Annex J

Summary of CIGRE 13.06 Working Group World Wide Reliability and Maintenance Cost Data on High Voltage Circuit Breakers above 63 kV

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SUMMARY OF CIGRE 13.06 WORKING GROUP WORLD WIDE RELIABILITY DATA AND MAINTENANCE COST DATA ON HIGH VOLTAGE CIRCUIT BREAKERS ABOVE 63 kV

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ABSTRACT

A summary is given of the most significant reliability data and maintenance cost data from the two CIGRE 13.06 Working Group world wide reliability surveys of the reliability of high voltage circuit breakers 63 kV and above. The first enquiry covered the years 1974 thru 1977 and included all interrupting technologies. The second enquiry covered the years 1988 thru 1991 and only included single pressure SF6 breakers.

A description is given of the scope and objectives of the CIGRE 13.06 Working Group. A brief description is given of some of the highlights from their studies.

INTRODUCTION

CIGRE 13.06 Working Group carried world wide reliability studies on high voltage circuit breakers during the fifteen year period 1971 through 1985. This included making the First International Enquiry on circuit breaker failures and defects in service. Studies were also made on new testing and maintenance methods for improving the reliability of high voltage circuit breakers. This work is reported in three CIGRE Study Committee No. 13 final reports [1][2][3]. Some of the CIGRE 13.06 WG recommendations have resulted in changes in International Standards for high voltage circuit breakers.

SCOPE AND OBJECTIVES OF NEW CIGRE 13.06 WG

In 1986 a new CIGRE 13.06 Working Group was set up on "Reliability of High Voltage Circuit Breakers" in order to obtain detailed information on circuit breaker performance in service as well as possible measures to improve the reliability and to reduce the maintenance costs. Two major tasks were undertaken:

1. Conduct a Second International Enquiry on the in service reliability of SF6 single pressure high-voltage circuit breakers with rated voltages 72.5 kV and above.

2. Study the parameters for permanent supervision in service as well as relevant diagnostic methods.

The results of the Second International Enquiry on circuit breaker failures and defects in service show the change in reliability since the First Enquiry. Monitoring and diagnostic methods aim to improve the reliability of operation and contribute to reducing the cost of maintenance. Studies on monitoring and diagnostic methods include all circuit breaker technologies because there is interest for both new and older circuit breakers.

Four papers have been published during 1992 to 1994 on the results of these studies[4] [5][6][7]. In addition, a Technical Brochure has been published [8] that gives extensive details on the reliability of high voltage circuit breakers above 63 kV and the changes in reliability that have occured during the fourteen year interval between the First and Second International Enquiries.

CIRCUIT BREAKER RELIABILITY DEFINITIONS USED IN TWO INTERNATIONAL ENQUIRIES

The CIGRE 13.06 WG wrote circuit breaker reliability definitions in 1971 for "failure," "major failure," "minor failure," and "defect." These definitions were used in both the First and Second International Enquiries and are given in Table 1. Thus world wide reliability definitions have existed for several years for high voltage circuit breakers and are now included in technical report IEC 1208 (1992) "Guide for High-Voltage Alternating Current Circuit Breaker Maintenance" by TC17 on Switchgear and Controlgear. It can be seen that the term "circuit breaker major failure" is equivalent to what system planning people would call a "forced outage."

The term "circuit breaker downtime" was clearly defined in the Second International Enquiry as "time from discovery of the failure until the breaker is returned to service, exclude deliberate delays." In the First International Enquiry "circuit breaker downtime" was calculated by adding two terms: (1) "time required to analyse the failure or defect, repair and return the circuit breaker to service, exlude deliberate delays," plus (2) "time required to get to site and obtain spare parts, exclude deliberate delays." This change in definition of "circuit breaker downtime" was made in the Second Enquiry because it was believed that some respondents in the First Enquiry may have misinterpreted what was asked for. However, it should be noted that deliberate delays for repair of the circuit breaker have been excluded in both enquiries when calculating "circuit breaker downtime."

RELIABILITY DATA FROM FIRST ENQUIRY

A total of 102 electric utilities from 22 countries submitted data on 20,000 circuit breakers above 63 kV. This included breakers

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of all technologies. Data were collected for the years 1974-77 on circuit breakers installed after January 1, 1964. This gave a total of 77,892 breakers-years of service during the four year period. This was a pioneering effort that required the development of: (1) reliability and maintenance definitions , (2) survey questionaire, and (3) the method of analysis of the data. This encouraged utilities to develop a failure reporting system. Countries submitting data were: Australia, Belgium, Brazil, Canada, Czechoslovakia, Denmark, Finland, France, Federal Republic ofGermany, Greece, Ireland, Italy, Japan, Morocco, Netherlands, New Zealand, Norway, Portugal,Spain, Sweden, United Kingdom, and Yugoslavia. The results from this First InternationalEnquiry were published in "Electra" [1].

The failure rate and downtime data are summarized in Table 2 with the data for major failure rate and minor failure rate shown separately. Average downtime data and the median downtime data are given for major failures.

RELIABILITY DATA FROM SECOND ENQUIRY

The enquiry includes the years 1988 thru 1991 and was limited to single pressure SF6 circuit breakers because most of the new breakers at these voltage levels now being purchased by electric utilities use this technology. The questionaire [8][9] was revised to be simpler than for the First Enquiry.

Data were collected for 1988 thru 1991 from 132 utilities in 22 countries on about 18,000 circuit breakers applied at 63 kV & above placed in service after January 1, 1978. There were a total of 70,708 breaker-years of service during the four year period. Countries submitting data were: Australia, Austria, Belgium, Brazil, Canada, Czechoslovakia, Finland, France,Germany, Italy, Japan, Netherlands, New Zealand, Norway, Paraguay, Rumania, Sweden, Switzerland, United Kingdom, United States of America, Union of Soviet Socialist Republics, and Yugoslavia.

Table 3 shows the major and minor failure rates separately. Average downtime data and median downtime data are given for major failures.

The questionaire for the Second Enquiry contains the additional major failure mode "locking in open or closed position." A study of this "locking" data indicates that about 13% were found during a command to open, about 37% were found during a command to close, and 50% were found by an alarm during normal service.

ORIGIN,CAUSE, FAILURE MODES, OPERATING-CYCLES

Tables 4 and 5 show the major and minor failure modes for the two enquiries. Table 6 shows the origins of failures, and Table 7 shows the causes of failures.

Table 8 shows the estimated average number of operating-cycles per year per breaker from the two enquiries.

DATA FOR USE IN SUBSTATION AND SYSTEM RELIABILITY STUDIES

Data from Tables 2 and 3 from the First and Second Enquiries have been used respectively to calculate the data shown in Tables 9 and 10. In both cases the major failures that occured during a command to open or close have been separated out from those that occurred without a command to open or close; this has been used along with the operating-cycles per year data to calculate the reliability data that is given in Tables 9 and 10. This shows the average number of major failures per 10,000 open commands or close commands of: "does not open on command", "does not break the current", "does not close on command", "does not make the current." These final results in Table 10 from the Second Enquiry can be compared with Table 9 from the First Enquiry. A footnote in each table gives the data for the two failure modes: "closes without command" and "breakdown across open pole;" these failure rates are very low, but may have a serious consequence when they occur on a power system.

COMPARISON OF RELIABILITY DATA BETWEEN THE FIRST AND SECOND ENQUIRIES

The final results from the Second International Enquiry for 1988 thru 1991 show that modern single-pressure SF6 circuit breakers applied at 63 kV & above have a major failure rate that is only 43% as much as older technology circuit breakers reported in the First International Enquiry for 1974-1977. The largest improvement has occurred at voltages above 200kV where the reported major failure rates are less than one-third as much. The minor failure rates are 30% higher in the Second Enquiry.

It is believed that utilities do a better job of collecting failure data now than was done during the First Enquiry. The biggest improvement is believed to have occurred in the collection of data on minor failures.

The "estimated average number of operating-cycles per year per breaker" were 42 and 26.5 respectively from the Second and First International Enquiries. These values have an effect on the calculated probabilities of breaker major failures per operating command. The Second Enquiry calculated the average number of operating-cycles per year per breaker by weighting each breaker equally. This is a better method than used in the First Enquiry where each questionaire answer was weighted equally, and some answers contained many more breakers than other answers. It is not believed that there has been a significant change in the number of operating-cycles per year per breaker between the First and Second Enquiries. If 42 operating-cycles per year per breaker had been used to calculate the probabilities of breaker major failures per operating command for the First Enquiry, the probabilities shown in Table 9 would have been lower by a factor of 1.58.

Tables 10 and 9 can be compared to show the number of major failures per 10,000 cycles, where a cycle is one open command plus one close command. For all voltages combined the

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Second Enquiry shows 0.829 versus 3.06 for the First Enquiry and is a factor of 3.7 lower. But 1.58 of this improvement is explained in the previous paragraph because of using an estimated average of 42 operating-cycles per year per breaker versus 26.5 from the First Enquiry; and 3.7 divided by 1.58 equals 2.33. Thus the number of major failures per 10,000 cycles has decreased by at least a factor of 2.33.

COMPARISON OF BREAKER DOWNTIME DATA PER MAJOR FAILURE BETWEEN THE FIRST & SECOND ENQUIRIES

The Second Enquiry had an average downtime of 94.6 hours per major failure versus 81.6 in the First Enquiry. But the median downtime was only 10.0 hours hours in the Second Enquiry versus 12.0 in the First Enquiry. Both enquiries show a highly skewed distribution where a small number of long downtimes result in the average being between about seven to nine times larger than the median value. Some people have questioned why the Second Enquiry had a longer downtime than the First Enquiry. A special detailed study has been made of the downtime data from the Second Enquiry. The increase in breaker downtime for SF6 single pressure breakers is primarily due to a much longer "time to obtain spare part." 64% of the 94.6 hours per failure of average breaker downtime for "all voltages combined" can be attributed to "time to obtain spare part." This would appear to be due to the policies of electric utilities on spare parts rather than the ability to repair the breaker. In 9% of the reported cases the "time to obtain spare part" was longer than the breaker downtime; this would indicate that the breaker was often placed back in service or was replaced before the spare part was obtained. The special study also found that there does not appear to be any significant difference in the breaker downtime between metal-enclosed and non-metal-enclosed SF6 breakers.

Data were not collected in the Second Enquiry on the breaker downtime for minor failures. This data were collected in the First Enquiry; and the average was 30.0 hours per minor failure with a median of 6.0.

SUBSTATION AND SYSTEM RELIABILITY STUDIES

The data in Tables 9 and 10 are a credible source of data based upon a large sample size. They can be used in substation and system reliability studies. Very few reliability studies use all of the breaker failure modes given in this data. The circuit breaker is the most difficult component to handle when making substation or system reliability studies because of the many different breaker functions and the associated failure modes.

λ_S is the major failure rate without a command to operate. 63% of these failures for all voltages combined include the failure modes: alarm-locking in open or closed position, fails to carry the current, other requiring manual removal from service within 30 minutes. These might be assumed to be passive failures. The other 37% might be assumed to be active major failures (breakdown to earth, breakdown between poles, breakdown across open pole, closes without command, opens without command).

$c \cdot \lambda_c$ is the major failure rate during commands to operate, either for switching or to remove faults.

$\lambda_{c1} + \lambda_{c2}$ is the probability of not opening on command or not breaking the current during manual or automatic opening to perform switching or to remove a fault. This could be considered the breaker stuck closed probability.

$\lambda_{c3} + \lambda_{c4}$ is the probability of not closing on command or not making the current during manual or automatic closing or reclosing. This could be considered the breaker stuck open probability.

The dominant breaker failure mode is "does not close on command" and should not be neglected in substation or system reliability studies. This failure mode: (1) can prevent equipment from being switched into service when needed, (2) can cause a transient line outage to become a permanent outage, or (3) can cause an outage of a line or generator to be extended beyond the normal outage time.

The failure mode "closes without command" has a very low failure rate. But its occurence sometimes results in all of the back up protection being defeated and in some cases has been the cause of major blackouts. The failure mode "breakdown across pole" has the highest electrical failure rate of the main interrupter; and backup protection must operate to remove the fault. The failure rates of "closes without command" and "breakdown across open pole" are both very low; but they can be larger than the double contingency failure rates typically calculated for other component combinations in a substation reliability study.

COST OF SCHEDULED SERVICING OF OLDER TECHNOLOGY BREAKERS

Table 11 shows the cost of scheduled servicing of older technology breakers (minimum oil, air blast, SF6, bulk oil, etc) that was collected from the First International Enquiry [1] for the years 1974-1977. The costs are shown separately for the labor effort and for the spare parts consumed. The 10, 50, and 90 percentiles cost values are given along with the average cost value for each voltage category. The number of data points in each voltage category ranged from 69 to 138. It can be seen that there is a wide variation between the 10 and 90 percentiles cost values for the labor effort, typically as much as six to one or more. There is even a wider variation in the costs of the spare parts consumed. These cost values indicate that many users of high voltage circuit breakers may be doing more scheduled maintenance than needed. In some cases it might be possible to reduce the maintenance effort without the use of additional diagnostic techniques. In other cases it might be desirable to use additional diagnostic techniques in order to detect degradation of the most probable failure modes before they occur in service[4][5]. Table 11 gives data that can be used to assist in estimating the maximum cost savings that might be possible from using diagnostic techniques on older technology circuit breakers.

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COST OF SCHEDULED OVERHAUL OF MODERN TECHNOLOGY BREAKERS

Table 12 shows the estimated cost of scheduled overhaul for single pressure SF6 breakers that has been collected during the four years (1988-1991) of the Second International Enquiry. The costs are shown separately for the labor effort and for the spare parts consumed for each voltage category along with the 10, 50, 90 percentile and average values. The number of data points in each voltage category ranged from 179 to 601. The data on the interval betweeen scheduled overhaul show that the 50 percentile value ranged from 6. to 8.5 years for the various voltage categories, but the 90 percentile value ranged from 12.0 to 15.0 years for all voltage categories. Most manufacturer's quote longer overhaul intervals than 8. years, and many utilities may not yet have sufficient confidence to fully exploit the longer overhaul interval possible with modern technology single pressure SF6 breakers. The variation in the labor costs ranged by a factor of six to one or more, and the spare parts consumed ranged by a factor or more than twenty to one; many of these utility estimates maybe based upon very limited experience with overhaul of single pressure SF6 breakers.

TIGHTNESS OF SF6 GAS SYSTEM

Table 6 shows that the tightness of the SF6 gas system was the origin of both minor and major failures in the Second Enquiry on SF6 single-pressure breakers. This included 39.6% of the minor failures and 7.2% of the major failures. The data in Table 5 show that 1297 minor failures were due to small SF6 leakage, and this was 39% of all minor failures. The minor failure rate for these 1297 failures is .018 per year per breaker.

There was a total of 33 major failures with the origin in the tightness of the SF6 gas system, and Table 13 shows the failure modes that resulted. 18 resulted in "locking in open or closed position" and 5 resulted in "opens without command." The major failure rate for these 33 failures is .00025 per year per breaker and is very low.

A density monitor is used to detect SF6 gas leaks, and this is the primary resson why most of the tightness failures are minor failures. However, 357 failures have also been reported of the density monitor.

Reliability improvements are needed in both the SF6 gas tightness system and in the gas density monitor.

FAILURE RATE OF METAL-ENCLOSED VERSUS NON-METAL ENCLOSED CIRCUIT BREAKERS

Table 13 shows a comparison of the failure rates from the Second Enquiry of metal-enclosed (ME) versus non-metal-enclosed circuit (NME) breakers for "all voltages combined, 100 kV and above." Most of the ME breakers are part of gas insulated stations.

The ME SF6 single-pressure breakers, 100 kV & above, have a lower failure rate than the NME breakers. But this difference can not be considered significant because it is mostly due to data from one country with a large population.

GENERAL CONCLUSIONS AND RECOMMENDATIONS

CIGRE 13.06 Working Group has collected and analysed world wide reliability data on high voltage circuit breakers applied on networks at 63 kV & above. These data are a large sample size and can be useful in substation and system reliability studies. Two important contributions to the knowledge of circuit breaker reliability are: (1) the failure mode data, and (2) the calculations of probabilities of not responding properly to an operating command to open or to close. The 1974-1977 data can be used for older technology circuit breakers, and the 1988-1991 data show the improvement that has been achieved with new technology single-pressure SF6 breakers. The major failure rate for modern SF6 single-pressure breakers is only about 43%as much as older technology breakers, and for voltages above 200 kV it is only one-third as much. Substation and system reliability studies should pay attention to this improvement. The lower major failure rate of circuit breakers may influence both the lay-out of primary plant and secondary systems.

The minor failure rate for modern SF6 breakers in the Second Enquiry is about 30% higher than for older technology breakers in the First Enquiry. Possible reasons for this may be: (1) better failure data collection by utilities and (2) increased number of alarms and (3) SF6 leakage problems.

The largest number of major failures on modern SF6 breakers occur on the operating mechanism and on the electrical auxiliary and control circuits. The largest number of minor failures occur from leaks on the SF6 gas system and from problems on the operating mechanism. Reliability improvements are needed on: (1) operating mechanism, (2) SF6 tightness, (3) electrical auxiliary & control circuits. The gas density monitor also needs improvement in reliability because the SF6 gas density is the most important parameter to monitor. The operating mechanism is also an important parameter to monitor.

Design and manufacture are the cause of about 50% of the failures of modern SF6 breakers.

Improved access to spare parts by utilities could significantly improve breaker availability by reducing the downtime after major failures.

The circuit breaker reliability definitions that were first written in 1971 are now accepted and used world wide. Thus it logical that these definitions become standards of the International Electrotechnical Comission (IEC) under Technical Committee No. 17 on Switchgear and Controlgear. It is recommened that the existing technical report IEC 1208 (1992) on "Guide for High-Voltage AC Circuit Breaker Maintenance" be upgraded to an IEC standard after the three trial period is completed.

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TABLE 1 - CIRCUIT BREAKER RELIABILITY DEFINITIONS

1. FAILURE - Lack of performance by an item of its required functions. Note: The occurenceofa failuredoes not necessarily imply the presence of a defect if the stress or the stresses are beyond those specified. 2. MAJOR FAILURE (OF A CIRCUIT-BREAKER) - Complete failure of a circuit-breaker which causes the lack of one or more of its fundamental functions. Note: A majorfailure will result in an immediate change in the system operating condition; e. g., the backup protective equipment being required to remove the fault, or, will result in mandatory removal from service for non scheduled maintenance (intervention required within 30 minutes).	3. MINOR FAILURE (OF A CIRCUIT-BREAKER) - Failure of circuit-breaker other than major failure; or any failure, even complete, of a constructional element or a sub-assembly which does not cause a major failure of the circuit-breaker. 4. DEFECT - Imperfection in the state of an item (or inherent weakness) which can result in one or more failures of the item itself or of another item under the specific service or environmental or maintenance conditions for a stated period of time. 5. CIRCUIT-BREAKER DOWNTIME - Time from the discovery of the failure until the breaker is returned to service.

TABLE 2 - FAILURE RATES AND DOWNTIME DATA FOR
HIGH VOLTAGE CIRCUIT BREAKERS ABOVE 63 kV
(from CIGRE 13-06 Working Group First International
Enquiry, 1974-1977, All Interrupting Technologies)

MAJOR FAILURE RATES						*MINOR FAILURE RATES		
Sample Size Breaker Years	Number of Major Failures	Major Failures per Breaker Year	*** Hours Downtime per Failure Average	Median	VOLTAGE kV	Sample Size Breaker Years	Number of Failures*	Failures* per Breaker Year
77,892	1,231**	.0158	81.6	12.0	All Voltages	46,272	1,641	.0355
33,877	138	.0041	29.3	5.0	63 ≤ V <100	24,716	409	.0165
26,743	437	.0163	94.4	12.0	100 ≤ V <200	13,915	581	.0417
9,939	257	.0258	58.5	11.0	200 ≤ V <300	5,614	359	.0639
6,224	283	.0455	83.8	11.0	300 ≤ V <500	1,682	275	.1635
1,109	116	.1045	142.0	27.0	500 ≤ V	345	17	.0493

NOTES: * Minor failures plus defects
** 45 of the 1,231 major failures had a fire and/or explosion
*** Downtime includes: time required to get to site, analyse the failure, obtain spare parts, repair and return circuit breaker to service. Deliberate delays have been excluded.

TABLE 3 - FAILURE RATES AND DOWNTIME DATA FOR SINGLE-PRESSURE
HIGH-VOLTAGE CIRCUIT BREAKERS APPLIED ABOVE 63 kV
(Final Results from CIGRE 13-06 Working Group
Second International Enquiry, 1988-1991)

MAJOR FAILURE RATES						*MINOR FAILURE RATES	
Number of Major Failures	Major Failures per Breaker Year	*** Hours Downtime per Failure Average	Median	VOLTAGE kV	Sample Size Breaker Years	Number of Failures*	Failures* per Breaker Year
475**	.00672	94.6	10.0	All Voltages	70,708	3,358	.0475
67	.00275	39.1	24.0	63 ≤ V <100	24,355	542	.0223
160	.00680	51.1	10.0	100 ≤ V <200	23,520	1,118	.0475
89	.00814	54.6	8.0	200 ≤ V <300	10,933	762	.0697
120	.01210	162.5	10.0	300 ≤ V <500	9,917	770	.0776
39	.01967	209.4	36.0	500 ≤ V	1,983	166	.0837

NOTES: * Minor failures plus defects
** 31 of the 475 major failures had a fire and/or explosion
*** Downtime includes: time from discovery of the failure until the breaker is returned to service, exclude deliberate delays.

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TABLE 4 - MAJOR FAILURE MODES OF HIGH VOLTAGE CIRCUIT BREAKERS (Results from CIGRE 13-06 WG Enquiries - All voltages, Above 63 kV)

1st Enquiry %	2nd Enquiry %	
33.7	24.6	Does not close on command
14.1	8.3	Does not open on command
1.7	1.0	Closes without command
5.2	7.0	Opens without command
1.6	1.7	Does not make the current
1.9	3.0	Does not break the current
2.5	1.5	Fails to carry the current
2.6	3.2	Breakdown to earth
0.5	1.5	Breakdown between poles
4.0	3.6	Breakdown across open pole, internal
1.2	1.5	Breakdown across open pole, external
*	28.5	Locking in open or closed position
31.0	14.6	Other failure necessitating intervention within 30 minutes
773	471	Number of Answers

* "Locking" failure mode data not collected in 1st Enquiry. Special study of 2nd Enquiry data found that half of "Locking" failures should probably have been reported as "does not close on command" (37%) or "does not open on command" (13%).

TABLE 5 - MINOR FAILURE MODES* OF HIGH VOLTAGE CIRCUIT BREAKERS (Results from CIGRE 13-06 WG Second Enquiry - All Voltages, Above 63 kV)

%	
30.	Air or hydraulic leakage in operating mechanism
16.	Small SF6 gas leakage due to corrosion
23.	Small SF6 gas leakage due to other causes
16.	Change of functional characteristics
15.	Others
3332	Number of Answers

* Data not collected in First Enquiry

TABLE 6 - ORIGIN OF FAILURES OF HIGH VOLTAGE CIRCUIT BREAKERS (Results from CIGRE 13-06 WG Enquiries - All Voltages, Above 63 kV)

Major Failures 1st Enquiry	Major Failures 2nd Enquiry		Minor Failures 1st Enquiry	Minor Failures 2nd Enquiry
*	44.0%	Mechanical in Operating Mechanism (Earthed)	*	39.4%
70.3%	10.4%	Mechanical in Other Parts of Circuit Breaker	85.6%	9.9%
10.6%	13.9%	Electrical (Main circuit	2.7%	0.9%
19.1%	24.5%	Electrical Auxiliary and Control Circuit	11.7%	10.2%
*	7.2%	Tightness of SF6-Gas System	*	39.6%
775	461	Number of Failures	1602	3233

* Not specified in First Enquiry

TABLE 7 - CAUSE OF MAJOR AND MINOR FAILURES OF HIGH VOLTAGE CIRCUIT BREAKERS (Results from CIGRE 13-06 WG Enquiries - All Voltages, Above 63 kV)

Major Failures 1st Enquiry	Major Failures 2nd Enquiry		Minor Failures 1st Enquiry	Minor Failures 2nd Enquiry
	25.4%	Design		24.7%
*45.3%		Design & Manufacture	*52.5%	
	28.7%	Manufacture		39.1%
0.7%	1.1%	Inadequate Instructions	0.3%	1.7%
9.3%	8.2%	Incorrect Erection	10.7%	7.1%
1.2%	6.0%	Incorrect Operation	0.2%	4.5%
8.1%	2.8%	Incorrect Maintenance	4.5%	2.6%
4.8%	3.4%	Stresses Beyond Specification	0.7%	1.8%
2.3%	5.4%	Other External Causes	1.7%	6.6%
28.3%	19.0%	Other	29.4%	11.9%
751	464	Number of Failures	1604	3294

* First Enquiry combined "Design" and "Manufacture"

TABLE 8 - ESTIMATED AVERAGE NUMBER OF OPERATING-CYCLES PER YEAR PER BREAKER (Results from CIGRE 13-06 WG Enquiries - All voltages, Above 63 kV)

	1st Enquiry	2nd Enquiry
AVERAGE	26.5	42
10% PERCENTILE	3.3	13
25% PERCENTILE	6.3	20
MEDIAN	13.1	30
75% PERCENTILE	28.8	50
90% PERCENTILE	53.1	76
95% PERCENTILE	78.0	84
MAXIMUM	548.6	1760
No. of Breakers		*64,676
No. of Answers	*422	

* First Enquiry weighted each answer equally and Second enquiry weighted each breaker equally

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TABLE 9 - RELIABILITY DATA ON HIGH VOLTAGE CIRCUIT BREAKERS ABOVE 63 kV THAT CAN BE USED IN SYSTEM RELIABILITY STUDIES (from CIGRE 13-06 Working Group First International Enquiry 1974-1977, All Interrupting Technologies)

1. Major Failures per Open Command $\lambda_{c1} + \lambda_{c2}$
2. Major Failures per Close Command $\lambda_{c3} + \lambda_{c4}$
3. Major Failures per Cycle** $\lambda_c = \lambda_{c1} + \lambda_{c2} + \lambda_{c3} + \lambda_{c4}$
4. Average Number of Cycles** per Year c
5. Major Failures per Breaker-Year During Commands to Open or Close $c \cdot \lambda_c$
6. Major Failures per Breaker-Year Occuring Without A Command to Open or Close λ_s
7. Total Major Failures per Breaker-Year $\lambda_M = \lambda_s + c \cdot \lambda_c$

λ_{c1} Does Not Open On Command	λ_{c2} Does Not Break the Current	λ_{c3} Does Not Close On Command	λ_{c4} Does Not Make the Current	λ_c Major Failures per10,000 Cycles**	c Average Number of Cycles** per Year	VOLTAGE kV	$c \cdot \lambda_c$ Major Failure per Breaker Year	λ_s Major Failure per Breaker Year	λ_M Total Major Failure per Breaker Year
MAJOR FAILURES PER 10,000 OPEN COMMANDS		MAJOR FAILURES PER 10,000 CLOSE COMMANDS							
0.84	0.11	2.01	0.10	3.06	26.5	All Volt.	.0081	.0077***	.0158
0.166	0.018*	0.562	0.010*	0.756	24.7	$63 \leq V < 100$	.0019	.0022	.0041
0.81	0.12*	2.60	0.05*	3.58	23.8	$100 \leq V < 200$	.0085	.0078	.0163
1.42	0.07*	2.54	0.32*	4.35	32.0	$200 \leq V < 300$	.0139	.0119	.0258
3.16	0.64*	5.39	0.24*	9.43	25.0	$300 \leq V < 500$	.0236	.0219	.0455
9.75*	0.00*	12.98*	0.00*	22.73*	26.8	$500 \leq V$	.0609	.0436	.1045

NOTES
* Small sample size in failure mode data - less than 8 failures
** A cycle is one open command and one close command
*** Approximately 10.7% of these major failures are "breakdown across open pole" and another 3.5% are "closes without command"

TABLE 10 - RELIABILITY DATA ON SINGLE-PRESSURE HIGH VOLTAGE CIRCUIT BREAKERS APPLIED ABOVE 63 kV THAT CAN BE USED IN SYSTEM RELIABILITY STUDIES (from CIGRE 13-06 Working Group Second International Enquiry 1988-1991)

Assumes that 13% of the "Locking" Failures Occured After a Command to Open and Another 37% of the "Locking" Failures Occured After a Command to Close

λ_{c1} Does Not Open On Command	λ_{c2} Does Not Break the Current	λ_{c3} Does Not Close On Command	λ_{c4} Does Not Make the Current	λ_c Major Failures per10,000 Cycles**	c Average Number of Cycles** per Year	VOLTAGE kV	$c \cdot \lambda_c$ Major Failure per Breaker Year	λ_s Major Failure per Breaker Year	λ_M Total Major Failure per Breaker Year
MAJOR FAILURES PER 10,000 OPEN COMMANDS		MAJOR FAILURES PER 10,000 CLOSE COMMANDS							
0.192	0.048	0.562	0.027	0.829	42.	All Volt.	.00348	.00324***	.00672
0.077	0.000*	0.167	0.009*	0.253	47.	$63 \leq V < 100$	.00119	.00156	.00275
0.161	0.043*	0.781	0.000*	0.985	40.	$100 \leq V < 200$	.00394	.00286	.00680
0.229	0.071*	0.648	0.095*	1.043	39.	$200 \leq V < 300$	.00407	.00407	.00814
0.524	0.113*	1.071	0.057*	1.765	36.	$300 \leq V < 500$	.00635	.00575	.01210
0.506*	0.336*	0.951	0.112*	1.905	45	$500 \leq V$	.00857	.01110	.01967

NOTES
* Small sample size in failure mode data - less than 8 failures
** A cycle is one open command and one close command
*** Approximately 10.6% of these major failures are "breakdown across open pole" and another 2.2% are "closes without command"

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TABLE 11 - AVERAGE COST OF SCHEDULED SERVICING of HIGH VOLTAGE CIRCUIT BREAKERS ABOVE 63 kV FROM FIRST INTERNATIONAL ENQUIRY FOR YEARS 1974-1977
(Includes Ordinary Servicing and Detailed Servicing for All Technology Breakers)

Interval Between Scheduled Servicing Average YEARS	Median YEARS	VOLTAGE kV	------Labor Effort------- Average MANHOURS	10	50	90	--Spare Parts Consumed*-- Average MANHOURS	10	50	90
				---Percentile--- PER BREAKER/YEAR				---Percentile--- PER BREAKER/YEAR		
2.3	3.0	63 ≤ V < 100	19.6	5.0	17.5	30.0	55.0	1.0	5.0	60.0
2.0	2.5	100 ≤ V < 200	34.0	10.1	30.0	72.0	38.2	3.0	12.0	60.0
2.0	3.0	200 ≤ V < 300	47.4	15.0	44.0	120.0	87.5	3.0	20.0	90.0
1.4	2.0	300 ≤ V < 500	48.5	13.6	50.0	169.0	72.7	10.0	38.0	157.5

NOTES
* Each country converted the cost of spare parts consumed into equivalent manhours using their labor rate. This resulted in manhours being used as an international currency for both labor effort and spare parts consumed.

DEFINITIONS IN TABLE 11
ORDINARY SERVICING - Servicing scheduled according to given operational conditions which would include a check of the operation measurement of the principal control devices, the measurement of the characteristics of insulation and arc-extinguishing media, cleaning, washing, lubricating, tightening, adjusting, replacing worn parts in accordance with given instructions, and the measurement of the operation characteristics such as lock-out pressures, operating time, insulation of auxiliary circuits, etc

DETAILED SERVICING - Scheduled servicing in accordance with the given instructions necessitated by long service, large number of operations, etc. It will include a more detailed examination of all the parts than carried during Ordinary Servicing.

TABLE 12 - ESTIMATED COST FOR SCHEDULED OVERHAUL of HIGH VOLTAGE CIRCUIT BREAKERS ABOVE 63 kV FROM SECOND INTERNATIONAL ENQUIRY - YEARS 1988-1991
(Includes Scheduled Overhaul for Single Pressure SF6 Circuit Breakers)

Interval Between Scheduled Overhaul Average	10	50	90	VOLTAGE kV	------Labor Effort------- Average MANHOURS	10	50	90	--Spare Parts Consumed*-- Average MANHOURS	10	50	90
	--Percentile-- --------YEARS---------					---Percentile--- PER BREAKER/YEAR				---Percentile--- PER BREAKER/YEAR		
7.6	4.0	6.0	12.0	63 ≤ V < 100	15.3	5.	15.	30.	25.4	2.	24.	61.
8.8	5.0	8.5	15.0	100 ≤ V < 200	17.4	3.	12.	43.	20.7	2.	8.	48.
8.2	4.0	7.9	12.0	200 ≤ V < 300	24.8	5.	15.	50.	31.6	1.	12.	74.
8.2	4.0	7.0	12.0	300 ≤ V < 500	31.0	5.	18.	56.	17.7	2.	8.	48.

NOTES
* Each country converted the cost of spare parts consumed into equivalent manhours using their labor rate. This resulted in manhours being used as an international currency for both labor effort and spare parts consumed.

DEFINITION IN TABLE 12
OVERHAUL - Work done with the objective of repairing or replacing parts, which are found to be below standard by inspection or test or as required by manufacturers maintenance manual, in order to restore the component and/or the circuit-breaker to an acceptable condition.