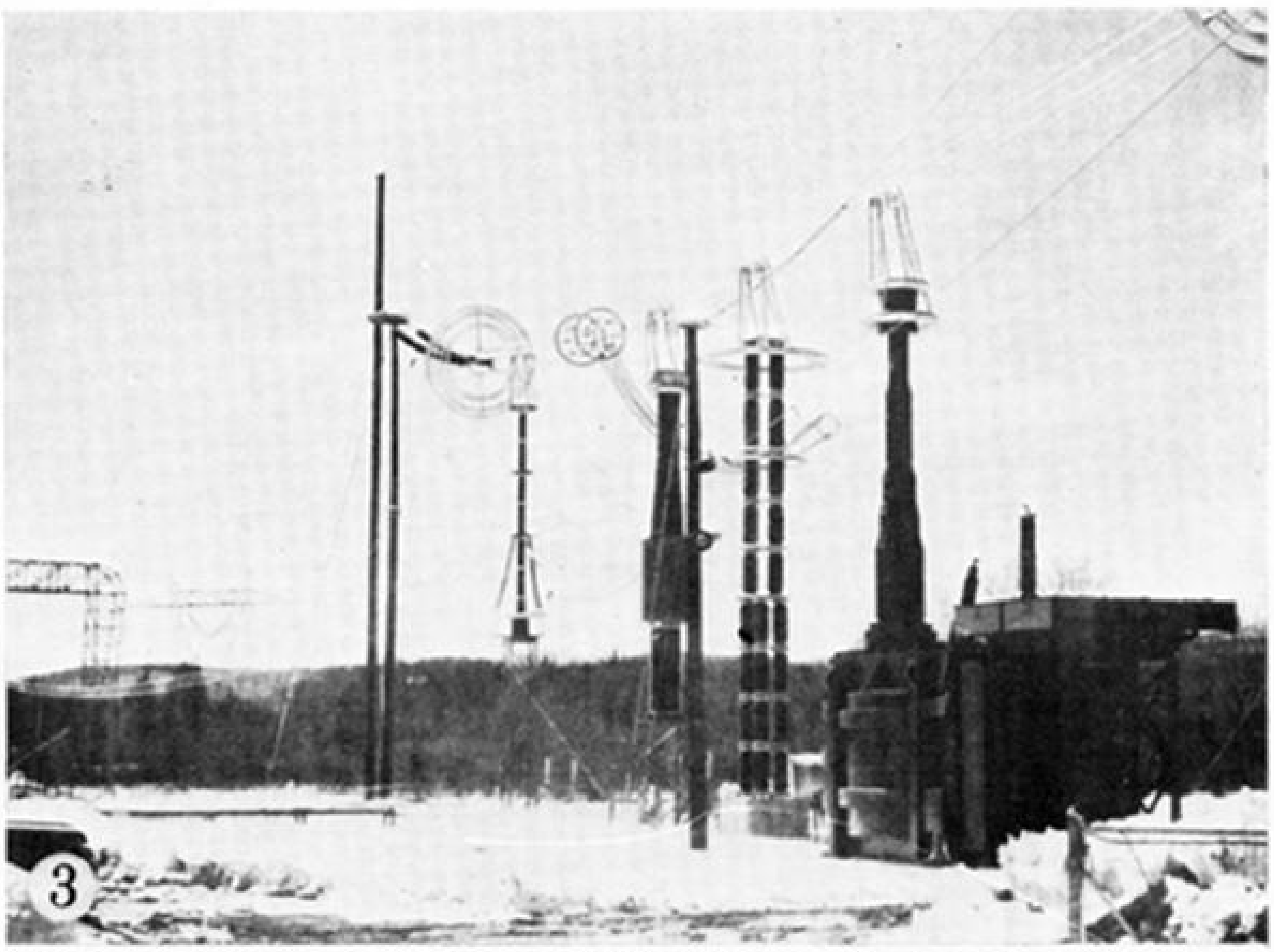
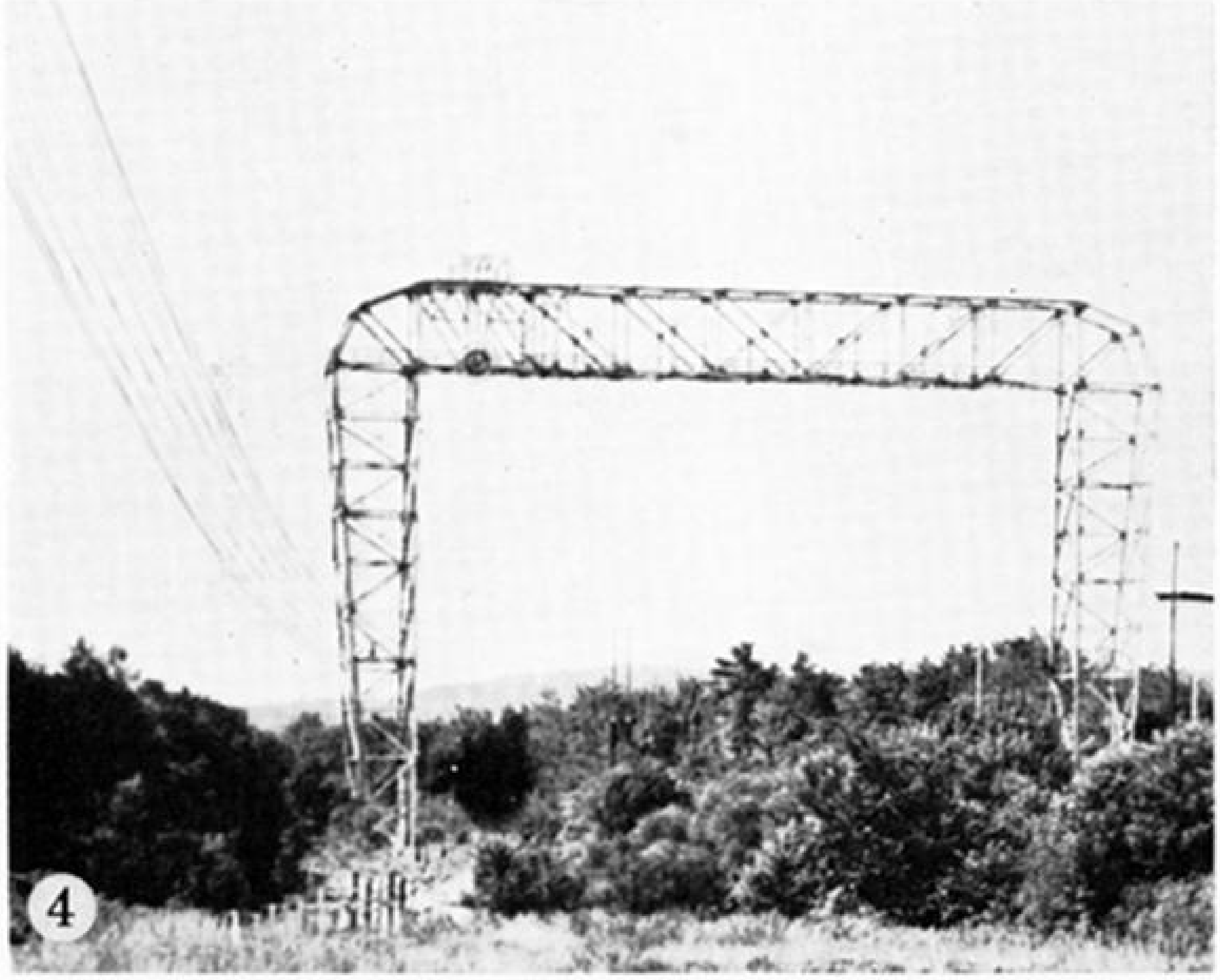
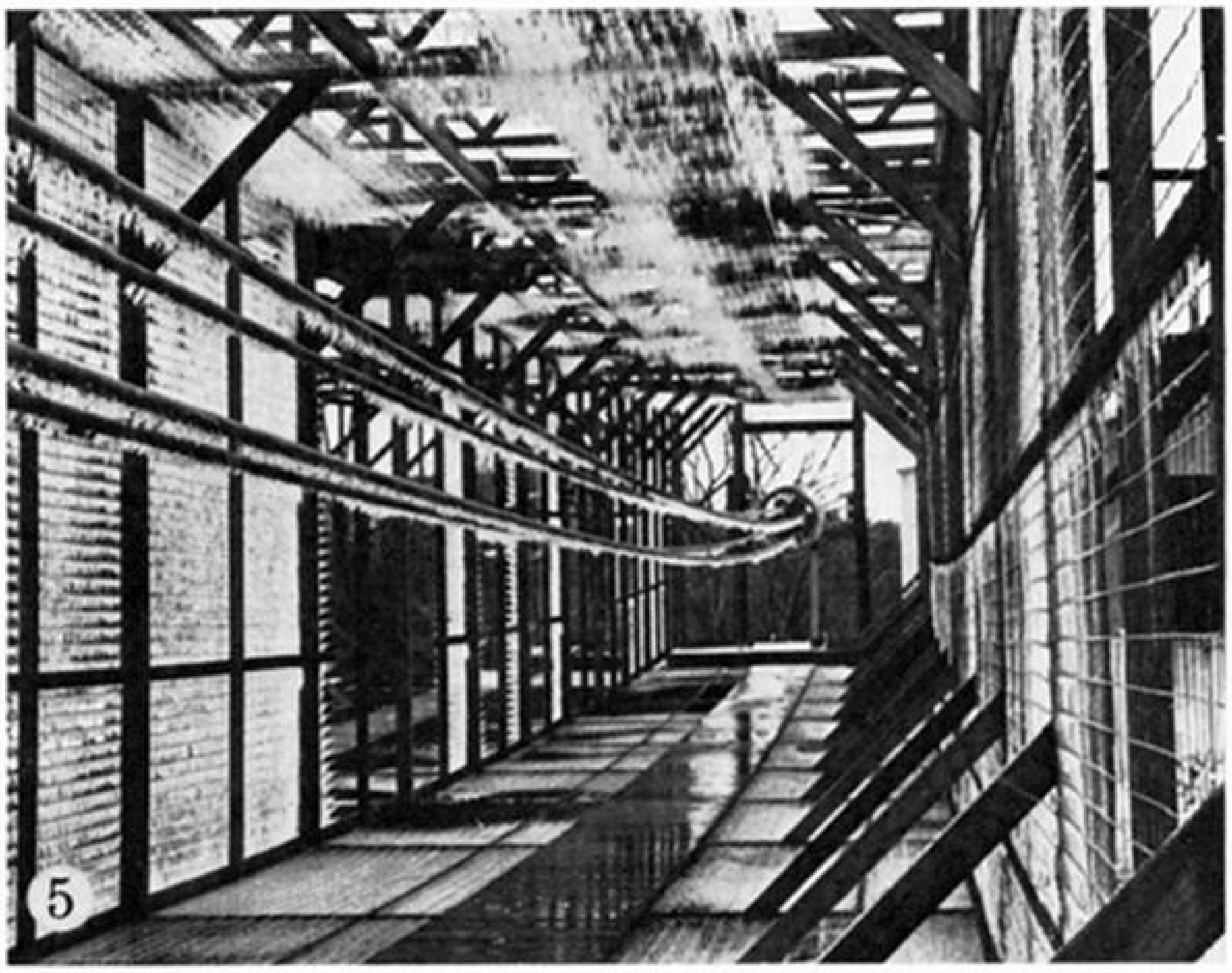








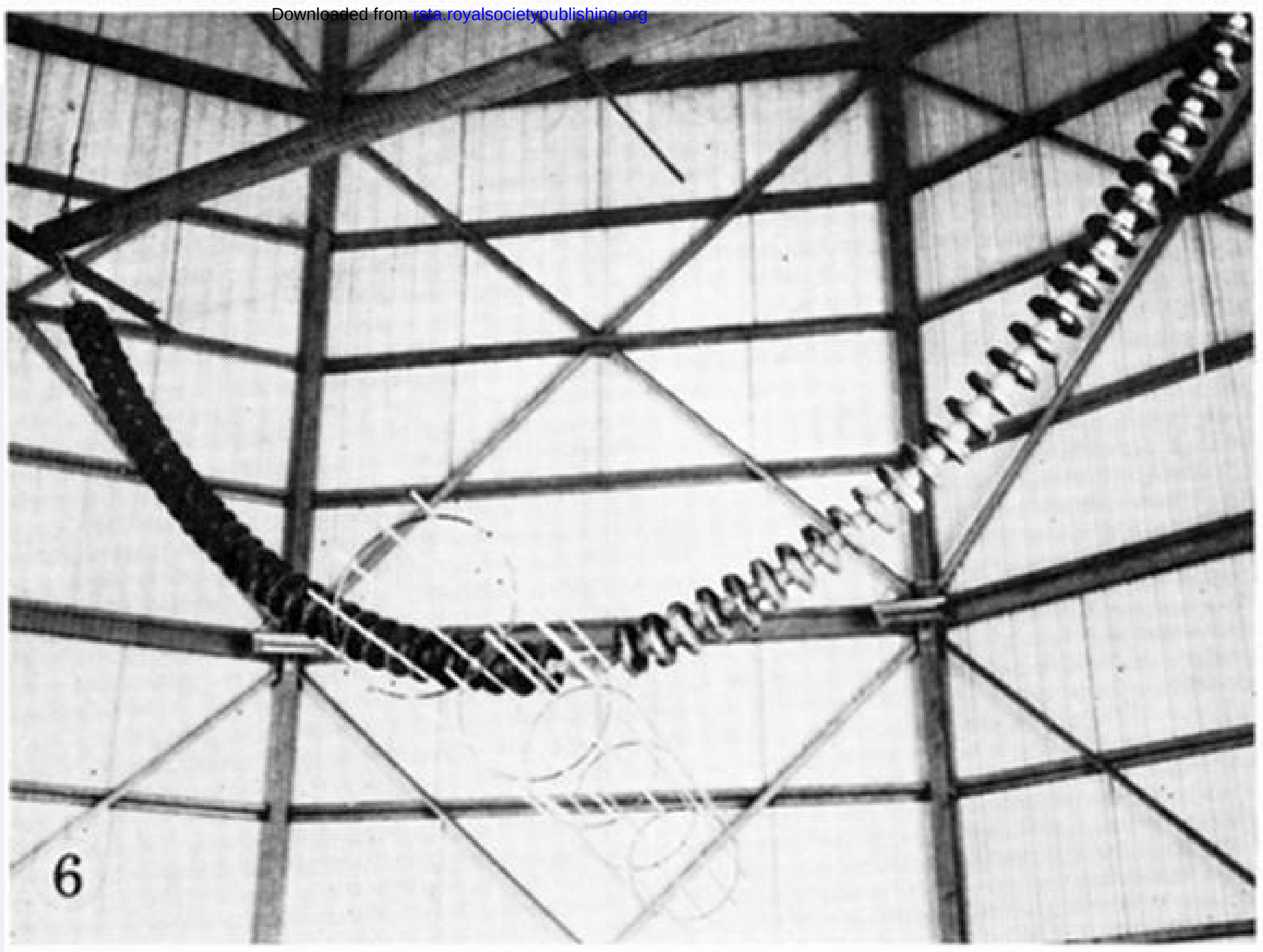


FIGURE 2. A view of Project UHV – a 1000 to 1500 kV transmission research project in Pittsfield, Massachusetts.

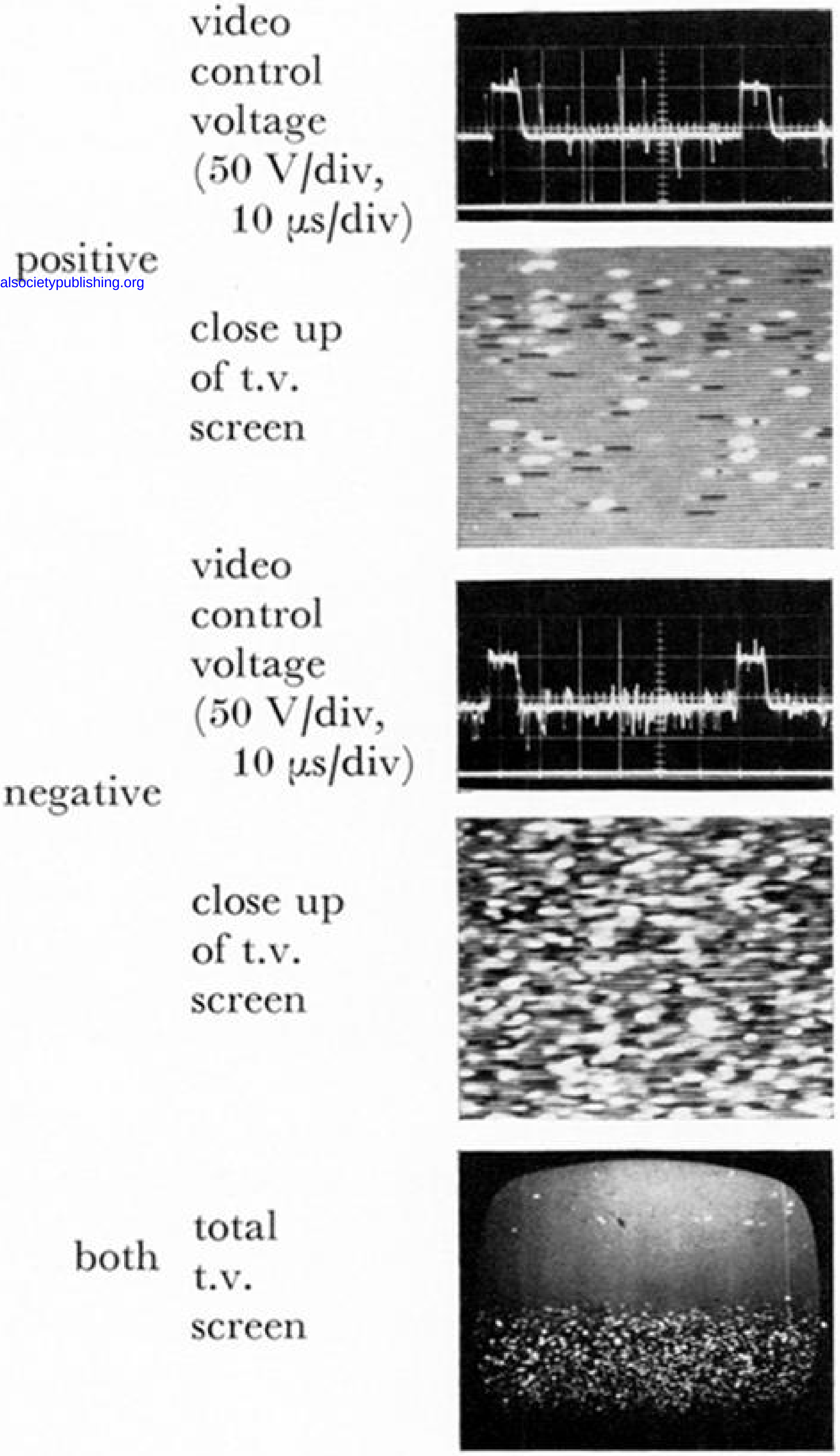
FIGURE 3. A single-phase $1500/\sqrt{3}$ kV 2500 kV BIL autotransformer and its associated 900 kV surge arrester and measuring devices.

FIGURE 4. A single 1300 kV 400 m bundle suspended for corona tests (16 subconductors 2.3 cm diameter with a bundle diameter of 1.4 m).

FIGURE 5. A corona testing cage for tests on bundles up to 1500 kV and 2 m bundle diameter.

FIGURE 6. U.h.v. insulators suspended for pollution-testing in a fog chamber (chamber is 26 m high and 26 m in diameter).

FIGURE 7. Outdoor surge generator and insulator – air gap testing tower.



IGURE 13. Pattern of television interference in a very weak t.v. signal area caused by wet-weather corona on an experimental u.h.v. line. Upper pattern – positive discharges, lower pattern – negative discharges.