AN EXPLORATION OF FUTURE ELECTRICAL TRANSMISSION AND DISTRIBUTION TECHNOLOGIES

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AN EXPLORATION OF FUTURE

ELECTRICAL TRANSMISSION

AND

DISTRIBUTION TECHNOLOGIES

FRANK J. DOYLE

Technological Forecasting Division,
Technological Forecasting and Strategy Branch,
Office of Science and Technology,
Department of Industry, Trade and Commerce.

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Table of Contents

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Introduction

The unpredededented period of post war growth in the industrialized nations of the world is a direct result of the vast and successful expansion of the energy delivery systems of these nations. Energy is the life blood of the industrial world and continued growth and development depend upon the ability of energy systems to deliver increased flows to its industrial and residential cells.

Growth of World Energy Consumption

World consumption of energy increased from 77,000 trillion BTU's in 1950 to nearly 190,000 trillion BTU's in 1968 - a growth rate of 5.5%. Per Capita consumption rose from 30.7 million to 54.5 million BTU's - a 3.5% rate of expansion. Table I lists the 1950 and 1968 data for the major industrialized nations.[1]

	Total Consumption in Trillion BTU		1968	
	1950	1968	Consumption Per Capita	% of World Consumption
Canada	2,707	6,162	296.3	3.2
United States	34,153	62,432	310.3	32.9
Western Europe	17,483	41,584	118.6	21.9
Japan	1,739	8,691	86.0	8.8
Eastern Europe	4,414	11,215	107.7	5.9
USSR	8,427	28,628	120.4	15.1
Total	62,923	158,712		87.8

While world GNP is growing at about 5% and energy consumption at 5.5%, electrical energy usage has been increasing at 8% per year.

The purpose of this study was to explore likely future developments in one of the key components of electrical energy systems - panelists were asked to state their views about the likely utilization of new technologies for the transmission and distribution of power during this century.

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1 Schurr, Sam H., "Energy, Economic Growth and the Environment", Johns Hopkins University Press, Baltimore, April 1971, p. 179.

The Dilemma of Technologists

In the early post World War II period economic and technological criteria were the principal determinants of change and the fundamental questions for decision-makers were:

- Is it technologically feasible?
- Does it have economic advantages over other alternatives?

Today the questions that decision makers face are both more numerous and more complex. Typical of the technologists' dilemma are the conflicting pressures faced by the electric power industry in developed countries. On the one hand rapidly increasing demand requires that more and more power be delivered to industrial and residential customers while at the same time environmental pressures are growing to limit the sources of power and the traditional bulk transmission structures designed to produce and deliver the required energy.

The Delphi panel in this study therefore was asked to consider not only the timing of technological developments, but also the impact upon the implementation of feasible future technologies of more subtle factors such as environmental demands, the evolution of societal attitudes, economic factors and political pressures before coming to a decision about the likelihood of a development being adopted.

Forecasting is an attempt to describe the nature, shape and timing of future events. The delivery systems for electrical power are the energy highways that allow industrialized nations to exist and grow and are so critically important to society that it is essential that decision makers in government and industry have access to forecasts of probable developments soon enough to allow long range plans to be formed and implemented. This study was made to help provide such information.

The specific areas examined in the study were:

- Use of AC and DC transmission.
- The evolving mix of underground and overhead transmission.
- Future trends in Ultra High Voltage transmission technologies.

- Developments in transformer and conversion technologies.

Methodology

Traditionally planners have relied upon quantitative projections of past trends to establish the parameters of the future. This approach has three problems.

a. In a world where the basic values in developed societies seem to be changing at an accelerating pace, substantial discontinuities might be expected to make the future significantly different from the past.

b. Affluence creates more alternatives, which, in wealthy nations, means that choices will more often be deliberately made from the available technological options based upon other than economic criteria. Projections cannot reflect the results of this choosing process.

c. Extrapolations of past trends are more useful when forecasting on a Macro basis for the whole economy as minor conflicting trends tend to balance out, but are unreliable when forecasting developments in a relatively small segment of the economy.

For these reasons qualitative forecasts, based upon a systematic evaluation of the interacting variables by qualified individuals, are becoming a much more important weapon in the planners arsenal. The Delphi technique, used in this study, is the best available technique for the systematic collection and analysis of qualified opinion in a given field. Delphi has been used extensively in government and business forecasting. A wide spectrum of subjects has been explored including computer developments, future educational and medical technology, and social change. The results from a Delphi study (or any other forecast) should be considered as an analytical input to, not as a substitute for, management decision making.

The Delphi Technique

Delphi was developed at the Rand Corporation by Olaf Helmer and Norman Dalkey. Essentially it was a method for developing and improving consensus on any numerical estimate. With the Delphi method a panel of individuals, who are knowledgeable in the area to be explored, forecast likely developments in that field. The distinguishing feature of the technique is that it utilizes two or more rounds of questionnaire to explore the opinions of the panel with statistical data and summaries of views of the other panelists being fed back to individual participants after each round. This procedure creates a modified form of group interaction and exchange of views. It, at the same time, removes many of the counter productive elements presents in face to face meetings such as the effect of status, group pressures to conform to majority opinion, the persuasive or dominant personality who may be quite wrong, and many other interpersonal variables. It replaces these influences with some distinctly different characteristics - notably anonymity, interaction and controlled feedback - all of which tend to foster calm, contemplative consideration of the issues. Reasonably comprehensive evaluations of the technique have found that it is a significant improvement over normal group meetings both in terms of arriving at a group consensus and in improving the accuracy of forecasts. [2]

In this study two rounds of questionnaire were used as follows -

Round I - posed a number of possible developments and requested the panelists to estimate whether or not the developments would occur and if so, the range of probabilities of occurrence over a thirty year time frame. Participants were also asked to suggest other possible events or developments to be included in Round II.

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2 Campbell, Robert M., "Methodological Study of the Utilization of Experts in Business Forecasting, Unpublished Ph.D. dissertation, University of California, Los Angeles, September 1966.

Round II - The median and interquartile range of answers, along with the comments, were fed back for each question. Panelists were asked to reconsider their answers in the light of the group opinion and came to a final conclusion for each question.

The Panel

It is clear that the quality of the results of a Delphi study depends entirely upon the calibre of the participants. Selected individuals with experience and skills in administration, research, planning, and engineering in the electrical power field from Canada, the United States, Great Britain, Sweden, France, Italy and Japan participated in this study. Respondents were asked to allow their names to be listed as participants. Those who agreed were:-

Mr. Keith Alexander,
Canada Wire and Cable Limited,
Noranda Research Centre,
Pointe Claire, P.Q. Canada

Mr. John G. Anderson,
General Electric Company,
Schenectady, New York. U.S.A.

Mr. Nabuo Anduo,
Hitachi Cable Ltd., Hitachi-Shi,
Ibaraki-Ken, Japan.

Mr. Franco Ariatti, E.
E.N.E.L. - D.P.T.,
Via G.B. Martini, Roma, Italy.

Mr. K.A. Austin,
Balfour Beatty Co. Limited,
Thornton Heath, Surrey, England.

Mr. Thomas Ayers,
Commonwealth Edison Company,
Chicago, Illinois. U.S.A.

Prof. R. Billington,
University of Saskatchewan,
Saskatoon, Saskatchewan. Canada

Mr. Clifford C. Diemond,
United States Department of the Interior, Bonneville Power Administration,
Portland, Oregon, U.S.A.

Mr. Lionel Boulet,
Hydro Quebec Institute of Research,
Varennes, Québec. Canada.

Mr. Don Brooking, Mr. R.E. Harrison,
Teshmont Consultants Ltd.,
Winnipeg, Manitoba. Canada.

Mr. Jack G. Cassan,
Ontario Hydro,
Toronto, Ontario. Canada.

Mr. B.B. Christensen,
Alcan Canada Products Limited,
Toronto-Dominion Centre, Toronto,
Ontario. Canada.

Mr. Jacques Cladé
Adjoint au Chef du CERT,
Paris, France.

Mr. Adalgiso Colombo,
c/o CESI - Via Rubattino,
Milano, Italy.

Mr. F.C. Creed,
National Research Council,
Ottawa, Ontario. Canada.

Mr. Marcel R. Moreau,
E.d.F. Service ERMEL,
Clamart, France.

Mr. John Dougherty,
Philadelphia Electric Company,
Philadelphia, Penn. U.S.A.

Mr. John M. Dyer,
Public Service Co. of Oklahoma,
Tulsa, Oklahoma. U.S.A.

Mr. John D. Endacott,
British Insulated Callender's Cables,
Belvedere, Kent. England.

Mr. P. Feintuch,
Direction des études et Recherches,
Electricité de France,
Paris, France.

Mr. R.M. Fraser,
Manitoba Hydro,
Winnipeg, Manitoba. Canada

Mr. Eric. T.B. Gross,
Rensselaer Polytechnic Institute,
Troy, New York. U.S.A.

Mr. A.R. Hailey,
Canadian General Electric,
Peterborough, Ontario. Canada.

Mr. A.N. Karas,
National Energy Board,
Ottawa, Ontario. Canada.

Mr. Stephen A. Mallard,
Public Service Electric and
Gas Company,
Newark, New Jersey. U.S.A.

Mr. Hein Mårtensson,
ASEA, Division for Power Transmission
Products, Fack, Ludivika, Sweden.

Mr. D. McGilles,
Hydro Quebec,
Montreal, Québec. Canada.

Mr. James E. Mielke,
Northern States Power Co.,
Minneapolis, Minnesota,
U.S.A.

Mr. Hisao Mukae,
Mitsubishi Electric Corporation,
Hyogoku, Kobe, Japan.

Mr. Kaneyoshi Murotani,
c/o Nissin Electric Co. Ltd.,
Jkyo-Ku, Kyoto. Japan.

Mr. Lucien Orgeret,
Société Delle-Alsthom,
Villeurbanne, France.

Mr. Luigi Paris,
ENEL, Centro Nazionale Studi e Progetti,
Roma, Italy.

Mr. Lucio Rebuffat,
c/o ENEL, Viale Kennedy Palazzo Laudiero,
Napoli, Italy.

Mr. France Reggiani,
c/o ENEL, Roma, Italy.

Dr. Lloyd Reid,
Institute for Aerospace Studies,
University of Toronto,
Downsview, Ontario. Canada.

Mr. Edward F. Reis,
Pennsylvania Power & Light Co.,
Allentown, Pennsylvania. U.S.A.

Mr. C.L. Rudasill,
Virginia Electric and Power Co.,
Richmond, Virginia. U.S.A.

Mr. A.R. Scott,
Dept. of Energy, Mines and Resources,
Ottawa, Ontario. Canada.

Mr. Thomas C. Shirley,
Kentucky Rural Electric Co-op Corp.,
Louisville, Kentucky. U.S.A.

Dr. G.R. Slemon,
Dept. of Electrical Engineering,
University of Toronto,
Toronto, Ontario. Canada.

Mr. Colin M. Stairs,
Canadian General Electric Co. Limited,
Peterborough, Ontario. Canada.

Interest in the study was consistently high and 91% of the panelists completed both rounds. We would like to thank our distinguished panel for their co-operation.

The Reporting Format of the Study Results

The study consisted of a general section which sought the opinions of panelists on the broad directions that electrical distribution systems would likely follow. This section included explorations of Overhead vs Underground transmission, the evolving patterns of use of AC vs DC systems and a number of possible unique or different long term approaches to the widespread provision of power to residences and industries. This general section was followed by two more detailed sections in which opinions were gathered on likely future technological developments in UHV and Underground transmission. The final section covered possible miscellaneous developments in electrical transmission and distribution.

The report will present statistical tables, comments and summaries of comments on these subjects in the same order as the questionnaire.

The statistical results include the panels' estimate of the probability of occurrence by the year 2000 and the Median, Interquartile Range and Range of those estimates which forecasted the use of technologies before 2000. An example is shown below.

▲ - Median Estimate of Responses Predicting Occurrence by 2000
— - Interquartile Range of Responses Predicting Occurrence by 2000
● ● - Range of Responses Predicting Occurrence by 2000

Technological Development	Probability of Occurrence by 2000	Probability During Period 72-75	76-80	81-85	86-90	90-95	96-2000
30% of new UHV system installations will employ self damping conductors	78%		●	—▲—	—	●	

This summary indicates that 78% of the responses forecast that this development will take place by 2000 and conversely 22% estimate it will not occur by then. A low probability of occurrence therefore is indicative that the panel as a whole believes the event is unlikely to happen and related statistics should be considered with that in mind. In the above case, those who expected the development to take place before 2000, that is 78% of the answers, predicted a median date of about 1986, the interquartile range of these responses was between 1983 and 1988 and the total range between 1976 and 1991.

In the few cases in which the answers of the experts on the panel differed markedly from the rest of the panel these results are shown separately, otherwise only the expectations of the total panel are given.

The System Characteristics Of Electrical Transmission And Distribution In The Future

The panel expected that by 1995 most new bulk transmission systems would either utilize ultra high voltage (UHV) transmission technology or underground facilities. UHV systems would dominate first and by about 1990 60% of new systems or major additions to old systems would use UHV technology. By 1995 however, 60% would use underground facilities with the bulk of the remaining 40% UHV.

Table I

Period in which about 60% of new bulk power transmission systems or major additions to existing systems will use the following technologies.

Median ▲ Interquartile Range ▬ Range ● ○

Technological Development	Probability of Occurrence by 2000	Probability During Period 72-75	76-80	81-85	86-90	91-95	96-2000
Ultra High Voltage Transmission	79%			●	▬▲	○	
Underground Transmission	66%				○	▬▲▬	○
Off Peak Production and Transmission of Hydrogen	27%				●	▬▲	●

The probability of occurrence of these forecasts by 2000 was 79% for UHV and 66% for underground technologies. The panel's view was summed up by this comment - "EHV transmission - 500 to 765KV - will serve as the backbone for bulk power transmission into the middle 1980's, then UHV transmission will play a larger role".

Other modes of energy transmission will probably not represent a significant percentage of new systems this century, although the panel thought there was a 27% probability of the off peak production and transmission of hydrogen by 1996 and a few panelists suggested that in the 21st century the transmission of hydrogen gas delivered in pipelines may be the predominant method of energy distribution. One participant expressed it this way - "Hydrogen might be produced by direct conversion using the heat from nuclear power plants, either fission or fusion. The gas would then be transmitted by underground pipes to load centers, where it would be converted to electrical energy or to another form of gas for consumer or industrial use".

Two schools of thought emerged about societal attitudes expected by 1990 toward transmission and power delivery structures. A typical comment by those who believe that society will be less stringent was, "I expect power shortages to appear prior to 1990 which will convince society they have to accept electrical equipment to obtain the power they will by then feel they must have". The second school of thought representing about 30% of the respondents, believe that more critical attitudes and more stringent limitations would require technological solutions and more public involvement in planning. As one participant put it, "The public will not accept proliferation of overhead transmission but will likely accept defined corridors. Substations, structures in corridors and distribution facilities must all be improved in appearance. Underground bulk transmission will be required from corridor to major switching substations". Another respondent pointed out, "In large urban areas by 1990 the power consumed could reach 1,000,000 KW/square mile. UHV underground facilities will be needed to supply the power needs for these centers". Another concept suggested was the widespread use of "common corridors" for a number of services, including power services, using aesthetically designed equipment.

Alternatives to Conventional Power Delivery Systems

The panel was asked to estimate when fuel cells would be utilized in 10% of industrial locations, residential complexes (apartments, condominiums, etc,) and in 10% of substations as peaking devices. The following Table II summarizes their answers.

Table II

Period in which fuel cells will be used in about 10% of the following locations

Median ▲ Interquartile Range — Range ⊙ ⊙

Use of Technological Development	Probability of Occurrence by 2000	Level of Expertise	72-75	76-80	81-85	86-90	90-95	96-2000
Industrial Locations	70%	Experts			⊙		—▲ ⊙	
	44%	Total panel			⊙		—▲	⊙
Residential complexes Apartments,etc.)	20%	Experts					▲	—
	40%	Total panel			⊙		—▲—	⊙
Large Fuel cells in substations as peaking devices	60%	Experts		⊙		——	▲— ⊙	
	42%	Total panel			⊙		—▲—	⊙

The participants opinion about the likelihood of fuel cells replacing electrical power systems in homes and residential complexes this century is summarized in this quotation: "In my opinion no new energy system which will be able to compete in economy and reliability with conventional power delivery systems has yet been proposed".

Interestingly, the only wide divergence of opinion between the experts and the total panel occurred in this question. The experts believed there was a 70% probability of industrial locations and 60% probability of large fuel cells in substations as peaking devices, compared to 44% and 42% estimates of the total panel. Table II illustrates that the expert segment of the panel also expected these events to occur at an earlier date.

The question of microwave transmission of power was posed in Round I of the study. The participants estimated there was an 85% probability that this would never occur and if it did it would likely be after the year 2000.

The Evolving Patterns of Usage of Underground and Overhead Transmission Using Direct Current and Alternating Current

The panel was asked to estimate the percentage of new systems installed by 2000 which would utilize various combinations of AC/DC and underground/overhead technologies.

Table III

Overhead	72-75	76-80	81-85	86-90	91-2000
AC	98%	96%	93%	89%	82%
DC	2%	4%	7%	11%	19%
Underground					
AC	96%	93%	86%	78%	70%
DC	4%	7%	14%	22%	30%

One panelist commented, "with the development of compact, economic AC/DC converter stations, there should be a dual trend to D.C. and underground systems which will arise from the more favourable underground/overhead cost ratio for DC". Another thought that "such developments as cryogenics and gas filled pipe systems could reverse the current trend to DC". Others believed that "in underground systems, few transmissions over long distances will use DC", and that "DC will not play a major role until the use of fusion reactors or MHD generation". One participant in Round II took issue with the latter two comments. In his view, "If an underground system is to be used over long distances DC transmission will have a definite economic advantage" and "compact DC terminals with compressed gas insulated switchgear will have a definite role in bulk power transmission to metropolitan areas" (irrespective of reactor or MHD generation).

The estimates of nearly all panelists agreed with the major trends shown in Table III - that the use of DC will increase gradually until 2000 and that DC will be approximately twice as prevalent in new underground systems as in new overhead systems. By combining the previous estimates of underground systems with these data it was calculated that the panel expected about 20% of all new systems installed will be DC by 2000.

Developments in Ultra High Voltage Technologies

The panel was asked to forecast the likelihood and timing of a series of technological developments in the UHV filed.

Table IV following summarizes these answers.

Table IV Developments in Ultra High Voltage Transmission Technologies

Median △ Interquartile Range —— Range ○ ○

Use of Technological Development		Probability of Occurrence by 2000	Probability During Period: 72-75	76-80	81-85	86-90	91-95	96-2000
UHV tower structures will be adopted which will economically meet aesthetic requirements at:	1000 kv	94%		○	—△—		○	
	1500 kv	84%			○	—△—	— ○	
	1800 kv	54%				○	—△	○
Insulators will be designed to overcome flashover problems at:	1000 kv	100%	○	△—	○			
	1500 kv	99%	○		—△—		○	
	1800 kv	86%	○		—	—△—	— ○	
UHV transmission will be introduced without serious noise emission		94%		○	—△—	○		
Circuit breakers will be installed for UHV systems at 1.5 times today's cost		100%	○		—△	○		
AC protective devices will be capable of handling the following interruption levels:	138kv 20GVA	89%	○	—△—		○		
	345kv 35GVA	100%	○	—△—		○		
	765kv 50GVA	100%	○	—△—		○		
AC protective devices will be capable of handling the following continuous levels:	138kv 1GVA	89%	○	—△—		○		
	345kv 2GVA	99%	○—	—△				○
	765kv 3GVA	100%	○	—△—		○		
High capacity DC cables will be introduced capable of carrying:	± 600kv	100%	○	—△—			○	
	± 1000kv	83%		○	—	△—	○	
	± 1500kv	60%			○		—△	○
	± 1800kv	38%				○	—△—	○
DC circuit breakers effective at 4000 MW will be introduced		74%		○		—△—	○	
30% of new system installations will employ self damping conductors		78%		○	—	△—	○	

Participants were also asked to estimate the current carrying capacity per circuit for overhead transmission by 1985. Table V below lists the averages of these responses.

	Maximum Economical Ratings	
Current Carrying Capacity	Average	Range of Answers
500 KV	2.4 GVA	1.5 - 5
700 KV	4.3 GVA	2.25 - 10
1000 KV	7.4 GVA	4 - 13
1500 KV	11.5 GVA	6 - 20
1800 KV	15.4 GVA	7.5 - 20

Typical Comments by Respondents are listed below:

Tower Design

"High voltage towers are inherently ugly".

"Many variable factors determine aesthetic requirements. In any case, design is a compromise between environmental and transmission/economic requirements".

High Capacity Cables

"It does not seem that any location in North America will need DC cable links capable of ± 1500 KV or greater. ± 1000 KV could only be used in large metropolitan areas".

"It is difficult to visualize the need for DC cables at 1500 and 1800 KV when you consider that a DC bipole of ± 1000 KV, 3000 amps has a capacity of 6000 MW - (3000 MW per pole).

DC Current Circuit Breakers

"The fully rated DC circuit breaker will be preceded by a DC load breaker designed for less severe duty".

Self Damping Conductors

"Will use current, albeit improved, technology".

"Possibilities for dampers include passive mechanical, spacer/damper and aerodynamic".

Respondents were asked to name the most important technological development required for UHV transmission by 1985. The results are summarized below.

Summary by Category

Category	% Listing This Category
Shielding - Noise Reduction - Ground level gradient control	45%
Insulation - Anti-pollution - Insulating cross-arms - Semi-conductor glazes	33%
Control - AC breakers - Overvoltage control in breakers - Power/Factor - Voltage %	30%
Tower Design - Aesthetic design - Reliability under exterme weather conditions - Bundle design	20%
DC - Transmission conversion equipment	15%
UHV System Considerations - Control of power system with computers - System stability - System design for large loadings	10%

General Comments

One panelist believed "the most significant breakthrough in our generation will be the development of saturable reactors for voltage control permitting larger transmission angles (more capacity per circuit) so that DC will never be able to compete. In fact UHV is at our doorstep - there are no insurmountable problems at 1200 KV". Another suggested "the continued evolution of DC transmission" as the key development.

An important change in the planning of systems was predicted by one participant who wrote, "the increasing trend to open planning, i.e. bring the public into the planning decisions will require new techniques to deal with right-of-way selection etc. If these problems are not solved many planned UHV networks will be delayed for many years". Another suggested, "structures must be aesthetically acceptable and the use of rights-of-way must be maximized for other purposes such as recreation, farming, etc. as well.

Developments in Underground Transmission Technologies

The estimates of the panel on a variety of possible developments in Underground transmission technologies are shown in Table VI.

Table VI — Developments in Underground Transmission Technologies

Median ▲ Interquartile Range —— Range ● ●

Use of Technological Development		Probability of Occurrence by 2000	Probability During Period: 72-75	76-80	81-85	86-90	91-95	96-2000
Underground 765kv will be introduced		94%		●	—▲—		●	
Underground UHV will be introduced		69%			●	——	▲—	●
Gas insulated cables will be introduced using:	CO2	54%			●		—▲—	●
	SF_6	98%	●		—▲—	●		
Cryogenic cables will be introduced		66%			●	—	▲	●
Superconducting cables (at near absolute zero temperature) will be introduced		57%			●		—▲—	●
1/3 of new system installations will use forced cooling		81%		●	——	▲—	●	
High voltage solid dielectric cables will be introduced		86%	●		—▲	—	●	

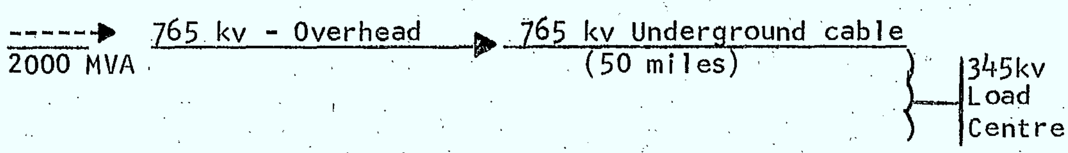
Typical Comments

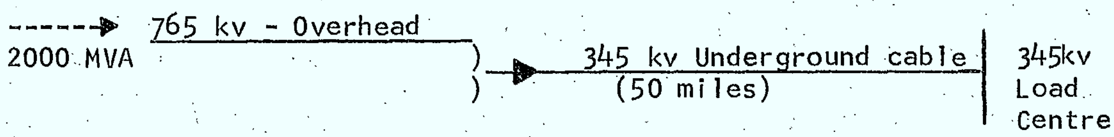
Underground Transmission

"Underground transmission for aesthetic reasons would be a deplorable waste of a nation's resources as it would consume large quantities of energy and materials and place the extra cost burden on the consumer".

"The load carrying capacity of underground lines must match the capacity of overhead lines. Changing currents on AC underground transmission lines must be minimized and the installed cost of facilities reduced without impairing their ability to withstand load cycling and voltage surges".

"More emphasis should be placed on increasing cable capacities at the lower voltages - say up to 550 kv - rather than striving for 750 - 1500 kv. Underground systems in many cases need MVA capability rather than the higher voltages needed for system stability in overhead ystems. For example:

1 -


2 -


"Alternative No. 2 may well be readily achievable and more economical using forced oil cooling gas or cryogenic, with fewer insulation problems".

"Bulk power eventually will have to be transmitted underground because the space required for overhead circuits will not be available, not to mention the aesthetic and economic problems associated with UHV overhead lines. I think that dialectric losses will restrict the use of conventional pipe cable to relatively low power circuits. Compressed gas systems, probably using sulphur hexafloride gas, seem most promising for high capacity underground systems in the near future, with cryogenic systems coming later".

"I don't think we will ever see a large percentage of our bulk power transmission carried underground. More feasible methods will be developed for transferring energy over long distancesthan by transmitting electricity".

Gas Insulated Cables

"SF_6 insulated cables will be the major area of development for 765 kv underground transmission through the 80s".

"British Columbia is now establishing short sections of SF_6 pipe at 500 kv".

"Foam insulated EHV is another alternative".

Forced Cooling

"New techniques such as heat pumps will be used".

"The economic benefits of this approach are unproven".

The panel was asked to name the most significant technological development required for EHV and UHV underground transmission. The results are summarized below:

Summary by Category

Category	% Listing this Category
Insulation or Cooling Technologies	76%
- Dialectic materials	21%
- Cryogenic cables	17%
- Flexible gas insulated cable systems	14%
- SF_6 cables	14%
- Superconducting cables	10%
Economic Installation Techniques	12%
Economic AC/DC Conversion Equipment	7%
Economic and Reliable components	7%
High Voltage cables	5%
Miniature DC stations	2%

Miscellaneous Technological Developments

Participants were asked their views of the likelihood and timing of a number of related miscellaneous technological developments. The results are summarized in Table VII

Table VII — Miscellaneous Technological Developments

Median ▲ Interquartile Range —— Range ● ●

Use of Technological Development		Probability of Occurrence by 2000	Total Range of Answers Before 2000 72-75	76-80	81-85	86-90	91-95	96-2000
Single generating unit size will reach:	2000 MW	100%	●		—▲—	●		
	5000 MW	70%			●		▲—	●
	8000 MW	42%				●		▲ ●
The size of substations used for new installations will be reduced 1/10 or 1/15 of today's units		92%	●		—▲—		●	
Gas insulation for substations will be introduced		100%	▲—		●			
Cryogenic insulation for substations will be introduced		56%			●		▲—	●
Modular transformers, capable of being assembled in the field, will be introduced		87%	●			▲—		●
Switching up to 1500 kv will be available within 1.5 times today's cost for 765 kv.		65%		●			—▲—	●
Reliable transmformers and switches for underground systems will be available meeting cost and size requirements		95%	●	—▲—			●	

Typical Comments of Participants are listed below:

Compact Substations

"Compact substations with attendant technologies will become the industry standard in a few years".

"Considerable technical activity will concentrate on the reduction of substation sizes and may be consistent with a complete SF_6 approach".

Gas Insulation for Substations

"Compact gas insulated substations will be used extensively in urban areas where land is expensive and appearance is important before 1980".

Field Assembled, Modular Transformers

"A good deal of material science is required in this area, such as the development of fully cast transformers".

"Field assembly is to be avoided because of high labour costs and quality control problems".

"Modular transformers with special arrangement of the case for assembly on site have already been introduced".

Switching up to 1500 kv

"EHV and UHV switching costs are determined by what type is needed. Modular concepts are used now to minimize costs".