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HANFORD ATOMIC PRODUCTS OPERATION – RICHLAND, WASHINGTON

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TITLE

RELIABILITY AND SAFETY OF THE ELECTRICAL POWER SUPPLY COMPLEX OF THE HANFORD PRODUCTION REACTOR

AUTHOR

F. D. ROBBINS

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RELIABILITY AND SAFETY OF THE
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COMPLEX OF THE HANFORD PRODUCTION REACTORS

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This document classified by
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Reactor Engineering Unit

HANFORD ATOMIC PRODUCTS OPERATION
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ERRATA IN DOCUMENT HW-66363

1. Page 12, Line 34:	The number "67" should be "47". The word "southwest" should be "southeast".
2. Page 14, Line 24:	"Figure 3" should read "Figure 4".
3. Page 14, Line 28:	"Figure 4" should read "Figure 3".
4. Page 15, Line 3:	The word "fault" should be "faults".
5. Page 15, Line 44:	The phrase "bank No. 4436" should be "bank No. A-336".
6. Page 15, Line 52:	The Phrase "635 MCM-ACSR" should be "636MCM-ACSR".
7. Page 15, Line 52:	The number "635,000" should be "636,000".
8. Page 17, Line 38:	Insert the number "125" between the words "by" and "volt".
9. Page 18, Line 41:	The word "destruction" should be "construction".
10. Page 19, Line 3:	The word "backs" should be "banks".
11. Page 19, Line 31:	Delete the "v" after "60".
12. Page 19, Line 34:	The phrase "by two 2500 KVA" should read "by one 5175 KVA and one 5000 KVA".
13. Page 19, Line 35:	The number "3000" should be "3250". Appropriate changes should be made on Figure 11.
14. Page 22, Line 12:	Change the word "manually" to "electrically" and delete the word "and".
15. Page 23, Lines 29: and 30:	Each "P and P" should read "P_4 and P_5". Correct Figure 6: Points P_4 and P_5 should appear at points of junction of F reactor stub lines and the loop.
16. Page 23, Line 38:	Delete the word "two".
17. Page 25, Line 44:	The phrase "bypass OCB" should be "bus tie OCB".
18. Page 26, Line 5:	The phrase "line No. 1 from the east" should read "line No. 2 from the east".
19. Page 31, Line 30:	The complex number shown as "K3.00-j29.00" should be "53.00-j29.00".

HW66363.

20. Page 36, Line 4: The number "1235" should be "1066" and the number "1425" should be "1230".

21. Page 41, Line 29: The equation shown as "$E = 1 - \frac{1}{1!} - \frac{1}{2!} - 1/3$ - - - -" should be "$E = 1 - \frac{1}{1!} - \frac{1}{2!} - \frac{1}{3!}$ - - - - - - $\frac{1}{N!}$"

22. Page 42, Equation (2): The symbol X_d should be X_d''.

23. Page 43, Line 19: The word "expolore" should be "explore".

24. Page 70, Figure 11: The 13.8/2.4 KV transformer banks serving 181-B and 181-C are now rated: No. 1 - 4500/5175 KVA, No. 2 - as shown, No. 3 - 4500/5000 KVA, No. 4 4500/5000 KVA.

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ERRATA IN DOCUMENT HW-66363 (SECRET) BY FLOYD D. ROBBINS

Attached is a list of errata identified as existing in the above document. Identification is by page number and by line number using a multilith edge counting the first typed line as 1.

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TABLE OF CONTENTS

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LIST OF ILLUSTRATIONS

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LIST OF TABLES

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I. INTRODUCTION

Safety has been and must continue to be the inviolable modulus by which the operation of a nuclear reactor must be judged. A malfunction in any reactor may well result in a release of fission products which may dissipate over a wide geographical area. Such dissipation may place the health, happiness and even the lives of the people in the region in serious jeopardy. As a result, the property damage and liability cost may reach astronomical values in the order of magnitude of billions of dollars. Reliability of the electrical network is an indispensable factor in attaining a high order of safety assurance. Progress in the peaceful use of atomic energy may take the form of electrical power generation using the nuclear reactor as a source of thermal energy.

Production of fissionable materials and power must, however, be accomplished as continuously and as efficiently as possible. The production of electrical power would make the Hanford network an integral part of the power grid of the Northwest which may require a rigorous compliance with utility operating reliability. In view of these factors it seems appropriate and profitable that a critical engineering study be made of the safety and reliability of the Hanford reactors without regard to cost economics.

The author's charter was to make this individual and independent technical engineering analysis without regard to Hanford traditional engineering and administration assignments. The main objective has been to focus attention on areas which seem to merit further detailed study on conditions which seem to need adjustment but most of all on those changes which will improve reactor safety. This report is the result of such a study.

II. SUMMARY

The study included all reactor areas except that the material for the K areas was extracted from a previous report and included for convenient references.[1] Emphasis has been on the consideration of the electrical engineering aspects of the problem viewed as an integrated network serving highly hazardous loads. The trend in the nuclear reactor operation has been toward ever increasing production and, therefore, toward ever increasing electrical power demand. As electrical equipment approaches its maximum capability, more care and precision must go into the operation and maintenance of the system. Each component must be scrutinized carefully to be certain that it performs its function with precision and, if it does not, to replace it. This report discusses the results of a critical engineering investigation of the safety and reliability of the entire electrical distribution system from Midway switching station of the Bonneville Power Administration to the point of use in each reactor.

Every aspect of operation, control, protection, capability and reliability of the electrical system was carefully evaluated by considering previous documents, making field surveys, discussing procedures with personnel, studying and updating existing drawings and specifications and by actually taking field data. This evaluation was then critically examined in the light of rigorous safety criteria for conformity. A comprehensive bibliography was prepared to support each section of this report. Records of data

[redacted]

were found to be not complete; drawings were found to be outdated so that they did not reflect changes. Simplified one line diagrams, as accurate as time would permit, were prepared and are included in this report with the hope that they will aid and assist all concerned in a better understanding of the electrical system. Some comments concerning personnel training and administration have been included without supporting documentation where such items seem to affect the safety and reliability of the electrical system.

III. CONCLUSIONS AND RECOMMENDATIONS

The following salient conclusions are supported by detailed discussion in the body of the report:

1. The 230 KV transmission lines are adequate for presently predicted needs to 1965.

2. If power is to be exported from N Reactor then transmission line capability must be evaluated in terms of the generator size finally selected.

3. Automatic reclosing after loss of 230 KV power offers definite possibilities.

4. Present division of load on the three high voltage transmission lines is inequitable.

5. Division of predicted future loads on the three high voltage transmission lines will be inequitable with the present network.

6. Operation of the present loop under critical power conditions is unsatisfactory.

7. Main 230/13.8 KV transformer banks are approaching critical loading especially upon loss of a bank.

8. An intertie to the 115 KV Benton-Franklin transmission line offers an alternate source of emergency power of about 150 MVA especially valuable in the event of complete outage at Midway.

9. Operation of the 13.8 KV synchronous motors could be improved by grounding the neutral.

10. There have been sufficient stator failures in the 4500 HP synchronous motor to justify rigorous testing.

11. Automatic reclosing to at least two process pump motors (4500 HP) after loss of power seems highly necessary.

12. An automatic emergency lighting system independent of the BPA supply and the emergency generator is needed. The present emergency portable battery lamp units should be considered as last ditch evacuation lights only.

[redacted]

The following conditions not supported by documentary references seem to prevail:

1. There is need for additional knowledge of electrical system fundamentals on the part of those concerned with its operation.

2. There is need for additional understanding on the part of operators of electrical equipment outside their immediate domain.

3. Effective and efficient handling of electrical system problems would be significantly improved by centralized coordination.

It is therefore recommended that:

1. An engineering study be initiated with a view to interconnecting the present system with the Benton-Franklin line through 230/115 KV transformers.

2. Serious consideration be given to the better utilization of the existing 795 MCM-ACSR transmission line known as No. 3.

3. Automatic fast reclosing of transmission lines be favorably considered.

4. Necessary steps be taken so that electrical power be restored to one or more main process pump motors with as little delay as feasible following loss of power.

5. Serious consideration be given to increasing the 230/13.8 KV transformer capacity especially at B-C area, D-DR area, H and F area.

6. An emergency lighting system be provided in strategic operating areas.

7. An educational seminar be inaugurated covering fundamentals of electrical power systems and their operation.

IV. CRITERIA FOR REACTOR SAFETY

The parameters of nuclear reactor safety have never been defined on a national basis or formulated in a set of standards such as the AIEE-ASA Standards in common use in the electrical engineering field.[2] Engineering criteria based on calculated risk and assigned factors of safety cannot be applied to the nuclear reactor because of the tremendous loss of life and property which would ensue upon reactor excursion, runaway and meltdown. In the past, most reactor installations were isolated and restricted, thereby forcing each to compose its own set of criteria for safety control and safe shutdown in case of malfunction. The advent of nuclear power generating plants such as Shippingport,[3] Indian Point,[4] Dresden,[5,6] Yankee,[7] and Fermi,[8] however, has focused attention on the problem since such stations will naturally be located near load centers and therefore near heavily populated areas. Dresden, for example, is located 47 miles from Chicago and will operate at a reactor thermal level of 626 megawatts.

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These plants must operate at a very high plant factor if they are to produce electric power economically and they must do this without endangering the life, health, and property of the public. Property liability from release of fission products from a meltdown of a Hanford pile such as K reactor has been estimated to be in the order of magnitude of from \$1 x 10^9 to \$10 x 10^9 (1,000 to 10,000 megabucks).[9] Ordinary factors of safety engineering cannot be applied here. Probability and calculated risk are not acceptable measures of reactor liability no matter what may be the end product of operation. The one chance in a million or "once in 25,000 years" may happen tomorrow with possible resultant catastrophe. Reactors must operate at the same high plant factor as other manufacturing equipment but with the probability of release of fission products approaching zero as a limit. This means safety protection in depth and, after all safety systems have failed, the ability to shut down without danger to life and damage to property outside the reactor building.[10] Even under conditions of total destruction of the reactor, fission products must be contained or confined to the immediate reactor area without danger to personnel. In a rather philosophical paper, Carson[11] quotes from McCullough, Mills and Teller,[12] " . . . there is encountered the necessity for attempting to define the notion of reactor safety, and what this notion shall include. Of course, absolute safety is not possible and what is really meant in connection with reactor hazards is the minimization of hazards until one has an accepted calculated risk." If both the requirements of continuity of operation and safety are to be satisfied, then it follows that the cooling system must be as perfect as possible, utilizing the best equipment available and the best engineering practices.[13] Performance of such a system under steady state conditions is dependent upon skill of the operators, maintenance, surveillance, and power supply. Failure of power supply may be caused internally by lack of skill, poor maintenance or careless surveillance, or by outside factors. Power failure may be either sustained or transient. Long term or sustained power failures must be corrected by substitution of an alternate system, the secondary system, and if this fails, by a second alternate, the tertiary system.

If the power supply of the primary system and the secondary system are both electrical, the transition can be completely automatic and with no time delay if the secondary system is already paralleled and is of adequate capacity. This also holds true if the secondary system is paralleled and the load is switched down to the capacity of the secondary system by suitable relays. This presumes that the reactor is adjusted, that such reduced electrical load provides sufficient cooling.

This thesis has been used throughout this report in judging the reactor system reliability.

The Hanford Operation, in the absence of any generally accepted standards, has developed its own set of criteria for reactor safety. These criteria have been most ably presented by Trumble,[9] and others.[14,15] Sufficient cooling of the fuel elements and control rods must be provided under all conditions of operation of the reactor. Present Hanford criteria for reactor cooling system reliability under all conditions except acts of war and sabotage require three independent and dependable sources of cooling as follows:

1. Primary Cooling System

   The primary cooling system shall provide adequate reactor cooling during all phases of operation and shutdown.

2. Secondary Cooling System

   The secondary cooling system shall be independent of the primary system, except for common piping and shall be capable of providing adequate shut-down cooling indefinitely under conditions of total loss of power to the primary system. It is permissible for the secondary system to contribute to the flow provided by the primary system during normal operation.

3. Tertiary System

   The tertiary system must provide adequate flow indefinitely under shut-down conditions with complete and concurrent loss of power to the primary and secondary systems. It shall be independent of both the primary and secondary systems including piping as far as the reactor manifolds.

An additional criterion specifies that failure of a single piece of equipment shall not cause failure of the entire system. This criterion merits some discussion because it is practically impossible to apply to the operation of the electrical system without interpretative stipulations.

In general, sustained failure of a piece of electrical equipment has no effect on the system except loss of function because such failure isolated the stricken equipment quickly and completely. Here, quickly means 3 cycles on a 60 cycle per second base or (0.05 second). Not all breakers operate this fast, especially on the low voltages, but the time element is of this order of magnitude for the major pieces of equipment involved in this discussion. In addition to this, the protective equipment may substitute an alternate piece of equipment motivated by the same signal that shut the stricken equipment down. In the case of transient faults, relays may perform an additional function of restoring the system through fast reclosing of the protective circuit breakers. Speed of restoration is in the order of magnitude of 17 cycles or 0.283 second. For example, a lightning strike on a transmission line is dissipated in a few microseconds, so that reclosure time is only limited by the duration of arc restrike conditions which is usually not more than 17 cycles.[16] The modified criterion for electrical equipment indluding transmission facilities includes consideration of:

a. Speed and dependability of separation of the circuit involved.

b. Speed and dependability of transfer to alternate equipment.

c. Speed and dependability of restoration of the circuit involved.

Detailed steady state and transient stability studies are beyond the scope of this report, but the fundamental principles involved have been taken into consideration.[17,18]

[redacted]

Modern thermal-electric power plants using nuclear fission as the primary heat source have all the electrical problems associated with conventional plants plus many new ones peculiar to the use of the nuclear reactor as heat source. Conventional plants have an enviable record of continuity of service built around assurance of fail-proof auxiliaries. This assurance has been attained by technological improvement in fast and reliable relaying, more dependable electrical switchgear and motors, elimination of human error by automation and by advancement in intelligence and instrumentation equipment. Assurance of continuity of operation based on these factors alone is not adequate for the modern plant using high temperatures, super pressure, and very large unit ratings because of the rigorous requirements of safe operation.(19,20,21) These extremely exacting demands for continuous operation with safety have been met by a horizontal electrical back-up system utilizing a multiplicity of independent sources of electrical power. The philosophy here has been that the power supply to auxiliaries shall not fail but in the event of complete electrical failure and as a last resort to go to steam driven auxiliaries.(22,23) This mode of operation is regarded as a shutdown "no other choice" or as a short term proposition enduring only until electrical supply can be restored. The accent has been put on high speed restoration of electrical power.(24,25) Over the years the records show that the philosophy is sound.(26)

Continuity of operation of the nuclear power plant for supply of electrical power to a utility network has suddenly focused attention on how to best accomplish the rigid continuity requirements of the conventional thermal plant and to satisfy the much more rigorous safety requirements of the nuclear plant as well.

In the nuclear portion of the plant "factor of safety" engineering is not enough even if the probability is 1: 25 x 10^6.(27,28,29) In the case of electrical power generating plants using nuclear reactors, the problem of safety is even more acute than the Hanford reactors because of the proximity of these new plants to major population centers. Dresden,(30,31,32,33) a 180,000 KVA plant is located 67 miles southwest of Chicago, Indian Point, a 275,000 KVA plant, is located 24 miles north of New York City.(34) Dresden station, for example, has four sources of electric power to its auxiliaries, its own main generator buses, a transformer tied into the 13.8 KV system and another tied into the 34.5 KV system of the Commonwealth Edison Company and a Diesel driven emergency generator.(5,6) Indian Point also has four distinct power sources, its own main generator buses, transormers connecting to the 13.8 KV system of the Consolidated Edison Company, a similar connection to another line of the same company, and a transormer connection to the lines of Orange and Rockland Utilities.(35,36,37) If an emergency generator (house generator) is included in the design, a fifth source will be available.

With the advent of production of electrical power from NPR, the Hanford electrical system will become a part of the Bonneville Power Administration high voltage grid.(38,39) The BPA system is an integral part of the Northwest Power Pool. Even though the original generating unit will be small, operation must be integrated into the network and the HAPO electrical system should be examined in the light of modern electrical system practices. Progress in the peaceful use of nuclear energy may result in all reactors at Hanford being examined for the possibility of utilizing heat energy not now utilized for production of electrical energy at least on a dual basis. At the present thermal level and a reasonable thermal-to-electrical conversion ratio this would represent a significant contribution of badly needed non-hydroelectric energy to the northwest electrical system. Whether electrical power production will proceed beyond the present plans for NPR is problematic; nevertheless, it is a possibility and the electrical system should not be a deterrent factor.

The philosophy evolved in the preceding discussion as applied to the Hanford reactors would require that the high voltage network be restored as fast as possible after loss of 230 KV power. The ideal would be to restore the entire electrical network after such a failure fast enough so that there would be no perceptible pause in electrical supply and no tripout of electrical equipment.

V. REACTOR COOLING

Nuclear reactor safety discussed in the preceding section depends upon a continuous and adequate supply of suitable coolant during starting, during operation, during and following shut-down.[40,41] A classic delineation of the situation was made by Trumble:[42]

> "A disaster at Hanford would, by definition, involve the large scale release of radioactive fission products to the surrounding countryside. Such a release can occur only if the fuel elements (slugs) melt, and perhaps oxidize, in the reactor . . .
>
> "It is believed that no disastrous release of airborne fission products is possible as long as adequate cooling water can be supplied to a Hanford reactor. Conversely, loss of cooling water (unless the reactor has been shut down for a very long time prior to the water loss) will almost surely result in destruction of the reactor and probably in the large scale release of fission products. This destruction will occur even though the reactor is made sub-critical by insertion of the safety rods immediately upon loss of water."

Recent modifications to B, D, DR, H, F and C reactors has made the situation even more imperative, in view to the increased production and consequent increased heat release.[43,44] The incentive for the modification has been the demand for increased output of product.[45,46,47] The significance of the changes as reflected in increased water fow is graphically illustrated by the following tabulation:[42]

	BEFORE PROJECTS		AFTER PROJECTS	
Reactor	Flow Rate GPM	Power Level MW	Flow Rate GPM	Power Level MW
B	48,000	900	74,000	1,800 max.
C	83,000	1,700	88,000	2,000 max.
D	53,000	1,000	74,000	1,800 max.
DR	50,000	1,000	74,000	1,800 max.
F	47,000	1,000	74,000	1,800 max.
H	57,000	1,200	74,000	1,900 max.

Details of the motor driven pump units to provide the flow listed above are shown in tabulated form in Section VI along with the driving motors. Basically B, D, DR, F and H reactors are almost the same as far as the main process motors are concerned. C reactor has a unique arrangement. Both types of main pump units will be also illustrated in Section VI. Simplified process water flow diagrams were drawn and are shown in Appendix B as Figure 1 for C reactor and Figure 2 as typical of B, D, DR, H and F reactors.

The shut-down flow is extremely important as indicated previously because scrams generally result from some malfunction. The water flow requirements are sized by the shut-down transient. A generalized curve is shown in Appendix B, Figure 3 and graphically illustrates the extreme importance of the time element in dealing with coolant supply. The coordinates used are Reactivity in inhours as ordinates, and Time after shutdown as abscissae. The flows demanded by the reactor corresponding to the shut-down transient and presuming loss of electrical power are shown in Appendix B as Figure 4.

VI. DESCRIPTION OF THE HAPO ELECTRICAL DISTRIBUTION SYSTEM

The power supply for the Hanford Atomic Plant is basically a part of the network of the interconnected Northwest Power Pool.(48) At the present time this consists of all the transmission and generating facilities of the geographic region from the Continental Divide west to the Pacific Ocean and from Canada (including British Columbia Electric) southward to California. The generation is predominately hydroelectric and badly in need of thermal generation plant back-up because of the adverse seasonal flow of the principal rivers in the region.(19) The backbone of the transmission grid is the 345 and 230-Kilovolt system of the Bonneville Power Administration.(49,50) This grid interconnects the various hydroelectric plants operated by the Bureau of Reclamation and the Corps of Engineers,(51) which includes most of the large power generating plants of the pool. At present and including generator number 13 at The Dalles,(52) the peaking capability in megawatts (1000 kilowatts) is over 7000. Numerous municipal, private, and utility district systems are served by the federal systems and thus are interconnected by the BPA network. By virtue of this fact and the size of network, the BPA organization controls the power system of the northwest.

Power from the federal plants is fed into the network through suitable switch yards at the generating plants over transmission lines to suitably located switching or substations.(53) Fault protection is attained by a system of very fast breaker operation controlled by high speed relays. The intelligence and relay system utilized microwave, carrier, shortwave radio and land telephone lines.

Electrically the power network is a grounded star system wherein zero sequence current can be utilized for sensitive fault relaying. This is especially important since approximately 80% of all power system fault are line to ground (zero sequence).(54) In general faults are cleared on the system by oil circuit breaker with a 3-cycle opening time (on a 60 cycle per second base). These breakers are generally also "single shot reclosing," which simply means they are automatically controlled by relays which cause the breakers to reclose immediately after opening. The reclosing time is approximately 17 to 20 cycles, thus making the restoration time following a fault about 20 to 23 cycles or 0.333 to 0.383 seconds. This time interval is usually sufficient to clear most transient faults with a scarcely observable flicker and well within the stability limits of the system. The inherent power capability of the network is behind time faults and is limited by line and generator impedances but may be very large so that these breakers in some instances must have an interrupting capability of 20,000 megavolt-ampere (20,000,000 KVA). These are extremely important considerations in dealing with the Hanford network and will be treated in more detail later. The system is so large and the protection so complete that a complete loss of BPA power may be considered an impossibility. The network in comparison to the HAPO system may be considered to be an infinite bus.

Hanford is connected into the power pool through the BPA at Midway switching station.(55) A simplified one line diagram of Midway was prepared for use in this report and is shown here as Figure 5. Standard (AIEE-ASA) graphic symbols have been used on this and all other electrical diagrams in this report.(56)

Midway is typical of the high voltage major switching stations discussed above. 230 kilovolt lines from Grand Coulee feed directly into the station; another 230 KV line connects directly to Columbia switching station thus connecting Midway to Rock Island and Chief Joseph. Priest Rapids, according to present plans, will also be tied into Midway. Lines to the south connect to Big Eddy switching station and therefore The Dalles and McNary lines. All lines are protected by 3 cycle single shot reclosing oil circuit breakers of 7500 to 15000 MVA interrupting capacity. Midway may be classified as having a double bus system with sectionalizing breakers. Any faulted line or section may be quickly cleared even those faults within the station, thus leaving other lines energized and operating. Three of the outgoing 230 KV leaving Midway go to the Hanford Atomic Products Operation and are connected to three different bus sections. These three lines are protected by reactance distance, ground directional overcurrent, impedance and timing type relays controlling fast opening (3 cycle) oil circuit breakers.(57,58) The lines are designated No. 1, 2, and 3 as shown on Figure 5. Line No. 1 is connected to bus section No. 3 through oil circuit breaker bank No. 4336 having an interrupting capacity of 15,000 MVA. Line No. 2 is connected to bus section No. 1 through oil circuit breaker bank No. A114 rated at 15,000 MVA. Line No. 3 is connected to bus section No. 2 through oil circuit breaker bank A56 rated at 15,000 MVA. These breakers are not equipped with recloser relays.

Lines No. 1 and No. 2 are typical wood pole H frame lines with 635 MCM-ACSR (635,000 circular mil-aluminum cable steel reinforced) and No. 3 is a standard BPA steel tower line with 795 MCM-ACSR conductors. All are 3 phase designed for 60 cycles per second alternating current 230 KV (230,000 volts)

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or higher. The steel tower line could be used for higher voltage. The layout of these lines is shown on Figure 6, a simplified geographic one line diagram. Each of the wood pole lines is protected by a more than adequate overhead grounding wire and a buried counterpoise to which it is grounded. Lightning faults should be harmless and pole fires from leakage to ground practically eliminated. The pole lines were not originally treated with preservative so that the poles are in process of being stubbed. This will increase the fire hazard which is always present with wood pole lines. A bad prairie fire could incapacitate either or both of these lines. Line No. 3 is an excellent steel tower line but has no overhead grounding wire but towers are well grounded. History of faults on these lines indicates that practically all have been line to ground.[59,60] Lines No. 1 and 2 are connected to reactors H and K by steel tower lateral lines and to reactors B, C, D, DR and F by wood pole lines. Line No. 3 extends entirely across the area and terminates at point P where it is interconnected to the lines No. 1, 2 loop through a switch which is normally open as shown. The length of line from the K reactor tap point P_2 to point P_1 is thus not utilized in normal operation. Points designated are shown on Figure 6. Salient features of the HAPO high voltage distribution network are shown on Figure 7, a simplified one line schematic diagram of the system. Graphic symbols used are standard as shown in ASA Y32.2.[58] Oil circuit breaker ratings are shown in MVA and have been checked against field data corrected to September 15, 1960. Various documents relating to the subject in part or wholly were abstracted from the early work of Bergdahl[61] to that of Maxwell,[62] and including two capacity studies by Hoffman.[63,64] Information of the NPR reactors was obtained from recent documents by Mollerus.[65,66,67] Some supervisory control over the system is maintained by the dispatcher at station A8 (Building 251) Figure 8. Basically 230 KV is brought into switchyards at each reactor where the voltage is stepped down to 13.8 KV by suitable transformers. Each reactor has a separate control room as shown on Figures 9 and 10 for these functions and metering which are supervised by operators under the supervision of the dispatcher mentioned above. The oil circuit breakers at each end of the three main lines at Midway and the reactors will open under 3 phase line to line faults (positive sequence), single phase line to line (negative sequence) and line to ground faults (zero sequence) and clear the lines but none will reclose automatically.

KE and KW Reactors

The K reactors are not part of this study, but the following material from HW-61887 is quoted verbatim for convenience. References and figure numbers refer to that document.

> "At each K reactor the power from two parallel 230/13.8 KV, 50 MVA (50,000 KVA) transformers is fed into the low voltage distribution network. Control of the metering and switching of this system is under the direction of separate operating groups and is not supervised by the load dispatcher. The switch gear and metering equipment are in a separate room as shown on Figure IX. Electrical details of the low voltage network are shown on Figure X, a simplified one line diagram of the system which conforms to ASA standards.

"Briefly 3 phase power at 13.8 KV is fed into two 13.8 KV busses intertied through two sectionalizing breakers.[7 and 10] The tie breaker is also extended to the other K reactor through a suitable breaker (9) and cable. The breaker at one + reactor is kept normally open and at the other normally closed. Each regular bus section serves 2-13.8/4.16 KV, 5 MVA (5,000 KVA) transformers all in parallel and 3 - 10,000 HP wound rotor induction motors driving 30,000 g.p.m. centrifugal pumps (high lift or secondary). The transformers are protected by air circuit breakers (ACB) No. 1, 6, 12, and 17, the pump motors by ACB's No. 2, 3, 4, 14, 15, and 16.

"The secondaries of the four transformers (IT1, IT2, IT3, and IT4) are connected to busses A, B-E, C-F, and D respectively, by ACB's 4, 17-17A, 26-26A and 38. The 4.16 KV network is a modified double bus system sectionalized. Essentially the bus sections E and F form the main bus and is sectionalized by two breakers 21A and 22A and bus sections B and C form two sections of an auxiliary bus sectionalized by breakers 21 and 22. Bus B is extended to form the single bus A from which it can be sectionalized by ACB No. 5, in like manner Bus C is extended to form the single bus, D, from which it can be sectionalized by ACB No. 36. Six river pumps driven by 1500 HP squirrel cage induction motors, six primary (low lift) pumps driven by 900 HP squirrel cage induction motors, four service water pumps driven by 300 HP squirrel cage induction motors, two hot water circulating pumps driven by 250 HP squirrel cage induction motors, two back-wash pumps driven by 300 HP squirrel induction motors, six 1000 KVA - 4160/480 volt transformers, three 500 KVA - 4160/480 volt transformers and a fence lighting circuit are all served from the 4.16 KV system. The primary power supply is BPA through the four 5000 KVA transformers, the secondary power supply is from three 5000 KVA steam turbine driven alternators connected as shown. Normally two of these generators operate at once in parallel with the BPA system at partial load. The third generator is kept in cold reserve. Details of the pump and the cooling water system are presented by Shoemaker in a separate document.[51] Circuit breaker operation is controlled by volt direct current furnished by storage batteries which are kept charged by motor-generator sets driven by alternating current motors supplied from the 480 volt system. There is no auxiliary charging source for backup. Breakers may be operated manually by operators or automatically by suitable relays. The customary potential instrument transformers and current instrument transformers are provided for relay, signal circuits and metering. Details relating to relays and metering circuits are purposely omitted from Figure X for the sake of clarity. Details of relaying and metering are shown on Drawings No. H-1-25858[19*] and H-1-25860.[20]

"Briefly the 230 KV incoming circuits are protected by OCB's, No. A-376, A-374 and A-372 (Ref. Figure VI) for KW and by OCB's No. A-396, A-394, and A-392 for KE. These breakers are controlled by bus differential, transformer differential, overcurrent, overcurrent ground, overcurrent ground backup, overvoltage and under-

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voltage relays. In addition, bus No. 1 and 2 have a synchronism check relay if OCB No. 374 is open (A-394 for KE).[52] Table I is a tabulation showing the circuit location, G.E. type, reference number and ASA function number,[53] of the relays protecting the 230 KV system.[54 to 60] NOTE: Refers to sequence number in Appendix A III REFERENCE DRAWINGS. The 13.8 KV system consisting of the transformer secondaries, the secondary breakers No. 5 and No. 13 and the 13.8 KV busses are similarly protected with transformer overcurrent, ground overcurrent, transformer differential and bus differential relays on both the 13.8 KV bus and the 230 KV lines and overcurrent and residual ground relays on the 13.8 KV breaker. The 10,000 HP high lift pumps motors on the 13.8 KV bus are protected by thermal overcurrent relays. Details of the 13.8 KV relaying are shown in Table II. The secondary (high lift) pump motor breakers are interlocked with the primary pump (low lift) breakers so that the secondary pump cannot start until the primary pump is operating. KE is a duplicate of this arrangement.

"The low voltage system (KW) consisting of four 13.8/4.160 KV transformers, the 4.16 KV busses the various loads on the 4.16 KV busses and the transformers serving lower voltage is protected by suitable relays on the 4.16 KV and busses and trip breakers on the lower voltages. In general, motor loads are protected by thermal overcurrent relays, the busses and transformers by bus differential, transformer differential, transformer overcurrent, and ground overcurrent relays.

"The generators are protected by overcurrent, ground overcurrent, differential field and directional overcurrent relays. The generators have the usual regulating equipment, voltage regulators, speed adjustment, synchronizing plug lockout overspeed turbine trip and field trip out on internal fault. KE equipment is essentially the same as that in KW. Table III shows the location and types of relays on the low voltage system."

B and C Reactors

B and C reactors receive electric power at 230 KV through 151 B substation connected to Midway No. 1 to the westward and a tie to KW substation to the eastward as shown on the simplified one line diagram. Appendix B, Figure 7. Essential details of the destruction is shown on a simplified one-line diagram Appendix B, Figure 11. The major equipment served is shown in tabulated form in Appendix C, Table A. The one-line diagram was drawn from existing drawings updated from field data.[68,69,70,71] The objective here was to provide an easily read one-line diagram using standard symbols for clarity in discussion. Simplicity may have been attained by the loss of detail, and it is recognized that there may exist some omissions of changes or additions made but not documented; but in the main, this and other similar drawings provide a graphic picture of the reactor circuitry.

Briefly the two 230 KV lines are brought into the 151 B (A2) substation and on to two high potential busses A and B. Bus A is protected by oil circuit breakers (OCB's) No. A322 on the Midway side and by OCB's, A326 on the K reactor side. Two main transformer banks No. 1 and No. 2 (Figure 12) are served from this bus. Bus B is protected by OCB No. A323 on the Midway side and by OCB No. A325 on the K reactor side. A third transformer bank is connected to this bus. All three backs are 3 phase, 60v cycle, 230/13.8 KV transformers rated at 31,250 KVA (31.25 MVA) and connected grounded star on the high voltage side (230 KV) and delta on the low voltage (13.8 KV) side. These transformers supply power to the 13.8 KV bus through suitable circuit breakers. The 13.8 KV bus system is arranged in four bus sections, a rear bus made up of sections No. 1 and No. 2 intertied by breaker No. C2-X80 and a front bus made up of sections No. 3 and No. 4 intertied by breaker No. C2-X 70. Transformer bank No. 1 is connected to bus No. 1 by breaker No. C2-X 100 and to bus No. 2 by a companion breaker also numbered C2-X100. In similar manner transformer bank No. 2 is connected to busses No. 1 and No. 2 by a similar pair of breakers numbered C2-X 200. Transformer bank No. 3 is connected to busses No. 3 and No. 4 by a pair of breakers numbered C2-X 300. For simplicity the word breaker and the symbol used indicates in each case a 3 phase breaker bank. These transformers are normally operated in parallel on the high voltage side but separated on the low side. As shown, transformer No. 1 is operated with the breaker to bus No. 1 closed and the breaker to No. 2 bus open. Transformer bank No. 2 is operated as shown with the C2-X 200 breaker to bus No. 2 closed and the breaker to bus No. 1 open. Thus the secondaries are not paralleled but serve only the load connected to the respective busses. The third transformer bank is operated with both C2-X 300 breakers closed and is thus connected to both bus sections No. 3 and No. 4 and serves the load connected to both these busses. Attention is invited to the fact that the three transformers could be all operated in parallel on both the high and low voltage sides by operating with all C2-X 100, C2-X 200, and C2-X 300 and the tie breakers C2-X 70 and C2-X 80, closed.

The eight main cooling water pump motors for B reactor are 13.2 KV, 3 phase, 60v cycle, 4500 HP synchronous connected through breakers to the 13.8 KV busses.

The river pumps 181 B, are served by two 2500 KVA, 13.8/2.4 KV transformer banks, the pump motors in Building 182 B, by two 3000 KVA 13.8/2.4 KV transformer banks, the pump motors in 183 B are served by two 3000 KVA 13.8/2.4 KV transformer banks. All these motors are squirrel cage induction type.

Since the 4500 HP synchronous motors driving the main process water pumps at B reactor are of primary concern and because they are typical of almost identical motors in D, DR, F and H reactors they are illustrated in a recent photograph shown in Appendix B, Figure 13. The control room for these motors is also typical of the other reactors and is illustrated in Appendix B, Figure 14.

C reactor is supplied with electrical power from the 13.8 KV bus structure described for B reactor.

The major groups of motors are shown in tabulated form in Appendix C, Table A.

The main cooling water pumps in this reactor are driven by ten 3500 HP, 3 phase, 60 cycle, 4.16 KV induction motors. Each motor is served by a separate 3 phase, 13.8 KV busses through a Δ-Y connected 13.8 KV/4.16 KV, transformer bank. A typical motor-pump set and its control panel at the control room in 190 C Building are shown in Appendix B, Figure 15 and Figure 16. The pump sets are unique to this reactor and consist of a 10,000 g.p.m. centrifugal pump, a speed reduction gear, a flywheel, the drive motor and a 400 HP steam turbine all connected together on one horizontal shaft as clearly shown in Figure 15. The turbines are kept hot at all times and are automatically supplied with steam upon failure of the electrical power supply. There is space provision in the control and pump rooms for two additional pump sets, transformers, and controls when needed for increased production levels.

Certain vital loads in each reactor group are supplied with emergency power automatically upon 230 KV power failure by two steam turbine driven alternating current 750 KW, 2.4 KV generators located in the 184 Building.

D and DR Reactors

As in the case of B and C reactors, both D and DR reactors are supplied with electrical power through one high voltage switch yard, Station A4, and a single 13.8 KV control and switch room, 151 D Building. A simplified one-line diagram[72,73,74,75] was prepared by updating existing one-line diagrams with field data, eliminating all confusing detail and arranging all essential switches and groups of motors in logical position on one sheet. This one-line diagram is shown in Appendix B, Figure 17. Details of the 230 KV system in relation to the other reactors is shown in Appendix B, Figure 6 and Figure 7 simplified one-line diagrams of the 230 KV system.

Electrical power at 230 KV is brought into the station (A4) by a 230 KV, 636 MCM-ACSR, H Frame, wooden pole transmission line from KE to the westward and by a similar line to H reactor to the eastward. The KE line is brought into the station through OCB No. A342 and the H reactor line through OCB No. A344 as is shown. The entire 230 KV network may be bypassed through a cross tie line with one air disconnect bank, not OCB's, normally kept open. There are four 13.8 KV bus sections served by 3 banks of 230/13.8 KV 31.25 MVA grounded star-delta connected transormer banks. Each secondary (13.8 KV) line is grounded through a zig-zag star connected grounding transformer and resistor. Transformer bank No. 1 can serve either bus section No. 1 or No. 2 or both through a pair of breaker banks X100 and transformer bank No. 2 can serve either bus section No. 1 or No. 2 or both through a pair of breaker banks No. X200. Transformer bank No. 3 can serve bus sections No. 3 and No. 4 through a pair of breaker banks No. X300.

Bus sections No. 3 and No. 1 can be connected through breakers No. X80 and bus sections No. 4 and No. 2 can be intertied by breakers No. X79. If a fourth transformer bank is required to increase the size of the process pump motor or add more process motors, the lines would probably connect into bus sections No. 3 and No. 4 by a new set of breakers.[76]

The main cooling water pumps in both D and DR reactors consist of eight 4500 HP synchronous motor-driven centrifugal pumps, making a total of 16 units. Individual lines at 13.8 KV connect each of these units to the 151 substation busses.

Each pumping unit is essentially the same as those in B reactor shown in Appendix B, Figure 13, and consists of the following components, all connected as a single horizontal unit:(77)

(190 D and DR Annex)

1. A 31 KW, 125 volt, D.C. generator (exciter).
2. A 4500 HP, 13.8 KV, 720 RPM synchronous motor.
3. A fly wheel whose WK^2 568-657 No. $ft.^2$
4. A flexible coupling
5. A 720/1800 RPM gear unit.
6. A two stage centrifugal pump rated at 10,400 GPM.

These and other major groups of motors were tabulated and are shown in Appendix C, Table B. Briefly, the connected motor load consists of 72,000 HP of synchronous motors and 23,500 HP of induction motors. There are fourteen 900 HP and one 450 HP induction motors in the river pumping plant (181 Building) operating from 2.3 KV busses in the same building served by 4 banks of 13.8/2.3 KV delta-delta connected transformers rated at 4687 KVA.

The motors in the 182 Building are connected to two 2.3 KV busses served by 2 banks of 13.8/2.3 KV transformers connected delta-delta and rated at 3,000 KVA each. As shown on Figure 17, the two busses may be operated intertied or as separate busses, each connected to one transformer. The motors in 183 Building are similarily connected to two busses served by two 13.8/2.3 KV transformer banks connected delta-delta and rated at 3,000 KVA each. It should be noted that four of the pump units in the 182 Building, two 1000 HP units and two 450 HP units are export water pumps.

The two reactors have a common steam plant (184 Building) with five steam boilers rated at 225 PSIG and 100,000 pounds of steam per hour and one emergency fast start (12 seconds) steam turbine driven AC generator. This generator serves certain selected vital loads upon failure of the 230 KV electrical power supply up to its rating of 750 KW.

H Reactor

The next reactor in the network is H reactor located between D-DR areas and F area. Electrical power at 230 KV is supplied to the reactor through the high voltage switch yard station A5 and thence to the 151 H Building containing the 13.8 KV controls, busses, and switch gear. A simplified one-line diagram along the same lines as those prepared for B, C, D, DR and K reactors was prepared by updating existing one-line diagrams with all available field data.(78,79,80)

[redacted]

This schematic circuit diagram is shown in Appendix B, Figure 18.

Referring to this figure and the two high voltage simplified one-line diagrams (Op. Cit. Figure 6 and Figure 7), a 230 KV H frame, 636 ACSR transmission line from D-DR area to the northwest passes in front of H reactor where two 636 MCM-ACSR steel tower lines connect to the reactor switchyard (A5). The H frame continues on to the southward to F reactor, through a bypass normally operated open. The line from the D-DR side enters the switchyard (A5) through OCB, No. A-352 and the F area line through OCB, No. A-256. The two lines are normally intertied through OCB, No. 354. There is also a bypass line in the yard normally operated open. All breakers are manually controlled and by suitable relays to be discussed later.

In the 151 H Building the 13.8 KV bus is divided into four sections, front bus sections No. 2 and No. 4 and near bus sections No. 1 and No. 3. Busses No. 2 and No. 4 may be intertied through breakers C5 x 80, and busses No. 1 and No. 3 may be intertied by breakers C5 x 70. Power is furnished these busses by two 230/13.8 KV, star-delta connected transformer banks rated at 31,250 KVA each and designated bank No. 1 and bank No. 2. Bank No. 1 may be connected to bus No. 1 on the front bus No. 2 by breakers C5 x 100 R and C x 5 100 F respectively. Bank No. 2 may be connected to either rear bus No. 1 or front bus No. 2 by breakers No. C5 x 200 R and C5 x 200 F. Operating all four breakers banks closed will parallel both secondaries and both busses No. 1 and No. 2 and both busses No. 3 and No. 4 through breakers C5 x 80 and C5 x 70. Either transformer may be connected to either the bus combination No. 1-3 rear or the combination No. 2-4 front.

The main cooling water pump group in H reactor consists of eight 4500 H synchronous motor driven centrifugal pumps. These motors are served by individual lines connected directly to the 13.8 KV busses through suitable circuit breakers. Each pump unit is essentially the same as those in B, D, and DR reactors and illustrated in the typical set shown in Appendix B, Figure 13. Each set consists of the following components connected as a single horizontal unit:(81)

1. A 31 KW, 125 volt, DC generator (exciter).
2. A 4500 HP 13.8 KV 720 RPM synchronous motor.
3. A fly wheel whose WK^2 is 568,657 No. ft^2.
4. A flexible coupling.
5. A 720/1800 RPM gear unit.
6. A two stage centrifugal pump rated at 10,400 GPM.

These and other groups of large motors are listed in Appendix C, Table C along with their nameplate ratings. Briefly, the connected motor load consists of 36,000 HP of synchronous and 15,785 HP of large induction motors. The 181 H Building containing the nine 600 HP river pumps is supplied by two banks of transformers rated 13.8/2.4 KV 5000 KVA and connected delta-delta. The transformers secondaries may be sectionalized with approximately equal loadings by the bus sectionalizing breaker X47 normally operated open.

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The motors in the 182 H Building are arranged on two approximately equal bus sections which can be sectionalized by breakers No. C5 x 55, normally operated open. The secondaries of the two 13.8/2.4 KV, 5000 KVA, delta-delta, transformers banks are then also isolated with approximately equal loads. It is noted that there is a 1000 HP export pump on each of these bus sections.

The bus arrangement in the 183 H Building is very similar to that in 182 H. The busses can be sectionalized by breakers X63 (normally operated open) thus isolating the loads on the two transformer banks. Each bank is rated at 13.8/2.4 KV, 5000 KVA, connected delta-delta.

The reactor has a steam plant, located in the 184 Building for supply of steam to the steam turbine driven process water pumps and to the emergency generator also located in this building.

Steam is supplied by four coal fired, water tube boilers rated at 225 psi, 100,000 pounds per hour with a twenty-four load capacity of 115,000 pounds per hour. The emergency generator is a 750 KW 3 phase, 60 cycle, 2.3 KV driven by a 3600 RPM non-condensing steam turbine capable of a 12 second start. The function of this generator is to take over automatically, certain vital electrical loads upon failure of the normal power supply, from the 230 KV network.

F Reactor

F area reactor is located generally southwesterly of H reactor. The A6 high voltage substation is connected into the high loop by two sub-transmission lines, both H frame construction 636 MCM-ACSR at points P and P. A bypass link between P and P is normally operated open, in contrast to H reactor there is no station bypass in substation A6. A simplified one line of the A6 switchyard, 13.8 KV circuit and the 2.4 KV network was prepared by up-dating existing drawings with all available field data.[82,83,84]

The completed one-line diagram is shown in Appendix B, Figure 19. Reference to this one-line diagram shows that the transmission line from H reactor enters the network through OCB No. 362 and the line to station A8 (251 Building) is connected through OCB No. 366, the two tie breaker OCB No. A364. OCB No. 362 was involved in a recent incident at F reactor presented in HW-66364 in which the circuitry of this breaker was discussed in some detail.[85] This discussion applies in general to the line OCB's in all the reactors. Busses in the 151 F Building are supplied by two banks of 230/13.8 KV transformers rated at 31250 KVA and connected star-delta. These banks are normally operated with their primaries (230 KV) in parallel, that is with OCB No. A364 normally closed. The 13.8 KV bus system consists of two identical busses designated the front bus and the rear bus.

These busses cannot be sectionalized. Transformer bank No. 1 can be tied to either (or both) front or rear busses by a pair of OCB's CX 100 F and C6X 100 R respectively. Transformer bank No. 2 is similarly connected through OCB's C6X 200 F and C6X 200 R. The secondaries (13.8 KV) of the transformer banks can and normally are operated not in parallel and thus, with segregated loads by use of the four breaker banks.

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The main cooling water pump group, almost exactly as in H reactor, consists of eight 4500 HP 13.8 KV synchronous motors driving two stage centrifugal pumps rated 10,400 g.p.m.

The description of each set is the same as for H reactor and is not repeated here. These pump motors are directly connected to the 13.8 KV busses through suitable OCB's. Four of these motors are on each bus and cannot be switched to the other bus. The physical appearance of the units is shown in Appendix B, Figure 13. All the other motors operate from 2.4 KV or lower voltage. The main groups of motors and their basic ratings were tabulated and are shown in Appendix C, Table D, along with the ratings of the 4500 HP motors.(86) All motors except the 4500 HP are induction type with the same general arrangement as in H reactor.

The river pump house (181 F Building) containing ten 450 HP induction motors is served by two 13.8/2.4 KV transformers banks rated at 3000 KVA each and connected delta-delta. The primaries (13.8KV) may be paralleled, even though connected to different busses by an air break type disconnect switch. The secondaries (2.4 KV) feed a bus which can be sectionalized, and normally is so operated, by a disconnect switch E6X 40. The motors in 182 F Building are arranged on two approximately equal bus sections which can be intertied by E6X 50 disconnect switches normally operated open so that the secondaries (2.4 KV) see segregated load groups approximately equal. In this group are two export pumps driven by 1000 HP induction motors, one on each bus section. The building is furnished power by two transformer banks rated 13.8/2.4 KV, 2500 KVA and connected delta-delta.

A very similar arrangement prevails in the 183 F Building where the motors are arranged on two bus sections which can be connected by the disconnect switch E6X 25, normally operated open, so that each transformer secondary sees a segregated load. The transformers are each rated at 13.8/2.4 KV, 3000 KVA and are connected delta-delta.

The steam power plant for this reactor is almost an exact replica of that in H reactor and is housed in the 184 F Building. Steam at 225 psi is supplied by four water tube boilers each rated at 100,000 pounds per hour and a twenty-four hour overload capacity of 115,000 pounds per hour, to steam turbine driven water pumps and to an emergency turbo-alternator set. The generator is driven by a non-condensing, 36,000 rpm, steam turbine capable of accelerating to synchronous speed in 12 seconds.

The generator is rated as 3 phase, 60v, 2.3 KV and 750 KW. Its function is to assume certain vital electrical loads quickly if the primary power supply is interrupted. The loads are about the same as in H reactor, including lighting and lines to 151 F Building, 182 F Building, and the loads in these buildings are:

151-F

182-F

183-F

184-F

[redacted]

Storage batteries furnishing 120v DC for operation of switch gear and emergency lights are located in 181 F, 182 F, 183 F and 151 F Buildings. Building 190-F has two such batteries. All batteries are kept fully charged at all times by suitable battery chargers. Protection is thus afforded against the possibility of not being able to do vital switching in the event of total loss of AC power.

SUMMARY

A number of salient facts emerge from the preceding discussion:

1. Reactors B, D, DR, F and H each have eight 4500 HP synchronous motors operating directly off the 13.8 KV, driving the main process water pumps.

2. All other motors are induction type.

3. Reactors KE, KW and C have large induction motors driving the main process water pumps.

4. Reactors B, C, D, DR, F and H each have a 750 KW steam turbine driven, quick start emergency generator for partial power supply normally operated as standby. KE and KW reactors each have three 5000 KVA generators as secondary power supply.

5. Electrical power supply from the 230 KV lines is supplied to the large motor busses at 13.8 KV by transformer bank connected star-delta with their primaries in parallel and their secondaries not parallel but serving segregated loads.

6. Reactors B, C, D, DR, F and H utilize 2.4 KV for other large motors (KE and KW, 4.16 KW) generally connected delta-delta with primaries isolated.

7. Grounding of the delta networks is accomplished by suitable grounding transformers.

VII. OPERATION OF THE HAPO ELECTRICAL SYSTEM

A. The High Voltage System

The 230 KV system is normally operated with the OCB's at Midway closed and with transmission lines No. 1, 2 and 3 energized. Each reactor area has a bypass OCB which is normally closed and a disconnect switch bypass which is operated normally open. H reactor area has two of these disconnect bypass circuits, both of which are operated normally open circuited. K reactor area has the air disconnect switch bypass around both K reactors, which is normally kept open. (See HW-61887.) In the event of a fault on the transmission lines, the relays on the breakers at the ends of the line in fault will open the breakers in three cycles, on a sixty cycles per second base, plus relay which is less than one cycle. This is in accordance with modern relay and circuit breaker practice.(87,88)

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Between reactors the two nearest breaker banks will open. K reactor area is in the peculiar position in that the receiver end of the three transmission lines may be considered as terminating there: line No. 3 direct from Midway, line No. 1 from the west through B-C reactor area and line No. 1 from the east through station A8, F reactor area, H reactor area and D-DR reactor area. Thus with No. 3 line out, lines No. 1 and No. 2 simply form a loop through the reactor areas in turn with both ends terminating at Midway. Critical power condition W and with line breakers open anywhere between KE reactor and the 251 Building (A8), some reactor area will be exposed to only one source of power, and No. 3 line is of no use in alleviating this condition. This is a strong argument for an intertie at point P_1 as recommended in HW-61887. This would be at the same point as the 115 KV line from Benton-Franklin as recommended in a later section of the present report. The line from the K area tap (point P_2) to point P_1 now exists and is not utilized. Attention is invited to the fact that if No. 3 line were tapped at each reactor similar to K (and including N), then the system would be a combination loop and radial system with No. 3 line operating nearer its capability with no portion of the system without two sources of power. A cross tie to the N area was considered as part of an analyzer study made in connection with the then proposed J reactor area.(89,90) This line would tap into the loop near the present load center. The point P_1 intertie is not near an existing substation, but this presents no great problem because the station need not be attended.(91)

Transmission lines No. 1 and No. 2 are H frame wood pole lines as already described but are unusually well protected against lightning strikes. Thunderstorms are infrequent so that the danger from lightning strikes is minimized. No. 3 line is not well protected because it lacks an overhead ground wire. Overall, the danger of outage from lightning and line faults seems small, but the possibility does exist and every precaution should be taken to make the reliability as great as possible. One way in which this reliability can be improved is by making the OCB's at the Midway end of the lines automatic "single shot" reclosing. Time is of the essence at a stricken reactor; and, in general, electric power should be restored as fast as possible.(28) Normally, the time for restoration of power by reclosing is from 21 to 25 cycles (0.350 to 0.417 seconds) from the time of fault. On sustained faults, breakers will open again in three cycles and stay open.(92,93) The question of closing into the load depends upon the conditions at the load busses. This subject will be discussed in detail in a later section of this report.

B. The Low Voltage System

The low voltage system is defined as that portion of the network other than the 230 KV portion. In general, the large size motors in B-C, D-DR, H and F reactors are operated on 13.8 KV and the smaller motors at 2.4 KV. Lights, controls, small motors and single phase motors are operated at other lower voltages provided by transformers, generally the standard 440 and 220-110 volt levels. Distribution circuit protection is standard and adequate,(94,95) consisting of relays and circuit breakers on the transformers and motors of the 13.8 and 2.4 KV levels and breakers or thermal fuses on the lower voltage levels.

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The problem of relay and fuse co-ordination has been given careful and extensive study. It seems to need little more comment except on a few special items.[96-101] It has been recommended that the undervoltage relays on the pump motor in the main pump house of B,D,DR and H reactors be removed because they cause unnecessary scrams and are deemed not needed as a result of maintenance studies and decay tests.[102]

A series of staged stability fault tests indicate that the 13.8 KV system is stable under most extreme and unlikely fault conditions.[103,104] Synchronous motors in B, D, DR, H and F reactors are normally operated somewhat below their full ability to correct power factor because of the need to control voltages within rated limits. Loss of large blocks of induction motors at K and C reactors when the synchronous motors are running at full over-excitation level, that is at leading power factor, would result in high voltages throughout the system. If the addition of Priest Rapids, Rocky Reach and later Wanapum hydroelectric projects into the network feeding into Midway means an increase in voltage above 230 KV at Midway, then the conditions under which these motors must operate will be dictated even more critically by voltage levels.

The effect of synchronous motor excitation is shown graphically by the voltage profiles plotted for the HAPO system from data derived from load flow studies.[105]

The profiles shown in Appendix B, Figure 20 depict the voltage conditions which would prevail at various reactor areas under the following conditions:[105]

Curve A: All reactors operating, power factor 0.80 leading, 230 KV at Midway. MVA load = 322-j26.

Curve B: All reactors operating, power factor 0.80 leading, 238 KV at Midway, MVA load = 320.5-j30.0.

Curve C: All reactors operating, synchronous motor reactive reduced 50%, 238 KV at Midway, MVA load = 322-j152.

The profiles shown in Appendix B, Figure 21, show the voltages which would prevail at the various reactor areas under the following conditions:[106]

Curve A: All reactors operating, all synchronous motors operating at full leading reactive capability, 230 KV at Midway and MVA load = 415.6-j110.8.

Curve B: All reactors operating, synchronous motor at B reactor with full leading reactive--all other synchronous motor at unity power factor, MVA load = 416.0-j201.9.

If it is desired to maintain 230 KV on the high voltage busses at all reactors with Midway voltages in excess of 238 KV and still utilize the reactive capabilities of the synchronous motors, autotransformers would be required at each area.

The 4500 HP synchronous motors are operated without their neutrals grounded. This creates a very complex unbalanced condition in case of stator faults to ground. Zero sequence and negative sequence voltages and currents can

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both appear superimposed upon the positive sequence values. Relaying must depend upon overcurrent and thus allow heavy damage to the winding. A neutral closed through current transformers serving differential relays and grounded through current transformers serving ground relays provides a precision system of relaying generally accepted as standard practice. This would, of course, prevent emergency operation with one or more coils in a phase group "cut out" in undesirable practice at the best. The precise and fast removal of faulted equipment without effecting other operating components is a fundamental concept in reactor safety and continuity of operation. A recent example of how unexpected malfunction can occur by an improbable combination of conditions and events not normally related is the recent scramming of H reactor initiated by a stator failure in a motor at F reactor.[85,107]

VIII. LOAD AND POWER FLOW STUDIES - SYSTEM CAPABILITIES

A. 115 KV System

One of the recommendations contained in a previous document (HW-61887) was as follows:

> "Attention is invited to the fact that a 266.8 MCM-ACSR line runs from the near vicinity of point P, (Figure V) to Benton switching station which is connected to Franklin switching station by two 115 KV lines, one 397.5 MCM-ACSR, and the other 250 MCM-CU. Franklin now has a connection at 230 KV, mostly 795 MCM-ACSR.[37] A 115 KV transformer bank with tap changers, suitable relays and OCB's located at point P, would connect the HAPO network to Benton, to Franklin, to McNary Dam. This would give emergency backup to the system, but independent of Midway switching station."

In view of the interest shown concerning this line a more detailed study was made of its capability.[108] A simplified one-line drawing was prepared showing the salient features of the circuit involved from data furnished by BPA.[109] This schematic is shown as Figure 22 and in connection with Figure 6 gives a comprehensive picture of the problem. Briefly, Ice Harbor and McNary Projects operated by the Corps of Engineers are connected to Franklin Switching Station through suitable transmission lines and OCB's. McNary has 14 generators now on the line with an aggregate nameplate rating of 980 MVA and Ice Harbor has 3 generators with an aggregate nameplate rating of 270 MVA not yet on the line. McNary is connected to Franklin through a 230 KV 795 MCM-ACSR transmission line and a 250 MVA, 230/115 KV auto transformer bank. Ice Harbor is under construction with the first generator due to be put on the line about December, 1961. The transmission line from Ice Harbor to Franklin and the terminal facilities at each end are under construction to be completed prior to the first generator cut in. Either the McNary line or the Ice Harbor lines will be able to handle the nominal load of the transformer at Franklin. The two lines from Franklin to Benton have a total normal loading capability of approximately the rating of the transformer bank at Franklin or 250 MVA.[110]

The line from Benton to the vicinity of point P_1, is 266.8 MCM-ACSR running northwesterly at an angle of 38.2° from north. The prevailing wind at Hanford in the month of July based on climatological records from 1912 is as follows:[111]

[redacted]

[redacted]

From West	9%
WNW	21%
NW	8%
WSW	9%

Thw wind velocity expectancy for July is 4 to 7 miles per hour for 37% of the time and 8 to 12 miles per hour 24% of the time. The hottest summer of record was 1958 and July the hottest month of the year with 21 days 100°F or above for an average for the month of 86.1°F. Thus the worst expected temperature condition can be taken as 100°F (38°C) in the month of July with a corresponding wind velocity component normal to the line direction of no less than 5 miles per hour.

Carrying capacity of various ACSR conductors were computed using the House and Tuttle[112] equation and standard conditions of 25°C ambient temperature, 75°C conductor temperature, wind velocity of 2 feet per second for black conductors in the clear sun. Values of current carrying capacity for various size conductors were computed. The results were plotted and are shown as Figure 23, Appendix B.

Calculations showed also that ambient temperatures have little effect on final temperature of the conductor and that wind velocity does have a critical effect on carrying capacity.

Maintaining the same Δ as before but with temperatures more realistic of conditions expected at Hanford that is 100°F (37.8°C) ambient and 190°F (87.8°C) with a black conductor in full sun data were computed for each size of conductor (266.8, 636 and 795 MCM) for various values of cross wind. Three curves were plotted and are shown in Appendix B, Figure 24. The effect of wind velocity on conductor carrying capacity is rather startling and shows in the case of the 266.8 MCM conductor that for a wind of 2 feet per second (1.36 mph) the current carrying capacity is 470 amperes but for a cross wind of 5 miles per hour it is 640 amperes. This is the safe carrying capacity of this line under the worst adverse conditions. In terms of KVA:

$$KVA = \sqrt{3} \times 640 \times 115 = 127,475$$

Allowing an overload to 1.2 per unit would call for a transformer bank size at point P, of 150,000 KVA.

This transformer bank would probably be made up of three single phase, tap changing under load autotransformers. The transformation ratio of 115/230 KV is particularly favorable to the autotransformer.[113,114] The KVA rating will allow critical transmission line loading at high ambient temperature and still stay within the allowable transformer loadings as specified on ASA-AIEE standards.[115,116]

OCB's would be modern 3 cycle opening with suitable protection relays, including synchronism check relays. Control of these breakers could easily be supervised from existing station A8. Supervisory control and telemetering circuitry should not be difficult. The breakers at Benton Switching Station are operated and controlled by the operators at Franklin by routine

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supervisory control, with no particular difficulty. From data furnished by BPA, the breaker protection now existing at Benton and Hanford substation, their specifications are:

Breaker No.	Line	Manu-facturer	Type	IC	KVA	Opening Time	Reclose Time
536	Richland-300 Area	G.E.	FK-439	800	159,344	5 cycles	1 sec-30 se
538	Franklin No. 2	P.E.	RHE-64H	1200	239,016	5 "	45 cycles
540	Midway	P.E.	RHE-64H	1200	239,016	5 "	20 "
542	Franklin No. 1	G.E.	FK-439	800	159,344	5 "	1 sec
544	Hanford	A-C	BZO-160	1200	239,016	5 "	2.9 sec.

It appears that the operating problems associated with this intertie are quite trivial whether the P_1 breakers are operated normally open or normally closed. When operated closed, loading could easily be controlled by tap changing. With the breakers closed and the 115 KV line lightly loaded, the system represents a distinct separate source of emergency power extremely valuable in the event of complete loss of Midway.

Operated normally open it is clearly a standby source of power but would need to be synchronized with the emergency generators. With either mode of operation and in dire emergency the complete capability could be quickly made exclusively available to HAPO by very simple switching operations. Even with McNary line to Franklin also out, Ice Harbor could still supply HAPO which should be rated as a priority load. The problem of power wheeling over this line is one of agreement with BPA and seems to be a minor one. If and when there is power available for export, the matter of power flow will surely need to be negotiated. The matter of stability should, of course, be determined on a power network analyzer. In view of the facts presented in the discussion, it seems axiomatic that the intertie proposed will be feasible and advisable as a semi-independent alternate source of electrical energy in accordance with the general philosophical concept developed in this report and this alternate source of energy will be even more important as reactor thermal levels are increased, coupled with the possibility of electrical power production for export.

B. Transformer Capability--230/13.8 KV

One of the most vital points in the network of each reactor is the power supply transformed complex. Power to all the reactors is fed to the 13.8 KV busses through banks of 230/13.8 KV transformers, Figure 12. In general, these banks are three phase, single case types.

A failure in any winding of the bank means outage of the entire bank. Total equivalent impedance of these transformers is high, of the order of 0.165 per unit. The ratings as discussed in the description of the HAPO electrical network, are 31.25 for the banks in the old reactors and 50 MVA for the banks in the KE and KW reactors. These transformers have been the subject of great concern, resulting in several studies over a considerable period of time.[117,118,119] The Baker and McLenegan report was especially complete and was based on predicted conditions existing after completion of Project CG 558 but did not consider K reactors. This report showed the predicted loading on each reactor and on each transformer bank in complex

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MVA but was generally low as compared to the actual peak loads in 1959 as reported in HW-61887, which also included the K reactors. Attention is invited to the fact that these are actual complex MVA based on the highest peak values reported up to September 1, 1959, not necessarily coincident, but considered so for purposes of this study. The values were as follows:

Reactor Area	$\dot{MVA}$
B-C	74.70-j 9.03
KE	53.00-j29.00
KW	49.50-j23.70
D-DR	74.70-j13.38
H	38.40-j 2.18
F	36.50-j 6.75

These values were updated with current field data to reflect any changes between September 1, 1959 and September 1, 1960. All reactors show an increase in peak demand except KE and H reactor so the value for use in the 1959 report is shown here since it is higher. The results are:

Reactor Area	$\dot{MVA}$	$\dot{MVA}$
B-C	75.15-j20.00	$77.70 \angle -14.9^\circ$
KE	K3.00-j29.00	$61.24 \angle -28.7^\circ$
KW	50.50-j26.52	$57.10 \angle -27.7^\circ$
D-DR	75.15- 12.60	$76.10 \angle -9.54^\circ$
H	38.40-j 2.18	$38.41 \angle -3.25^\circ$
F	36.96-j 5.26	$37.35 \angle -8.1^\circ$

Referring to Document HW-61887, the total coincidental demand on Midway was found to be (as of September 1, 1959):

$$338.10 - j91.69 = 350.2 \angle -15.2^\circ \ \dot{MVA}$$

This represents actual values assuming that all peaks are coincident and that the quadrature components remain unchanged. A subsequent study made by others in co-operation with Bonneville Power Administration with an assumed predicted loading of 416 M.W.(106) An IBM 650 computer was used to compute the power flows to the various areas under a variety of synthetic conditions.

Assuming all reactors up with the synchronous motors at B reactor with maximum leading reactive and all other synchronous motors operating at unity power factor and with 230 KV at Midway, the complex power was:

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$\dot{MVA} = 416.0 - j201.9 = 462.\underline{/-25.9^\circ}$

Assuming 230 KV at Midway but with all synchronous motors at all reactors operating at full capability leading reactive, the data shows:

$\dot{MVA} = 415.6 - j110.8 = 429\underline{/-14.93^\circ}$

The first condition of operation is unrealistic as compared to the second condition because normally, the synchronous motors should be operated as with as high an excitaticn as possible. It should be noted that the angle obtained for actual operation, coincident peak, was -15.2° and that for the second condition above the angle was -14.93°.

Summation of the power flows into the various areas including 251 and 100N for condition No. 2 above yields 413.4 MW for the real power. Subtracting this value from the real component of case No. 2 yields:

415.6 - 413.4 = 2.2 MW

The line losses. This value varies, of course, with the MVA loading, as a function of (I^2).

Numerous documents were reviewed to obtain some evaluation of the effect that plans for increased prodnction would have on the electrical system, in particular the effect on these transformer banks.[119,120] The above documents seem to substantiate the validity of the IPD power forecast through the year 1965.[121] Unfortunately, the values forecast are in terms of real power increases only and not substantiated by documentation. Assuming that the KW increases are as accurate as present planning will permit, and using the real component of the present (1960) peak as a base, the predicted total MW load at each area will be:

Area	1960	Increase	1965
B-C	75.15	15.40	90.55
KE	53.00	25.00	78.00
KW	50.50	24.00	74.50
NPR	---	18.00	18.00
D-DR	75.15	15.70	90.85
H	38.40	7.30	45.70
F	36.96	6.50	43.40

Assuming that the per unit increase of the quadrature component in per unit is the same as the per unit increase in the real component, thus reflecting the increase in the quadrature component the new complex power may be computed. This procedure is mathematically valid and is realistic because of the large available range of reactive adjustment on the synchronous motors.(12

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Computing the quadrature components on the above basis and adding to the complex power tabulated for 1960, yields the predicted complex powers for 1965:

Area	MVA	$\dot{MVA}$
B-C	90.1-j10.9	90.8/-7.54°
KE	78.0-j42.7	88.9/-28.7°
KW	73.5-j35.2	81.5/-25.6°
NPR	18.0-j 9.6	20.4/-28.1°
D-DR	90.4-j16.2	91.8/-10.17°
H	45.7-j 2.59	45.7/- 3.25°
F	43.0-j 7.95	43.7/-10.48°
Total	438.7-j118.1	454 /-15.1°

Adding (15-j10.6) for the 251 area (from HW-63895) yields:

Total $\dot{MVA}$ = 453.7-j128.7

= 472/-15.85°

This value will be used in a later discussion.

The specifications for the various transformer banks in general are three phase (single case) 230/13.8 KV star-delta connected two winding. KE and KW have 50 MVA banks and all other reactors have 31.25 MVA banks.

Data were prepared using actual values from the peak conditions for 1960 showing the flow through each transformer bank in each area. The values were tabulated along with the name plate, fan cooled (FA) rating of each transformer and are shown in Appendix C, Table E. Assuming that the per unit loading will remain the same under the predicted increased load, a similar tabulation was prepared for the predicted 1965 loads shown above. These data are shown along with the transformer ratings in Appendix C, Table F. A third tabulation was prepared using data derived from HW-63895 for the case of 230 KV at Midway and all synchronous motors up to full leading reactive capability and is shown in Appendix C, Table G.

Summary

Analyses of the preceding discussion and the comparison charts show that at the present time all transformers are operating on their force cooled (FA) ratings and that for bank No. 3 in B-C and D-DR reactor areas the loading approaches the maximum rating. A fault in any part of the transformer bank, even a bushing failure, means outage of the entire bank. Should this occur with the present loadings (Figure II) the surviving bank or banks in some reactors would be overloaded beyond the maximum forced air cooling. The degree of seriousness of this overload would depend upon the duration of the overload and the ambient temperature at the time of overload.

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All Banks Operating

Reactor Area	Number of Banks	Per Unit Load Per Area
B-C	3(93.75)	0.870
KW	2(100)	0.936
KE	2(100)	0.936
D-DR	3(93.75)	0.901
H	2(62.50)	0.635
F	2(62.50)	0.629

One Bank Out of Service

Reactor Area	Banks Remaining	Per Unit Load Per Bank
B-C	2(62.50)	1.306
KW	1(50.00)	1.872
KE	1(50.00)	1.872
D-DR	2(62.50)	1.352
H	1(31.25)	1.270
F	1(31.25)	1.258

The loading is again critical in all reactor areas and prohibitive in KW and KE reactor areas.

It is quite evident that increased capacity will certainly be required, if additional load is to be added to all reactors. If the possibility of a transformer bank outage is considered and there are no spare banks, the situation is even worse. Serious attention possibly should be given to the increased capacity attainable by installation of a suitable heat exchanger and forced oil circulation. It is unfortunate that the banks are not made up of single phase units thus making the matter of spare transformers much cheaper and easier.

C. 230 KV Transmission Lines

The description of the HAPO high voltage electrical system mentions that the conductor specifications for the three main transmission lines from Midway were 636 MCM-ACSR for lines No. 1 and No. 2, and 795 MCM-ACSR for line No. 3. The curves plotted for use in the discussion on the 115 KV line from Franklin show that for an ambient temperature of 25°C (77°F), conductor temperature of 75°C (167°F), cross wind of 1.4 miles per hour, old oxidized conductor in bright sunlight the 636 MCM-ACSR (code name Egret) lines 1 and 2 will carry 820 amperes and line No. 3 (795 MCM-ACSR--code name Drake) will carry 950 amperes. The safe carrying capacity of ACSR, has been the subject of extensive research for several years by Kaiser, Alcoa and Reynolds Aluminum Research Laboratories. Field experience seemed to indicate that the Alcoa tables accepted by electrical utilities for many years were very conservative. As a comparison, these tables show a nominal carrying capacity for 795 MCM-ACSR as 900 amperes and for 636 MCM-ACSR, 780 amperes.

The values of 950 amperes for 795 MCM and 820 amperes for 636 MCM are accepted as safe, steady state, sustained load carrying capacities of these

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The values of 950 amperes for 795 MCM and 820 amperes for 636 MCM are accepted as safe, steady state, sustained load carrying capacities of these cables. Short term loads of 1.3 per unit can be safely carried for one hour and 1.5 per unit may be carried for 15 minutes in emergency under the conditions stated. Transmission lines No. 1 and No. 2 then may carry a sustained load of 1235 amperes for 1 hour and 1425 amperes for 15 minutes. These are not recommended values but are realistic where reactor safety is involved. Moreover, the study made in connection with the 115 KV line (Part IX A) indicates that ambient temperatures have little effect on carrying capacity but that wind velocity is critical as shown on Figure 24. With a wind component of even 5 miles per hour normal to the line, the carrying capacities of the lines are increased to nominal values of 1330 amperes for 795 MCM line No. 3 and to 1100 amperes for 636 MCM (lines No. 1 and No. 2). Wind velocities of this magnitude or greater can certainly be expected practically without fail. Study of the climatological data and the direction of the various lines reveals that seldom will any section of the line have a wind velocity less than 2.5 mph. Sustained current carrying capacities for this wind and other conditions the same (never in excess of 50°C) will be:

Line No. 1	930 amperes	370.5 MVA
Line No. 2	930 amperes	370.5 MVA
Line No. 3	1130 amperes	450.1 MVA

Calculations are based on 3 phase balanced load with 230 KV line to line as Midway. The study made of loadings for the various reactor areas for Part IX B also yielded the total transmission line loads, except for line losses by simple summation. For the 1959 study the coincidental peak summation was 350.2 MVA. The 1960 summation exclusion of line losses was 357.0 MVA. The predicted load from document HW-63895 with all reactors up and all synchronous motor at full leading reactive was 429 MVA. The predicted load shown on Table F was 472 MVA. For convenience of discussion, these are designated cases I, II, III and IV.

For Case I, the division of load was found from actual readings furnished by BPA for the peak load up to September 1, 1959, and was computed in per unit.

Applying this per unit division to the 1959 and 1960 summation yields the line loadings:

Year	Line	Per Unit Load	MVA
1959	No. 1	0.424	148.4
(350.2)	2	0.244	85.7
	3	0.332	116.2
1960	No. 1	0.424	151.3
(357.0)	2	0.244	87.1
	3	0.322	118.5

For case III and IV the division shown in document HW-63895 was used with the following results:

[redacted]

Year	Line	Per Unit Load	MVA
1965	1	0.430	184.5
(429)	2	0.229	98.4
	3	0.341	146.3
1965	1	0.430	203.0
(472)	2	0.229	108.0
	3	0.341	161.0

Compared to the line capabilities for standard conditions (1.4 mph wind) yields:

Line Number		Computed Load MVA	Capability MVA	Loading Per Unit
Case I	1	148.4	326.7	0.454
	2	85.7	326.7	0.262
	3	116.2	378.4	0.307
Case II	1	151.3	326.7	0.463
	2	87.1	326.7	0.267
	3	118.5	378.4	0.313
Case III	1	184.5	326.7	0.565
	2	98.4	326.7	0,301
	3	146.3	378.4	0.387
Case IV	1	203.0	326.7	0.621
	2	108.0	326.7	0.331
	3	161.0	378.4	0.426

Similar computations based on line capabilities with a 2.5 mph wind yield:

Line Number		Computed Load MVA	Capability MVA	Loading Per Unit
Case I	1	148.4	370.5	0.401
	2	85.7	370.5	0.231
	3	116.2	450.1	0.258
Case II	1	151.3	370.5	0.408
	2	87.1	370.5	0.235
	3	118.5	450.1	0.263
Case III	1	184.5	370.5	0.498
	2	98.4	370.5	0.266
	3	146.3	450.1	0.325
Case IV	1	203.0	370.5	0.548
	2	108.0	370.5	0.291
	3	161.0	450.1	0.358

The two loading capabilities computed for 1.4 mph wind and 2.5 mph wind were used as a base against which the loadings shown in Case II, III and

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IV could be compared with various combinations of 230 KW transmission lines in service. Division of load for the condition of No. 1 line out of service and for the condition with No. 3 line out was obtained from HW-63895. The division of load with No. 2 line out was taken as being inversely proportional to the complex positive sequence impedances of the paralleled line sections, that is, to the K area tap.[89] Division of load for all lines in service was already shown.

Data was computed for all other combinations of line outages and tabulated as Table 4, Appendix C. Loadings are given in per unit of line capabilities with 1.4 mph wind. A second set of data was prepared using the same technique but assuming a 2.5 mph wind. These data are shown as Table I, Appendix C.

Analysis of these two tables seems to indicate that these lines are adequate for all cases studied so long as the three lines are in service. For the worst case (IV) with a total load of 472 MVA, line No. 1 with the highest per unit load is operating at only 0.628 (62.8%) per unit of its capability. With an increase in wind velocity to 2.5 mph the per unit loading on this line drops to 0.548 (54.8%) of capability.

Failure of line No. 1 means that B-C reactor area will have to get all its power from the direction of K reactor, thus loading the two, lighter loaded lines, boosting their per unit loadings to 0.539 for line No. 2 and 0.780 for line No. 3, neither of which is critical even for Case IV. Outage on line No. 2 will open the long leg of the loop and force H, F and D-DR areas to get power from the direction of K area, thus loading line No. 1 and No. 3 to 0.799 per unit (79.9%) and to 0.554 per unit (55.4%). These loadings are not critical for line No. 1 or for line No. 3, except for the first span at Midway.

Loss of line No. 3 puts the entire burden on lines No. 1 and No. 2. The new loadings will now be 0.960 per unit (96%) for No. 1 and 0.483 per unit (48.3%) for No. 2 for Case IV. The MVA on line No. 1 is now critical and approaches its safe carrying capacity. This MVA corresponds to 817 amperes at 230 KV which exceeds the continuous current rating of the line section to B-C area (Station A2). The MVA loading on line No. 2 corresponds to 366 amperes at 230 KV which makes OCB's No. 386 and No. 384 at the 251 areas in a critical position. Since the load at 251 area is only (15-j 10.6) MVA, this leaves 323 amperes flowing toward F area with the OCB's there in a possible critical position. The subject of breakers will be discussed later.

Failure of both lines No. 2 and No. 3 clearly overloads line No. 1 beyond its capability for Cases II, III and IV. Voltages at F and H reactor areas would also be prohibitive. The value of an intertie to the 115 KV network at point P_1, as proposed in Section IX is clearly shown here since it would be possible to continue operation with this connection and line No. 1. Failure of both lines No. 1 and No. 3 throws all the load on line No. 2 with consequent prohibitive overloading of the lines and the breakers at 251 H area, F area and possibly D-DR. Since the path is much longer, voltages would also be prohibitive. As in the case above, the proposed transformer at P_1 might make it possible to operate until one of the other lines can be restored.

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IX. CIRCUIT RESTORATION

The preceeding general discussion in this report has developed the philosophy that electrical power supply circuits should be energized as fast as possible following a fault. In the case of loss of one or more of the 230 KV transmission lines from Midway, this implies fast reclosing at the Midway end. Fast in this connection means opening of the oil circuit breakers in about 3 cycles (1/20 sec.) of 60 cycle per second wave and reclosing as soon as practicable. Normally, restoration of power by reclosing is from 18 to 22 cycles on a 60 cycle per second base, without restrike on most transient, making a total elapsed time of from 21 to 25 cycles or 0.350 to 0.417 seconds from time of fault. If the fault is sustained, the breakers will reopen and lock open in an additional 3 cycles or less making a total elapsed time of 24 to 29 cycles or 0.400 to 0.483 seconds.[126] This is standard practice for BPA and other large utility networks.[127,128]

Fast reclosing of transmission lines which have been cleared of the receiver load presents no problem. Such loads as lights and small motors also presents no problems even if not cleared. Reclosing large motors, either synchronous or induction types, presents engineering problems which have several variables including the speed of reclosure, load at time of failure, speed of decay, HP and voltage rating, stability, and voltage regulation of the system.

Preliminary investigation in the case of K reactor which has only induction motors indicated definite possibilities for fast reclosure and was so reported in document HW-61887.[1] Due to voltage regulation and stability problems the entire block of induction motors in the K complex may present some engineering problems if restored simultaneously and not fast enough. Stability of the K plants has been the subject of numerous engineering studies primarily brought about by a continual upgrading of the thermal level of these reactors.[129,130,9] Great concern has centered around the emergency generators in the power supply network of these reactors and have been the subject of numerous reports and analyzed studies.[131,132,133] Loading of these generators has been carefully examined from the operational safety standpoint and on the basis of peak trimming of purchased power.[134,135,13 The motor complement of K reactor has also been the subject of several engineering studies made to determine both stability and safety of operation[137,13

The most recent study is a very excellent one which utilized the system analyzer to determine stability and other factors concerning the K area rotating equipment.[139] The subject of relaying has been adequately covered by relay studies and tripout tests.[140,141]

The foregoing discussion is intended as a review of the reliability and safety of the K area reactor electrical system rather than a new study. Document HW-61887 was prepared as a critical survey which would focus attention on certain areas which might be investigated in greater detail. One area was the fast reclosing of the 230 KV system following clearing of a fault. Document HW-65711, a subsequent document, clearly points out the extreme importance of this and recommends further. Such a study is now in progress and normally will be "proofed" on the network analyzer. This document also demonstrates that the K area system will be stable under various extreme conditions which will require a very unlikely sequence of events.

History of incidents at HAPO have usually followed a "sequence of improbably events" such as the incident at H-F reactors on 11 March, 1960. It is therefore important to give credence to the probability of occurrence of the unlikely sequence of events on which some of the tests were based. The author concludes, in general, that reclosure is important; and that if fast enough, could possibly pick up the system without losing the reactor.

The problem of high speed restoration of the 230 KV system following a fault to the remaining reactors (except NPR) presents a quite different set of problems which have not been exhaustively explored to date. Reactors B, D, DR, F and H have essentially the same type of network as already described in another section of the present report. Briefly, this consists of a lagging power factor load consisting of numerous but not large squirrel cage induction motors and forty 4500 HP squirrel cage start synchronous motors driving centrifugal water pumps and equipped with heavy flywheels with a WK^2 of 568,657 pound feet squared ($lb\text{-}ft^2$).[137,142] Reactor C has twelve 3500 HP induction motors and therefore presents about the same electrical problems as K reactors in so far as circuit reclosure is concerned, but simpler because of their size and the fact that a steam turbine is floating on the same shaft. The main problems then are concerned with the restoration of power to the network which is typical of B, D, DR, F and H reactors.

A study was conducted using typical data to formulate the following items:

(1) Speed decay

(2) Torque angle

(3) Transient current

(4) Voltage drop

(5) Stability

(6) Relaying

Electrical parameters for the 4500 HP synchronous motor were somewhat indeterminate and had to come from several sources, some of which were indirect and required computation.

<u>Speed Decay</u>

Speed decay curves for K reactors have been already discussed and presented in document HW-61887, Figure XI and included here for convenience as Figure 25.[143] Typical curves were prepared for B, D, DR, H and F reactors which were so nearly identical that only one is presented here as Figure 26, for H reactor and regarded as typical.

A separate curve was prepared for C reactor because of the radically different speed decay characteristics of this reactor and shown as Figure 27, Appendix B. All curves are based on latest data in each case and were tested for validity by comparison with a theoretical plot.[144-148]

[redacted]

Basically the time decay can be thought of as an electrical-mechanical energy convension in which electrical energy supply is suddenly terminated and the electrical machine becomes a potential generator and the hydraulic system still continues as a pump. Power to supply any load which may be still connected to the busses and the power necessary to maintain hydraulic flow must come from the flywheel stored energy. In the case of the 4500 HP synchronous motor pumping units such as at H reactor the WK^2 of the motor and its shaft load was given earlier as 568,657 pound ft.^{2} Such a decay can be represented by an equation of the form:(149,150)

$$S = S E^{-kt} + S_1 E^{-at} - S_2 E^{-bt} \qquad (1)$$

where S = instantaneous speed in per unit of synchronous speed.

S = synchronous speed in per unit

$K = \frac{1}{2}$ nt

T = break time

t = time in seconds

a and b = arbitrary constants

S_1 = positive decrement

S_2 = negative decrement

$$E = 1 + \frac{1}{1!} + \frac{1}{2!} + \frac{1}{3} + \ldots\ldots = \lim_{n \to \infty} \left(1 + \frac{1}{n}\right)^n = 2.71828\ldots$$

For the first 10 seconds, the second and third terms cancel and the test curve matches the curve plotted from the empirical equation $S = S_0^{-kt}$.

Observation of the curve for H reactor shows a drop in speed to 0.98 per unit in 1 second (60 cycles on a 60 cps base) after trip out and the C reactor curve shows a drop in speed to 0.99 per unit after 1 second after trip out. These curves provide a positive check on the synchronizing angle analysis to follow. Reclosing breakers on a large synchronous motor following a power interruption may cause undesirable or prohibitive transients in that motor.(151,152) If the field is still on the machine, it becomes a generator and will supply any electrical load connected to its terminals for a period of time at a frequency and voltage depending upon its rate of speed decay. The energy for this supply must come from the stored energy in the rotating members. Reclosing under these conditions is the same as synchronizing an alternator and has the same requirements.

Briefly, the incoming machine and the line must have correct phase sequence, and should have when connected to the line:

[redacted]

1. Equal voltages

2. Equal frequencies

3. Voltage in step

In this case the important item which may be critical is speed decay which causes frequency to decrease causing the voltage wave of the generator (motor) to lag the line voltage. Frequency drop in the first 30 cycles is not the critical factor as such but does determine the phase position or synchronizing angle. In this discussion, the synchronizing angle will be designated by the symbol delta (Δ). It is well known that synchronizing machines out of step may cause torques; and, consequently, currents which may be equal or exceed short circuit currents.[153]

Stone and Kilgore state that "It is of course well known that throwing a machine on a large system out of phase by more than 60° produces a worse electrical transient than a sudden short circuit."[154] The machine constant which limits this torque is the subtransient synchronous reactance (X''_d) for various values of (Δ). Actually the reactance of the circuit into which the machine is closed also helps to limit the transient current so that basically the transient electric torque is:

$$T = \frac{E^2}{X_d + X_n} \sin\Delta \left(1 - \cos wt + \tan\frac{\Delta}{2} \sin wt\right) \qquad (2)$$

Where

E = generator voltage

X''_d = subtransient reactance

X_n = circuit reactance

Δ = synchronizing angle

$w = 2\pi f$

The torque developed in the rotor during synchronizing may be readily put into the form previously used for speed decay:

$$T = AE^{-at} - BE^{-bt} \cos wt + CE^{-ct} \sin wt. \qquad (3)$$

A, B and C are functions of Δ

Δ = angle of synchronizing.

a, b and c are decrement factors.

Equation (2) has been evaluated by a number of authors and when plotted against Δ yields a sine loop with two maximum points.[155] Such a curve is shown in Figure 28, Appendix B.

Another curve shown on this same paper illustrates the safe closing areas for various values of the synchronizing angle Δ based on a wide range of ratios of X_n to X''_d. A similar curve was plotted and is shown as Figure 29, Appendix B. This curve indicates that it is safe to reclose up to 10° displacement for all ratios of X_n/X''_d and that larger values of the angle Δ may be tolerated for high ratios of X_n/X''_d. It should be noted that this curve was for 30,000 KVA machine but gives a good idea of the problems involved.

Evans in a classic paper published in 1940, used vector diagrams to determine currents which might be expected for machines closed unequal voltages for various values of synchronizing angle Δ, based upon subtransient reactance X''_d.(156)

Curves plotted from such data exhibit the typical V curve shape and show that with an incoming machine voltage of 0.92 per unit and a synchronizing angle Δ of 60° currents will be about 4.2 per unit. It seems evident that reclosure should be completed before the synchronizing angle has reached 60°. The next step was to expolore the actual decay characteristics and the starting characteristics of the actual 4500 HP synchronous motors used in B, D, DR, F and H reactors. The speed decay curves give a good picture of the actual speed of the machines at various time intervals from which the frequency can be computed since

$$S = \frac{120\, f}{p}$$

S = speed in rpm

f = frequency in cycles per second

p = number of poles

The angle Δ caused by this drift and by any load which is on the machine bus could be computed by use of vector diagrams, but the method proved slow and indeterminate. It was decided to use actual oscillograms taken on trip out tests. Data were taken from oscillograms taken on all the busses in the D-DR complex serving the 4500 HP synchronous motors. Three tests were run on each group titled busses I, II, and III. Actually this arrangement is as shown on Figure 17.

The actual position of the voltage wave referred to the timing wave was determined for each case using the oscillograms. The results are shown in Appendix C, Table J for 1, 10, 20 and 30 cycles after trip out.

An average was computed for each bus and these values were used to plot the curves shown on Figure 30, Appendix B. These curves clearly show the phase angle drift of the synchronous motors on these bus groups as related to time. The drift in phase angle is the synchronizing angle Δ already discussed. These curves give a realistic picture of conditons as they actually exist and show clearly that if the 60° value of Δ is used as a criterion, reclosure time on each bus group would be 12.8 cycles on Bus I, 14.4 cycles on Bus II and 18.2 cycles on Bus III. If a value of Δ of 70° could be tolerated, then the values would be 15.2 cycles, 17 cycles, and 21.2 cycles respectively. It should be noted at this point that transition from a generator to a motor is smooth, and there is no danger of phase sequence reversal. It should also be observed that if the motors were operating overexcited, which would normally be the case, the current would lead the line voltage and in the case of the synchronous generator overexcited, the current would have to lag the generated voltage until the machine again becomes a motor. For steady state below saturation, only fundamental frequencies and positive sequence currents are involved.[151,16]

The above discussion means that when the power supply fails, the motor (now a generator) should exhibit no decline in voltage and possibly a voltage rise at its terminals depending upon the load on the bus to which it is connected. An actual plot was made of the data derived from the same source as used above. Since there was induction motor load on the bus group (III) the regulation due to loading (IZ and drop) and to speed decay was offset by the overexcitation, and the voltage remained flat until after the motor breaker was tripped at which time the voltage rose to the value corresponding to the excitation level, and then decreased as the speed decayed. The curve is shown in Appendix B, Figure 31. It is evident that voltage drop is not a problem in the region of fast reclosing, insofar as it affects synchronization conditions.

The next area of investigation centers around determination of the magnitude of current to be expected under starting and transient conditions. The starting characteristics of these motors was determined by use of the actual starting record charts and acceptance test data.[142] Data were derived from these records taken on H reactor from which curves of voltage, current and speed on per unit versus time (in seconds) were plotted. These curves are shown in Appendix B, Figure 32. A second curve was plotted to graphically illustrate the voltage level (in KV) during the starting period, shown in Appendix B, Figure 33.

A third curve showing the actual current in amperes is shown in Appendix B, Figure 34. These curves are all based on the procedure of starting one motor at a time connected to one bus only. The effect of using two 13.8 KV busses in parallel and thus two 230/13.8 KV transformers in parallel while starting a motor is shown in Appendix B, Figure 35.

In the case of the single bus method of starting the motors, normal current is restored and current reaches the steady state at approximately 52 seconds from standstill. Synchronous speed and synchronous operation is attained normally from 5 to 10 seconds prior to this. Standstill current reaches approximately 5.5 per unit or 1078 amperes limited primarily by the subtransient reactance (X''_d). The valve of X''_d furnished to the author by vendor for these motors was 0.18 per unit on full load current base.

Typical values for this parameter for salient pole synchronous motors with damper (amortisseur or squirrel cage) winding lies between 0.20 and 0.50 per unit.[157,158] This method of starting (separate busses) has the advantages that two motors may be started simultaneously and that the current is also restricted to some extent by the voltage droop. The parallel bus system has a better voltage regulation but allows the current to go to approximately 6.0 per unit with only a small gain in acceleration,

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steady state current being attained at about time 45 seconds. Starting characteristics of these motors up to the time of application of the field follow the basic principles and exhibit typical behavior of squirrel cage induction motors.[159,160] The significant point in this discussion is the fact that for each speed of the motor operating without excitation, that is as an induction motor, there exists a corresponding unique value of back electromotive force and current which is approximately the same whether the machine has reached this speed by either positive or negative acceleration. Thus, if the rate of speed decay of these motors is considered to be as presented in Figure 26, there exists a region where fast reclosure is a possibility. This reasoning would apply to K area as mentioned in HW-61887 to C area and to the other reactor 4500 synchronous motors if deprived of field excitation.

Document HW-65711, a stability study of K area where the largest induction motors are located, indicates that the critical motors are stable under transient faults, even under unusual and unlikely conditions. Further investigation is now in progress but even if fast restoration is possible should be proved on the power system analyzer.

In case of the 4500 HP synchronous motors in B, D, DR, F and H operating as synchronous motors with normally overexcited field (leading current) the machines become overexcited generators (lagging current) upon loss of 230 KV power. Fast reclosure in 17 cycles or less seems to be a definite possibility; and, if the reactor scram signal can be delayed until after 22 to 25 cycles, the reclosure might be accomplished without losing the water flow and the reactor.

Present practice with a power loss and auxiliary time delay relays, delays opening of the motor breaker for about 28 cycles so that if the fault clears and power is restored, the motors will continue to operate. This duplicates fast opening and reclosure but in a much less precise way.

Beyond 60 cycles the motors will be cleared from the line and the field opened, so there is no reason why the 13.8 KV cannot be re-energized; and because the motors now affect induction motors with a small speed decay, they can be restored rapidly by pair and restore the reactor if time can be saved in operating procedure by bypassing the cone valve and eliminate the lock out relay and the "permissive switch" routine.

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74. H-1-262 — 100 D AREA 13.8 KV SINGLE LINE SWITCHING DIAGRAM. NONE.

75. H-1-390 — ELECTRICAL RELAY DIAGRAM 100 D AREA, 2 SHEETS. UNCLASSIFIED.

76. SK-1-2823 — ELECTRICAL - INCREASED ELECTRICAL POWER CAPACITY REACTOR WATER PLANTS ONE LINE DIAGRAM. (100-D DR) (DO-0217). UNCLASSIFIED.

77. D-DR Reactor — OPERATIONS MANUAL. OUO

77. P-1670 — ELECTRICAL POWER SYSTEM ONE LINE DIAGRAM. (CG 558) (100 H AREA). UNCLASSIFIED.

79. H-1-3514 — ELECTRICAL RELAY DIAGRAM 100 H AREA (2 SHEETS). UNCLASSIFIED.

80. H-5-483 — 100 H AREA 13.8 KV SINGLE LINE SWITCHING DIAGRAM. UNCLASSIFIED.

81. H Reactor — H REACTOR SECTION - OPERATING MANUAL. UNCLASSIFIED. OUO

82. H-1-26850 — ELECTRICAL 100-F AREA ONE LINE DIAGRAM (CG 558). UNCLASSIFIED.

83. H-1-277 — 100 F AREA 13.8 KV SINGLE LINE SWITCHING DIAGRAM. UNCLASSIFIED.

84. H-1-391 — ELECTRICAL RELAY DIAGRAM 100 F AREA (2 SHEETS). UNCLASSIFIED.

85. HW-66364 — ENGINEERING ANALYSIS OF THE ELECTRICAL POWER FAILURE AT H REACTOR ON MARCH 11, 1960. Floyd D. Robbins. SECRET.

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98. HW-50111 RELAY & FUSE COORDINATION STUDY REPORT 100 D-DR AREA. W. R. Thorson. UNCLASSIFIED.

99. HW-50112 RELAY & FUSE COORDINATION STUDY REPORT 100 D-DR AREA. W. R. Thorson. UNCLASSIFIED.

100. HW-52269 RELAY & FUSE COORDINATION STUDY REPORT - 100 F AREA. W. R. Thorson. UNCLASSIFIED.

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102. Report IPD-FEO: MONTHLY RECORD REPORT. W. Windsheimer, Manager.

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104. HW-52442 FINAL REPORT ON STABILITY FAULT TESTS ON 13.8 KV SYSTEM 151 H SUBSTATION. l. F. Higginson. UNCLASSIFIED.

105. HW-40572 OPERATION OF 4500 HP SYNCHRONOUS MOTORS -- EFFECT OF EXCITATION ON HANFORD ELECTRICAL SYSTEM. D. S. Baker. UNCLASSIFIED.

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106.	HW-63895	LOAD FLOW STUDY OF HAPO 230 KV SYSTEM. R. F. Haynes. UNCLASSIFIED.
107.	HW-64676	HAPO POWER FAILURE - H REACTOR PLANT. E. J. Filip, G. W. Wells. SECRET.
108.	Letter	COMMENTARY ON DOCUMENT HW-61887. F. J. Mollerus Principal Engineer. FEO. UNDOCUMENTED-UNCLASSIFIED.
109.	38913-A	PACIFIC NORTHWEST TRANSMISSION SYSTEM. Bonneville Power Administration. UNCLASSIFIED.
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111.	HW-57722	A CLIMATALOGICAL STUDY OF THE HANFORD AREA. D. E. Jenne, R. E. Kerns. UNCLASSIFIED.
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113.	Book	ALTERNATING CURRENT MACHINERY. A. L. McFarland. Van Nostrand Co. UNCLASSIFIED.
114.	Book	TRANSFORMER ENGINEERING. L. F. Blume, et al. Wiley and Sons.
115.	C 57	TRANSFORMERS REGULATORS AND REACTORS. ASA-AIEE. UNCLASSIFIED.
116.	C 57.92	GUIDE FOR LOADING OIL IMMERSED DISTRIBUTION AND POWER TRANSFORMERS. A.I.E.E. Standard. Appendix to ASA C 57.12. UNCLASSIFIED.
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118.	HW-45521	REACTOR AREA 13.8 KV POWER SUPPLY TRANSFORMER BANK REPORT. R. C. Hoffman. UNCLASSIFIED.
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130. HW-51750 — WATER PLANT EXPANSION 100 KE and KW PROJECT PROPOSAL CG 775. D. E. Newby. SECRET.

131. HW-29-800 — STABILITY OF EMERGENCY GENERATORS IN 100 K AREA. McCracklin, Peabody. UNCLASSIFIED.

132. HW-49702 — EMERGENCY GENERATOR OPERATION 165 KW. F. J. Mollerus. SECRET.

133. HW-59166 — 100-K AREA EMERGENCY GENERATORS MAXIMUM LOADING. F. J. Mollerus. SECRET.

134. HW-41234 — THE REDUCTION OF PEAK ELECTRICAL LOADS BY THE USE OF STEAM DRIVEN EQUIPMENT. J. R. Young.

135. HW-65220 — STUDY OF K AREA GENERATOR LOADING. L. M. Keene. UNCLASSIFIED.

136. HW-65764 RD — K AREA GENERATOR OPERATION STUDY. Lewis M. Keene. UNCLASSIFIED.

137. HW-33697 — STABILITY OF SYNCHRONOUS MOTORS IN 100 AREA WATER PLANTS. A. J. McCracklin, E. P. Peabody, D. S. Baker. OUO.

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138. HW-59190 K WATER PLANT RELIABILITY TASK FORCE STUDY COMMITTEE: ADDITION TO K PLANT SYSTEMS. R. E. Trumble. SECRET.

139. HW-65711 TRANSIENT STABILITY STUDIES ROTATING EQUIPMENT K-PLANTS. F. J. Mollerus (Principal Engineer HAPO), J. R. Eleanson (Industrial Application Engineer - Seattle G.E.), Jacobs J. Dunki (Engineer Industrial Power Systems, Schenectady, N. Y.). UNCLASSIFIED.

140. HW-57801 RELAY & FUSE COORDINATION STUDY 100 K AREA. W. R. Thorson. UNCLASSIFIED.

141. HW-53284 FINAL REPORT ON STAGED FAULTS TESTS ON 100 K 230 KV 13.8 KV and 4.16 KV. ELECTRICAL SYSTEMS. L. F. Higginson. UNCLASSIFIED.

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146. PT-IP-303 I PRODUCTION TEST F REACTOR. SECRET.

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[redacted]

APPENDIX B

ILLUSTRATIONS

[redacted]

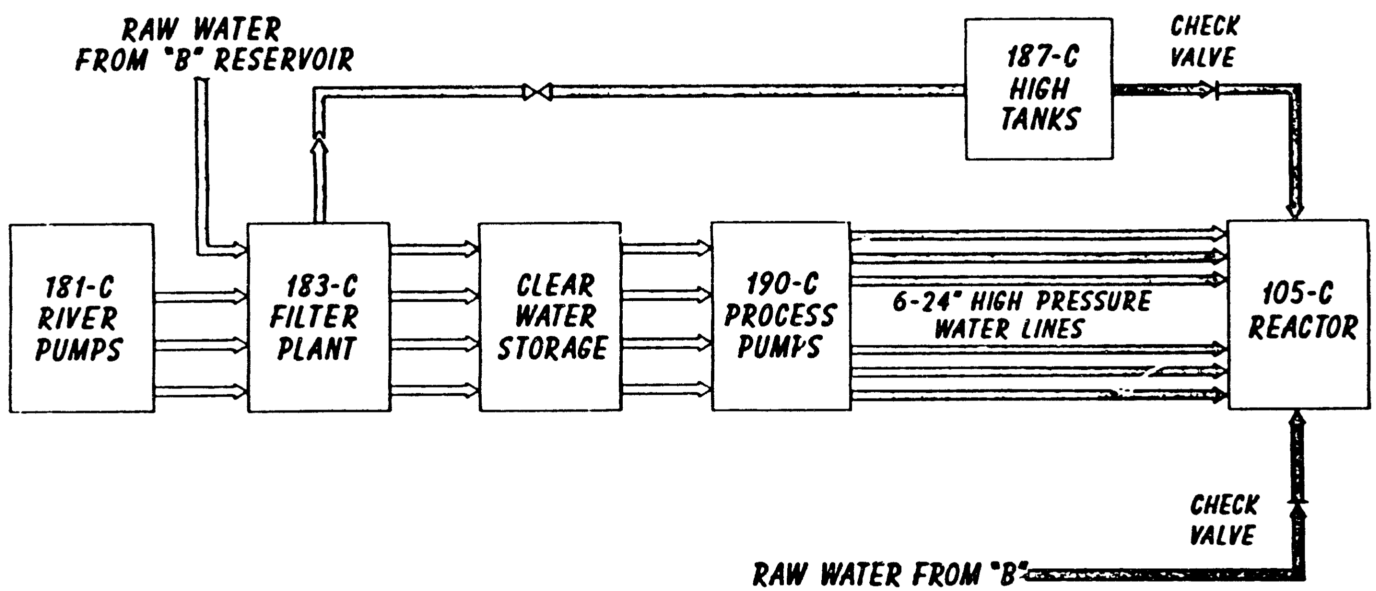

FIGURE 1

Simplified Water Flow Diagram - C Reactor

[redacted]

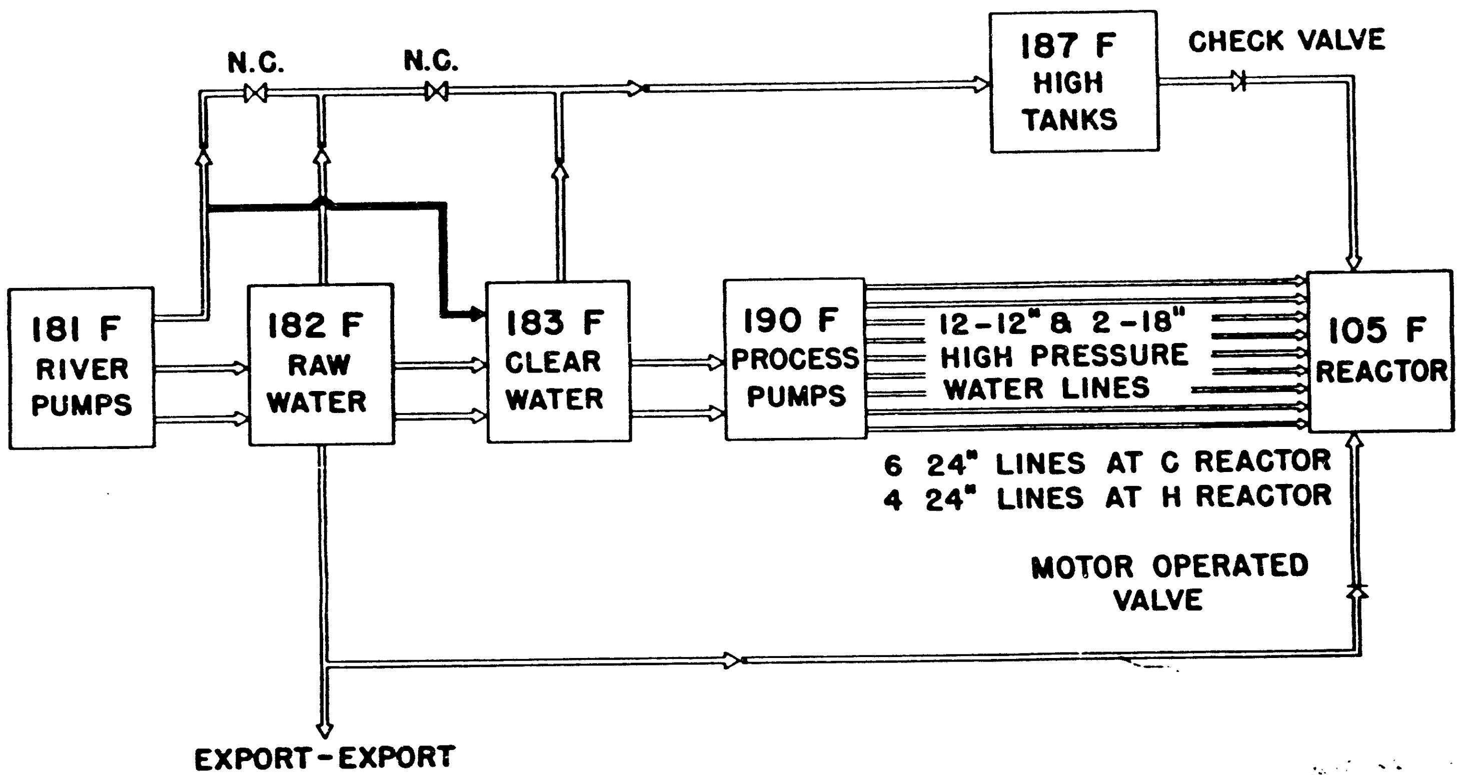

FIGURE 2

Simplified Water Flow Diagram - F Reactor

[redacted]

[redacted]

(REPRESENTATIVE ONLY)

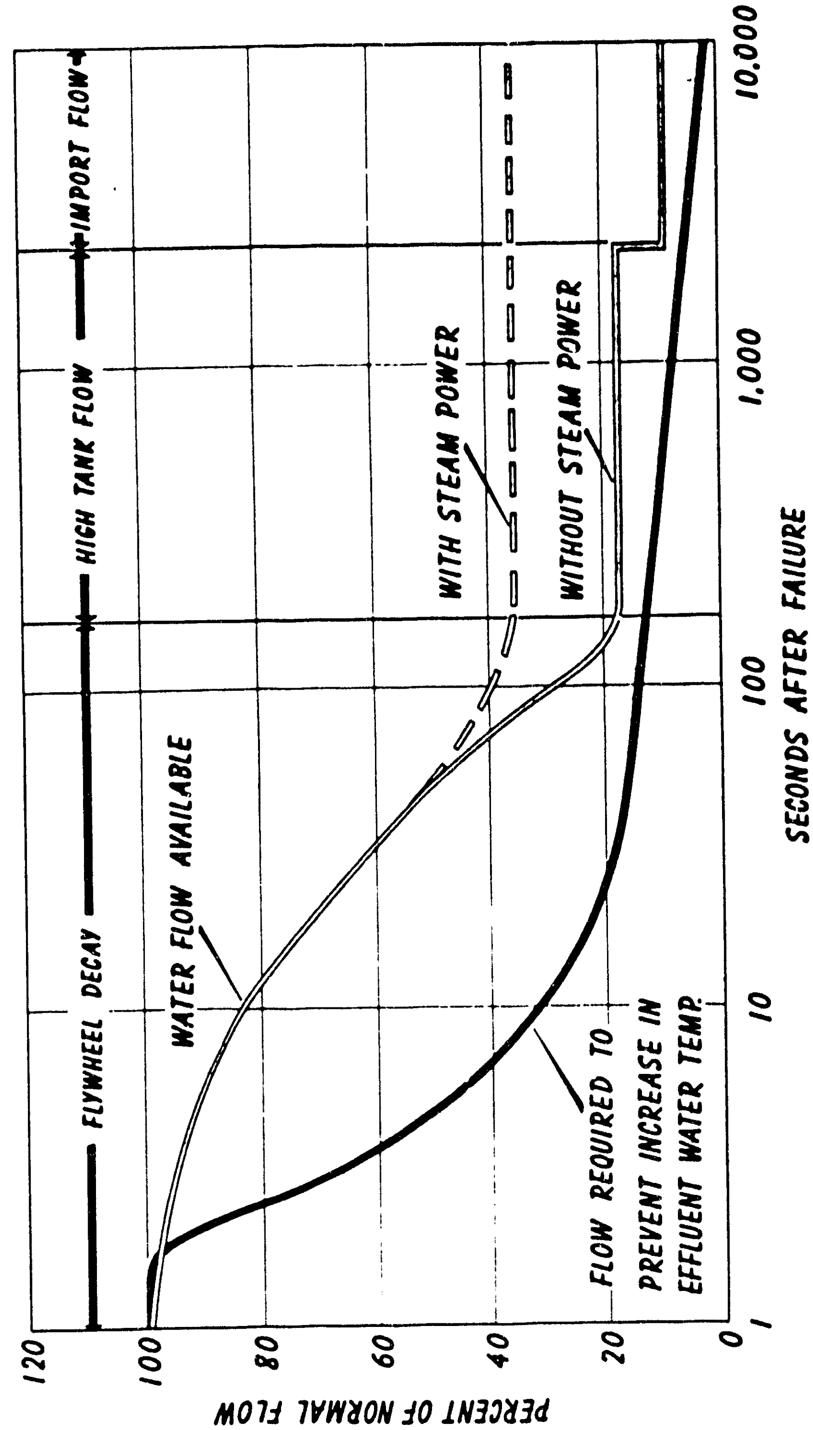

FIGURE 3

Water Flow After Loss of Electric Power - C Reactor

G 9·744

[redacted]

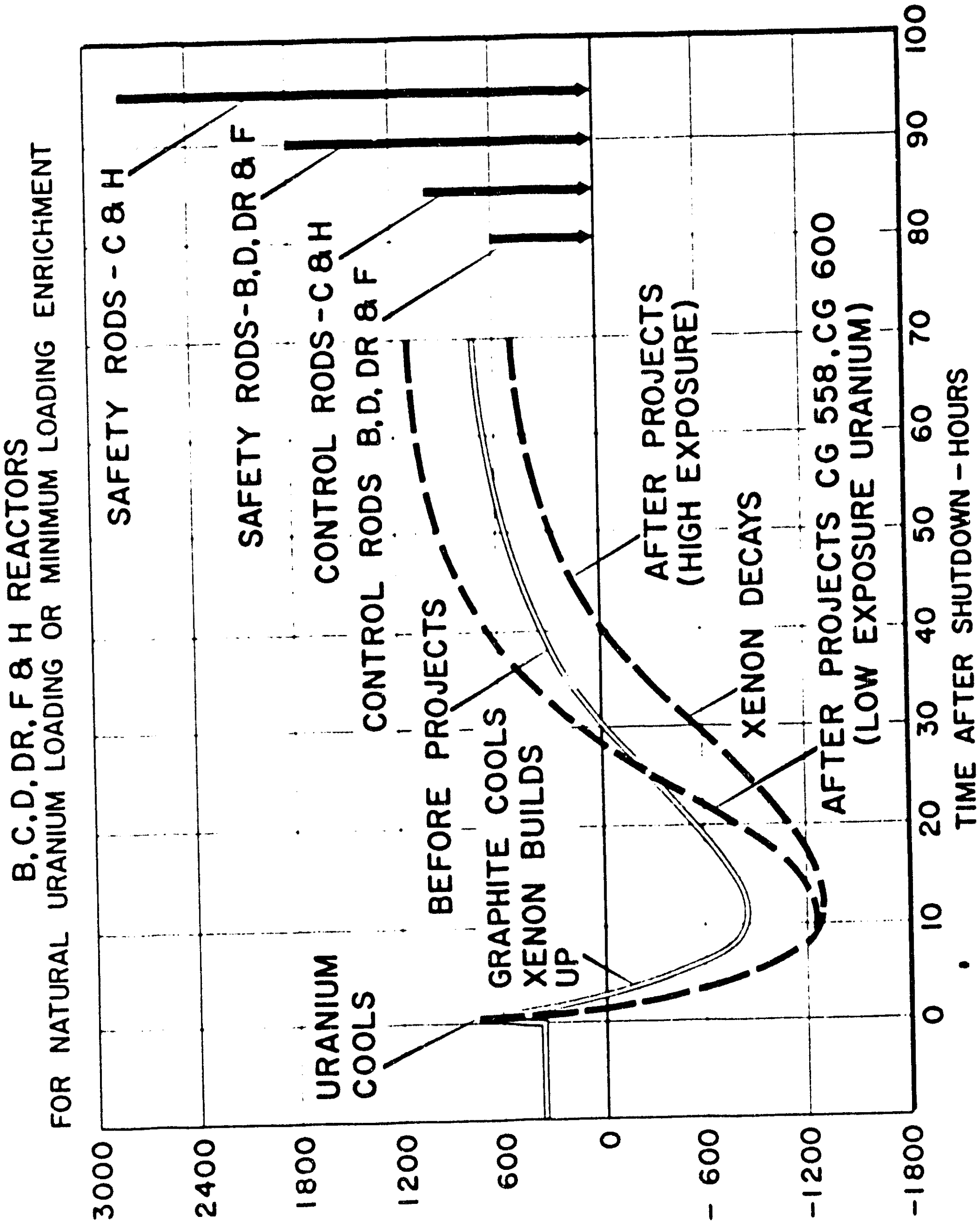

FIGURE 4

Representative Shutdown Reactivity Transients - Old Pile

[redacted]

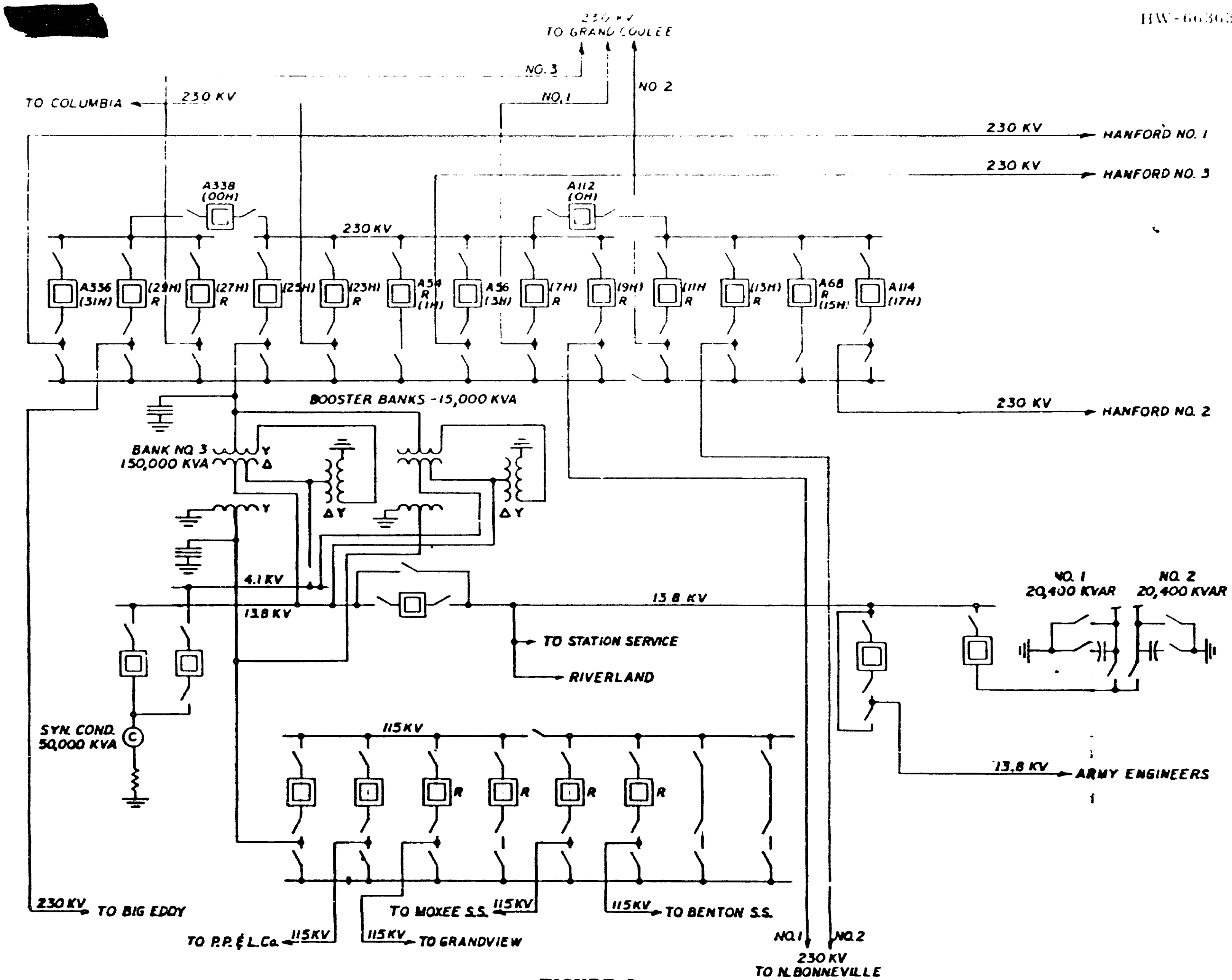

FIGURE 5

Simplified One Line Diagram of Midway Switching Station

[redacted]

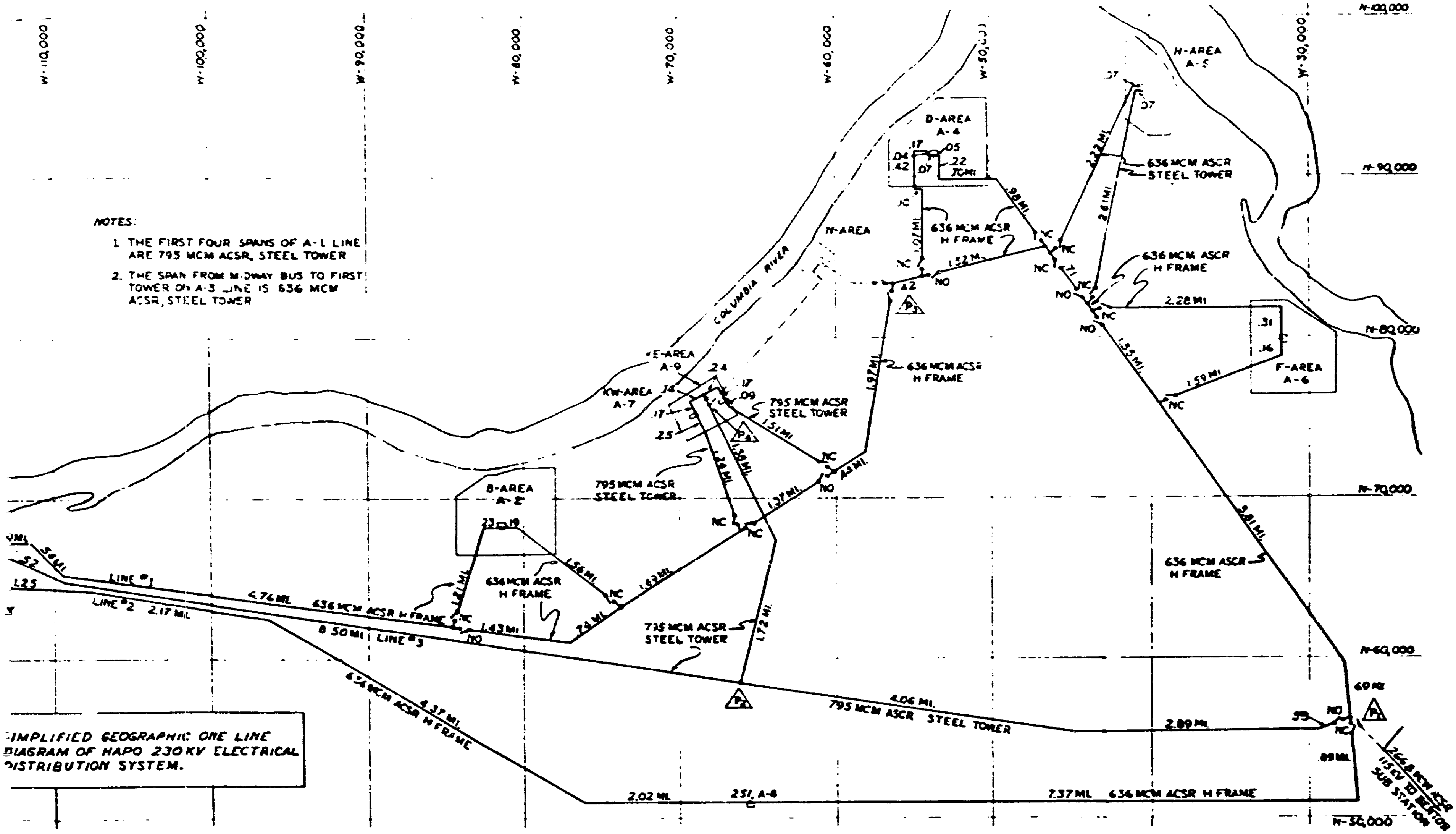

FIGURE 6

Simplified Geographic One Line Diagram - HAPO 230 KV System

DECLASSIFIED

[redacted]

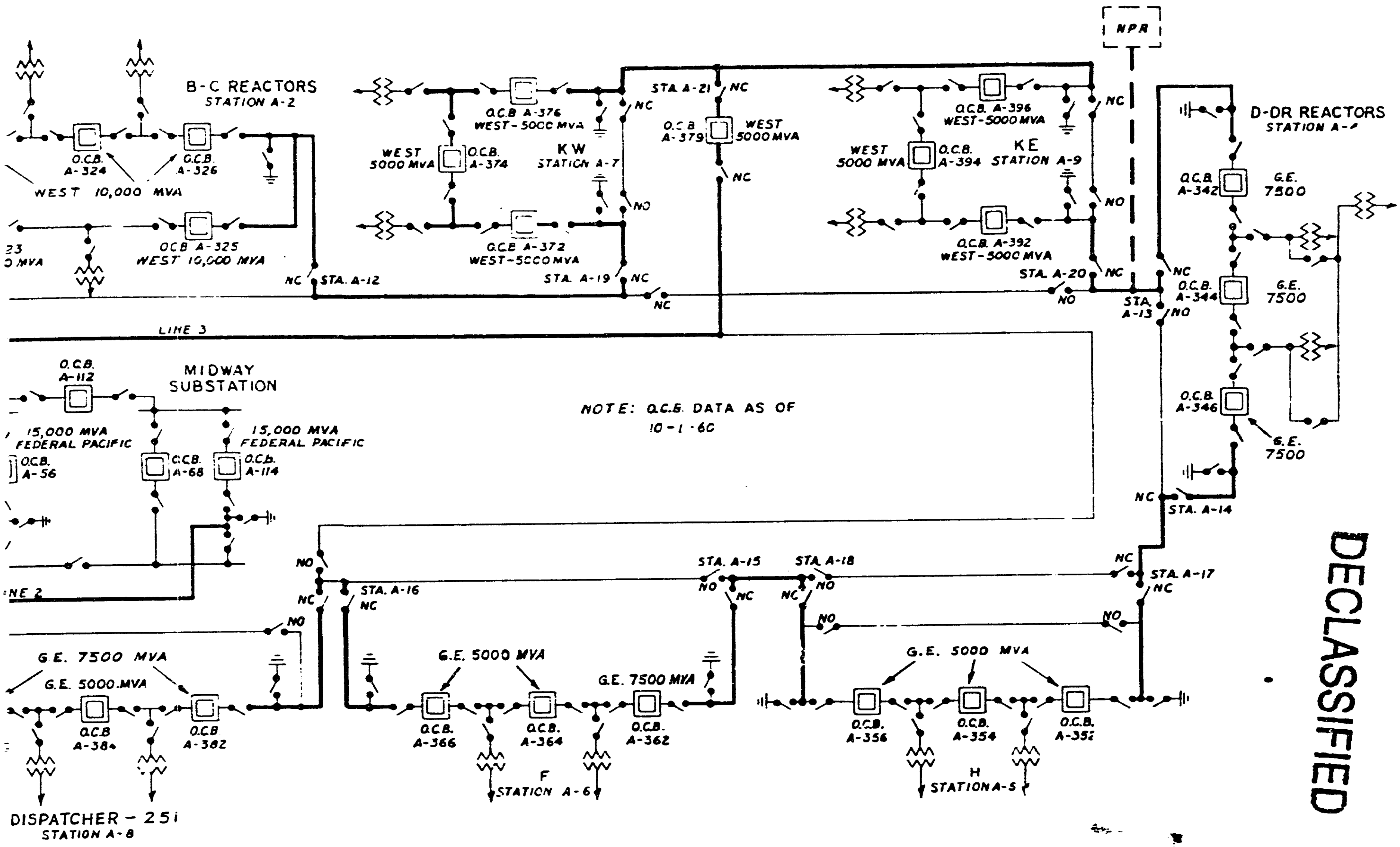

FIGURE 7

Simplified One Line Diagram of HAPO 230 KV System

[redacted]

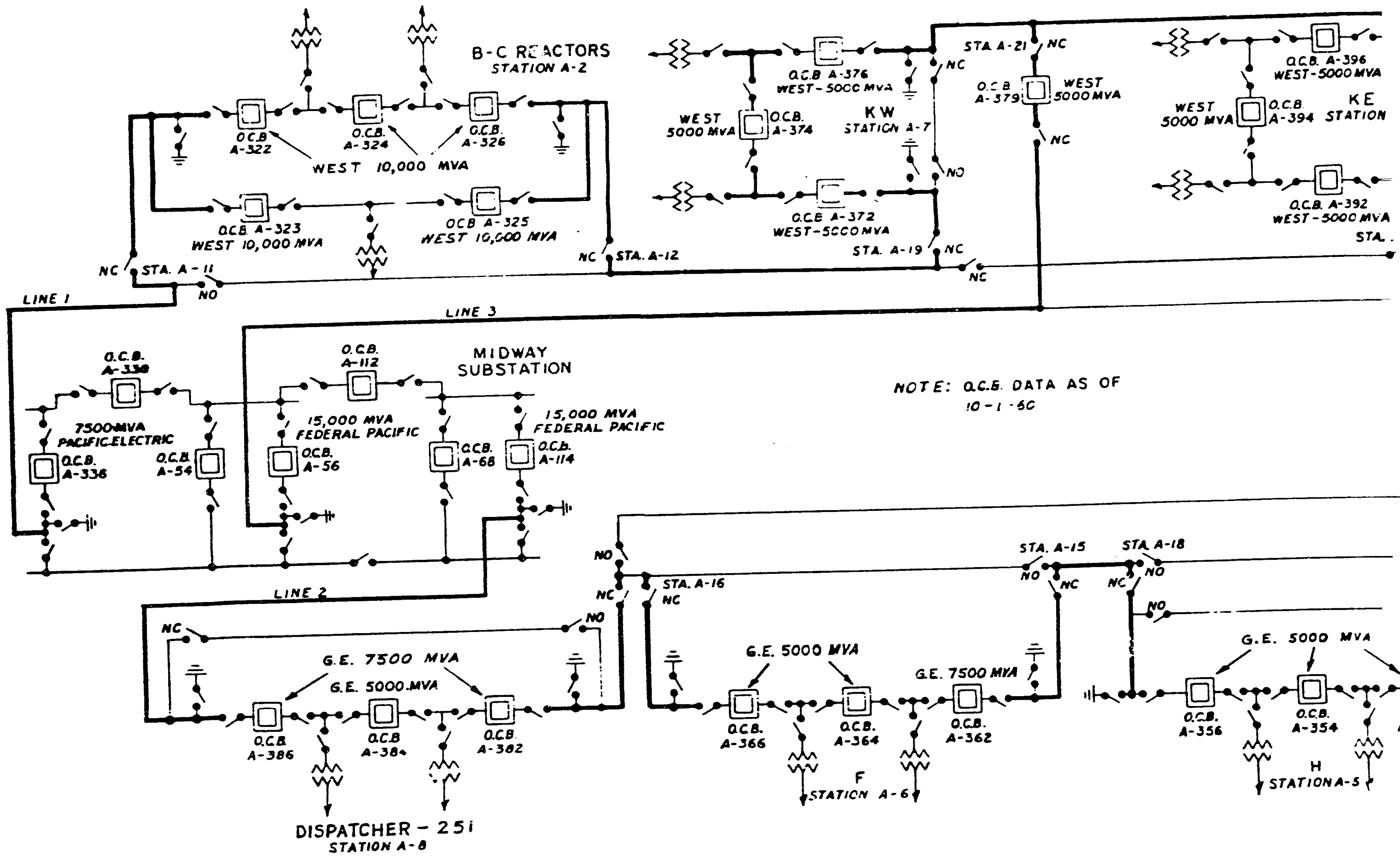

FIGURE 7

Simplified One Line Diagram of HAPO 230 KV System

[redacted]

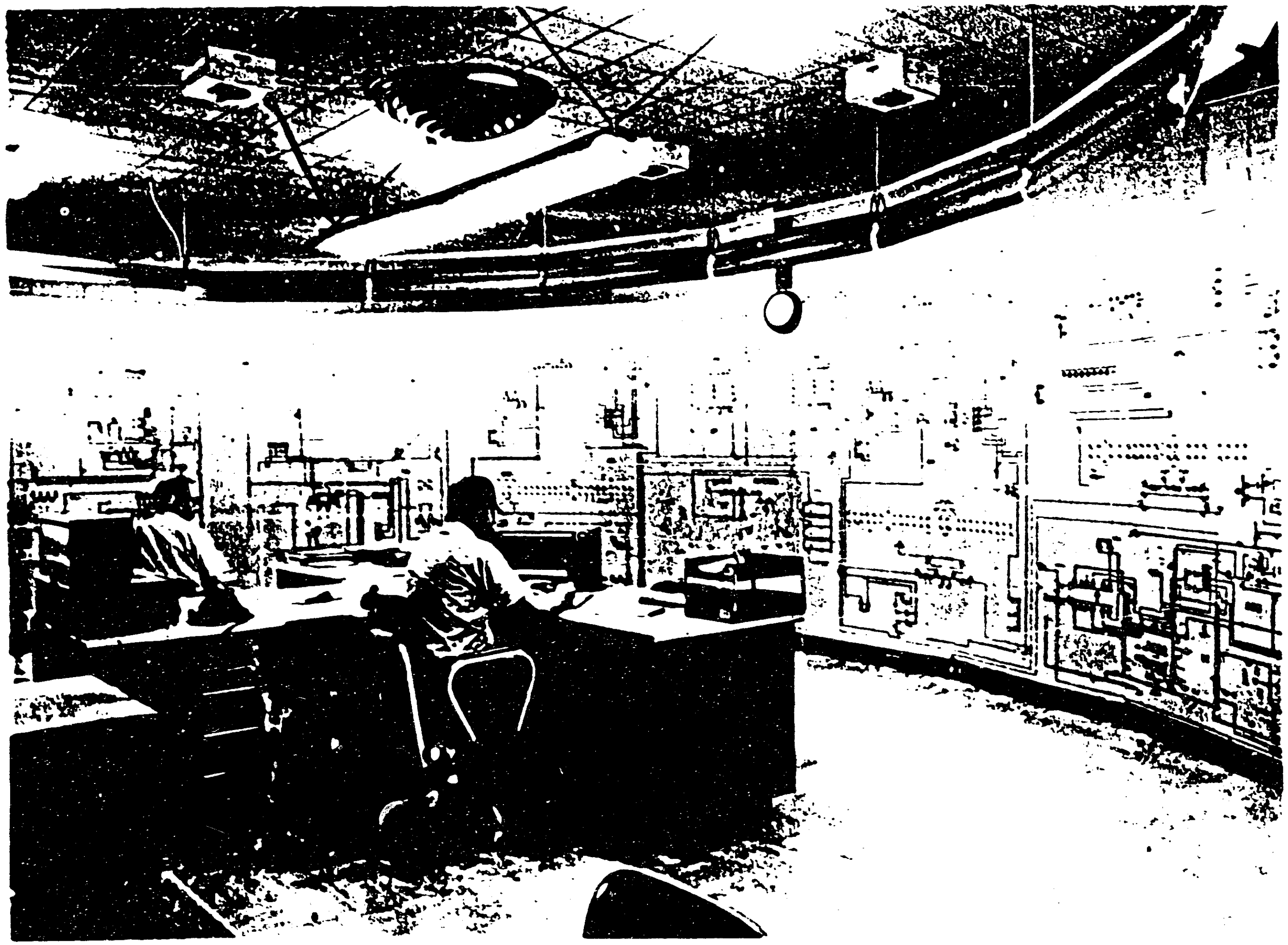

FIGURE 8

Photo of Dispatcher Panel - 251 Bldg .

[redacted]

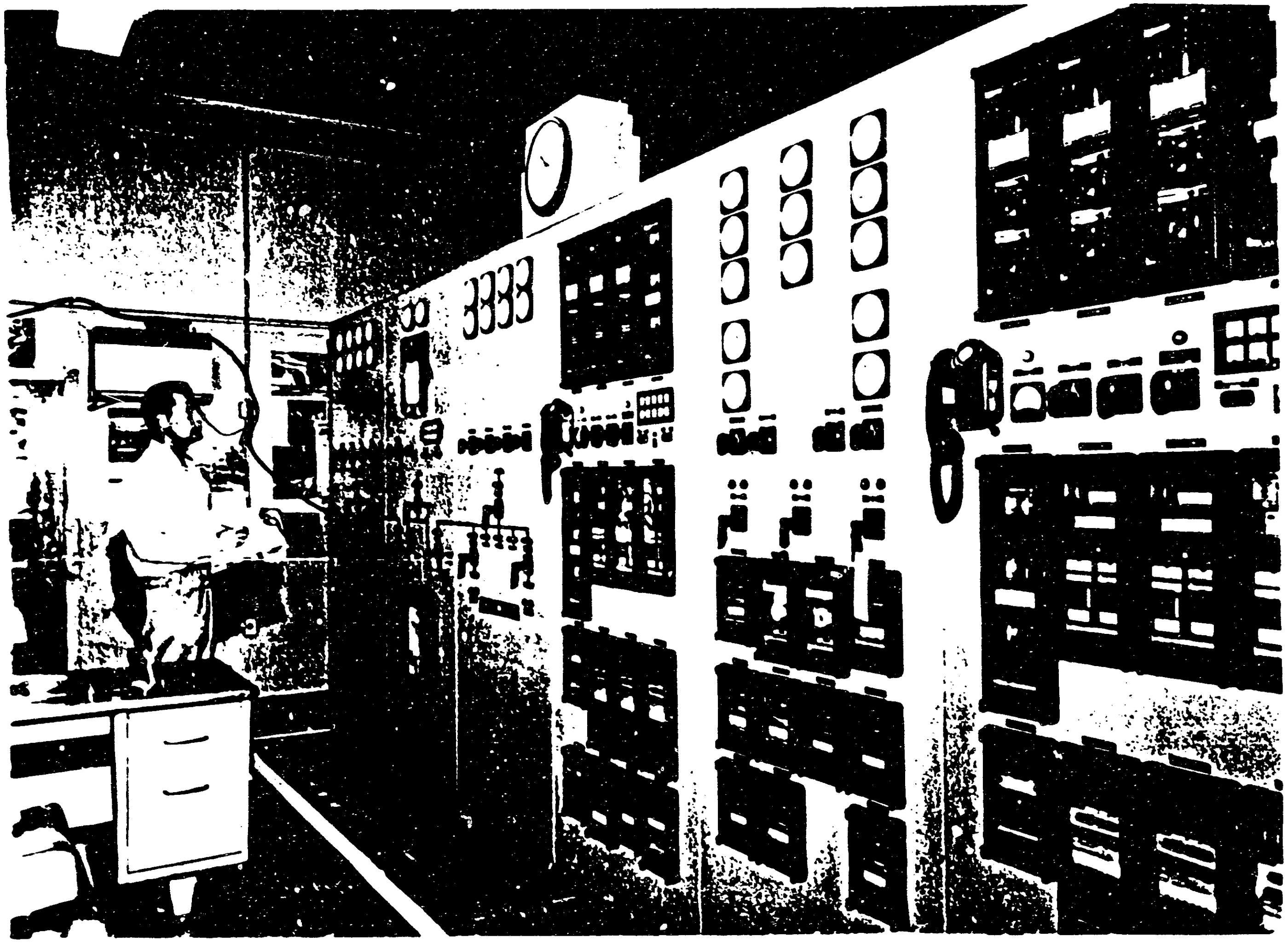

FIGURE 9

Photo of Electrical Control Panel 230 and 13.8 KV Switchgear - 151 K

[redacted]

DECLASSIFIED

HW-66363

[redacted]

FIGURE 10

Photo of Electrical Control Panel 230 and 13.8 KV Switchgear - 151 B

[redacted]

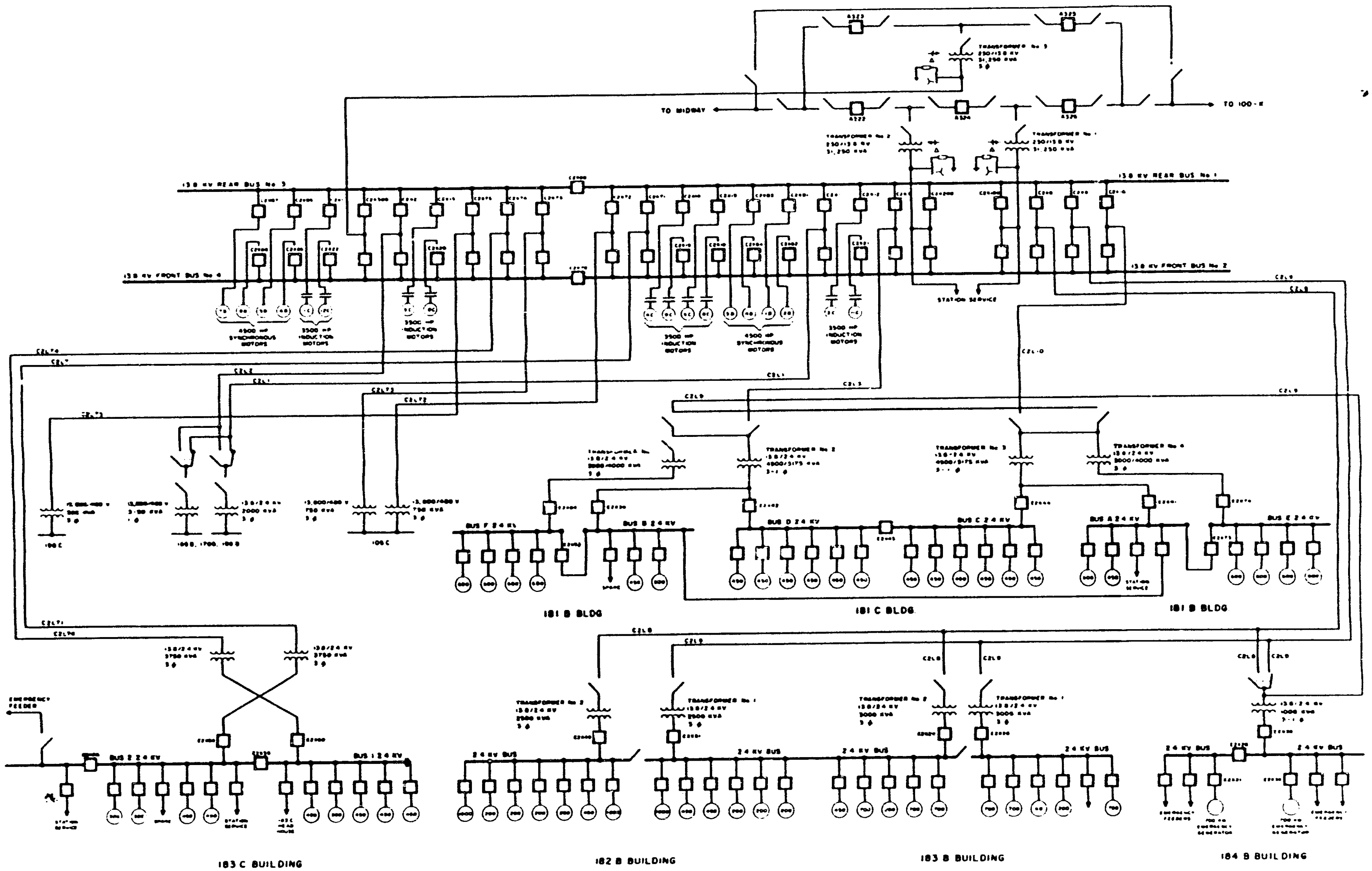

FIGURE 11

Simplified One Line Diagram of 100 B-C Area

DECLASSIFIED

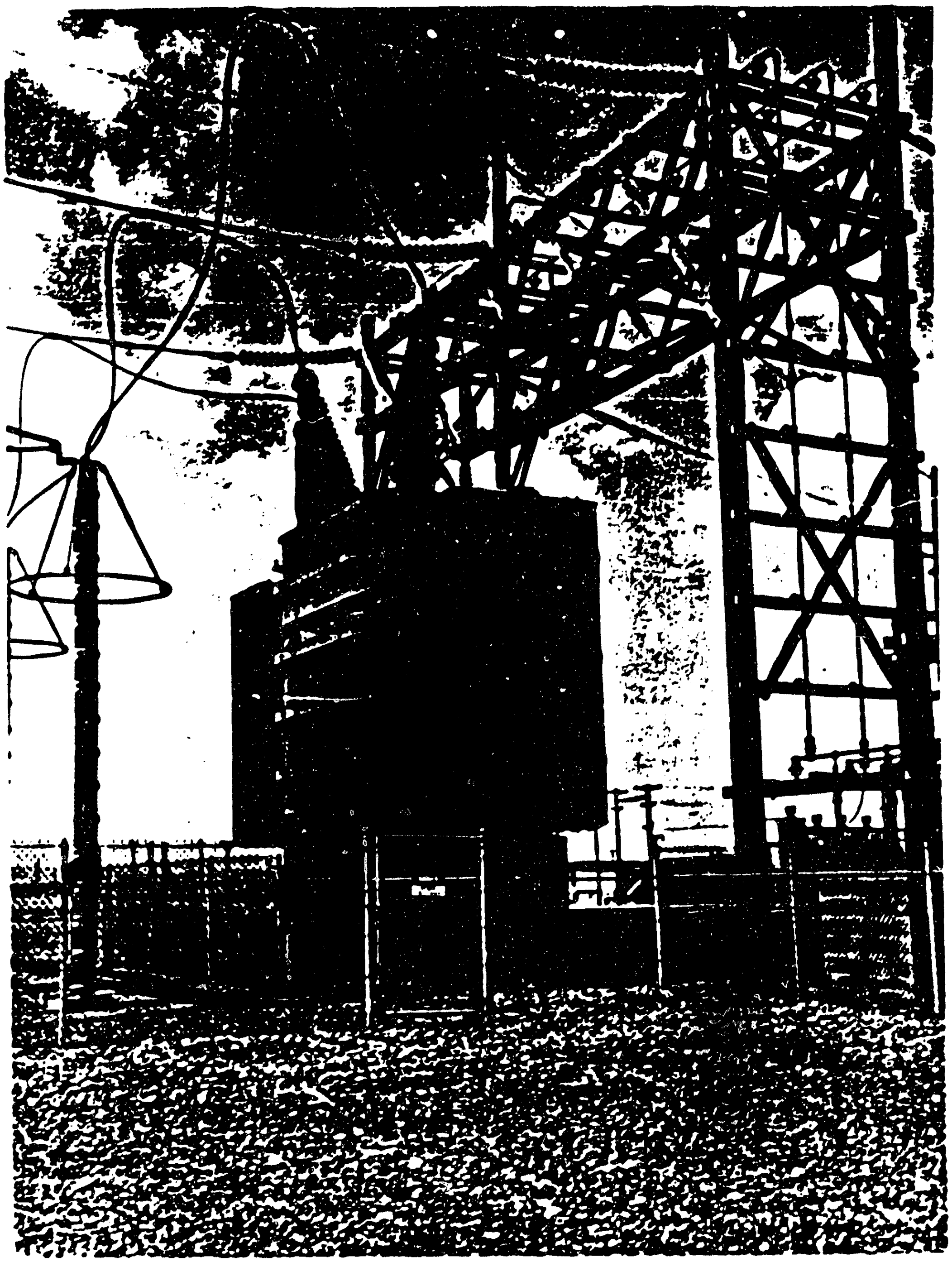

FIGURE 12

Photo of Typical 230/13.8 KV 31,250 KVA Transformer Bank

[redacted]

FIGURE 13

Photo of 4500 HP Synchronous Motor and Pump Unit - 190-B

[redacted]

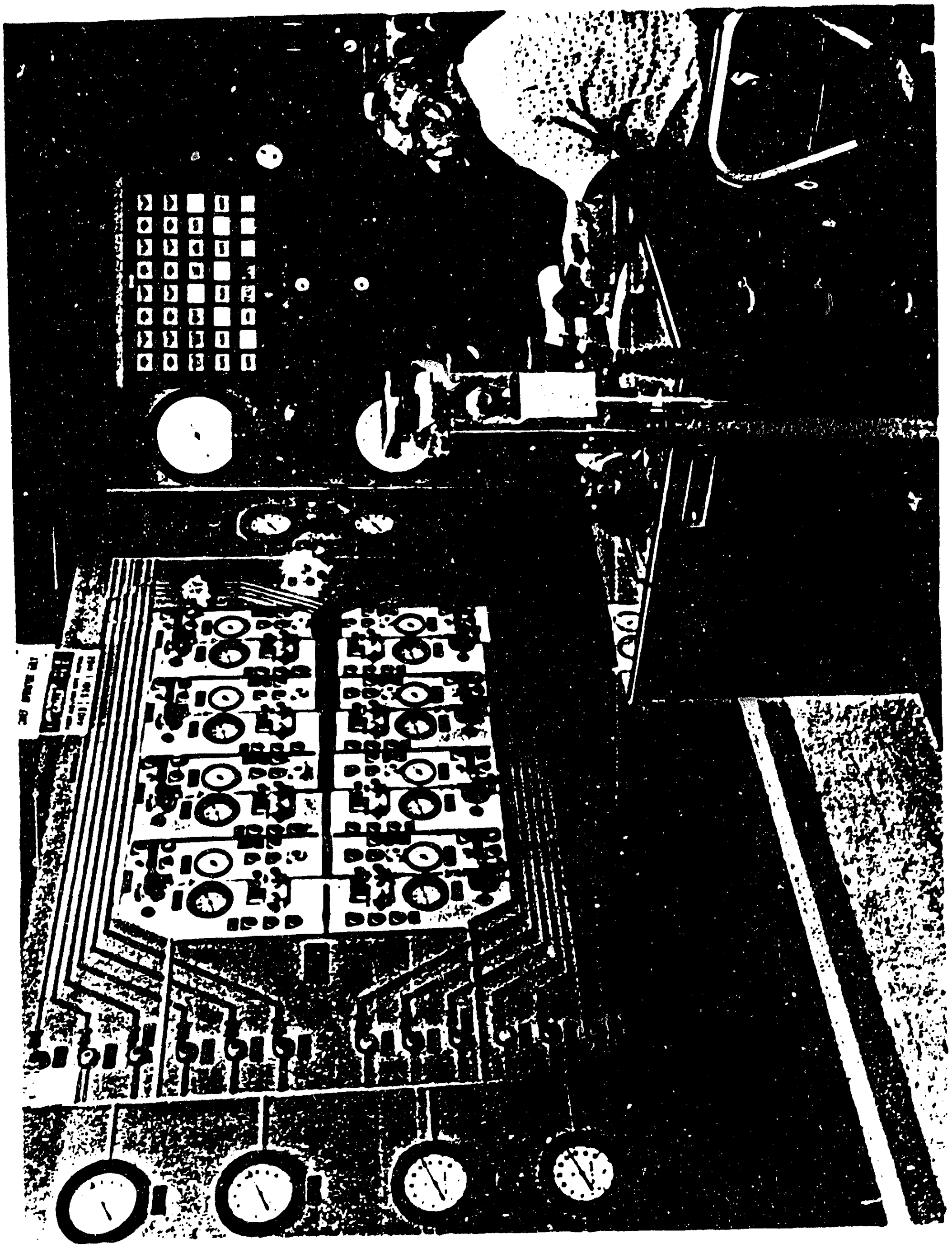

FIGURE 14

Photo of Motor Control Room 190-B

[redacted]

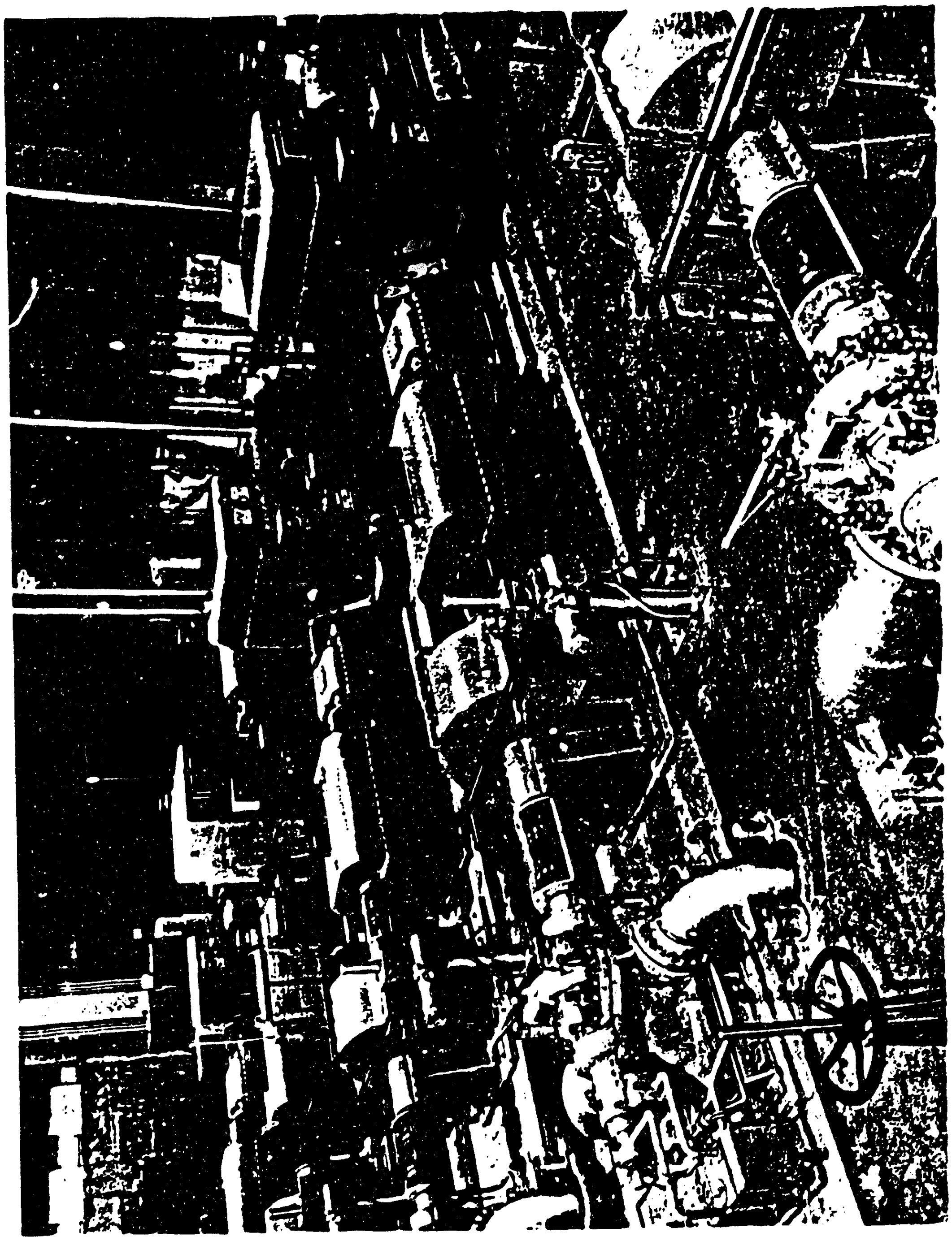

FIGURE 15

Photo of Motor - Pump Set - 190-C

[redacted]

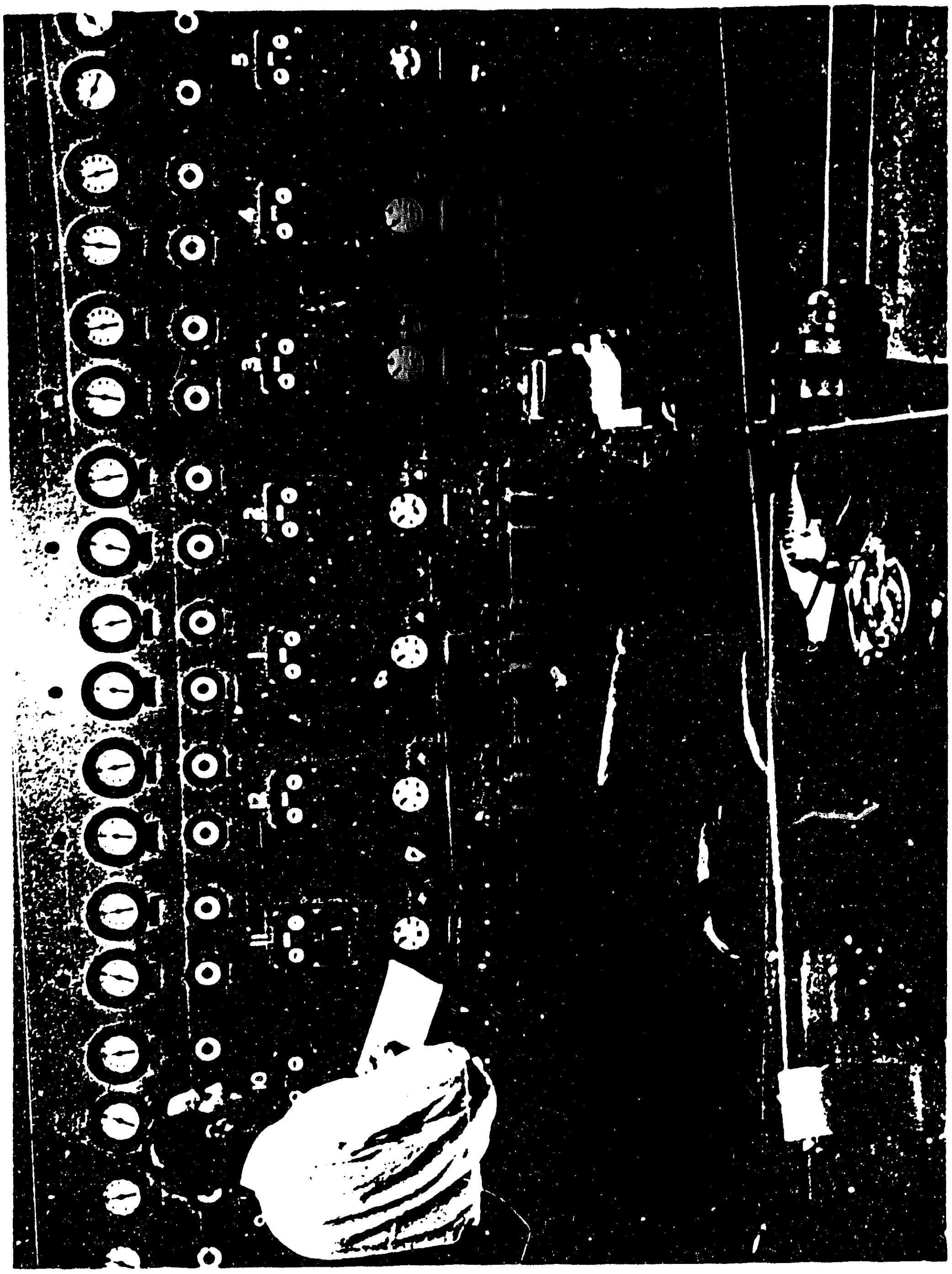

FIGURE 16

Photo of Motor Control Panel - 190-C

[redacted]

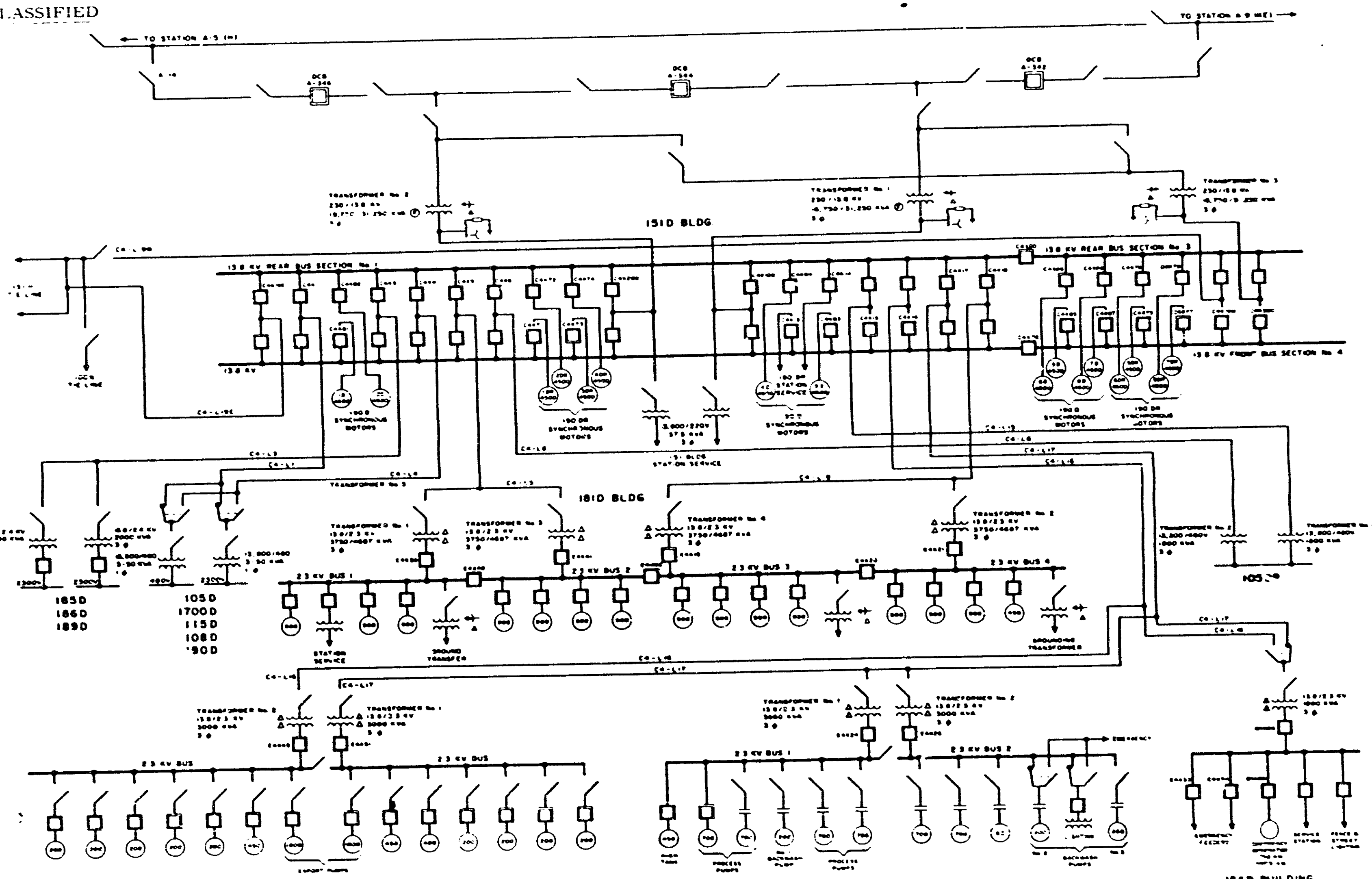

FIGURE 17

One Line Diagram of 100 D-DR Area

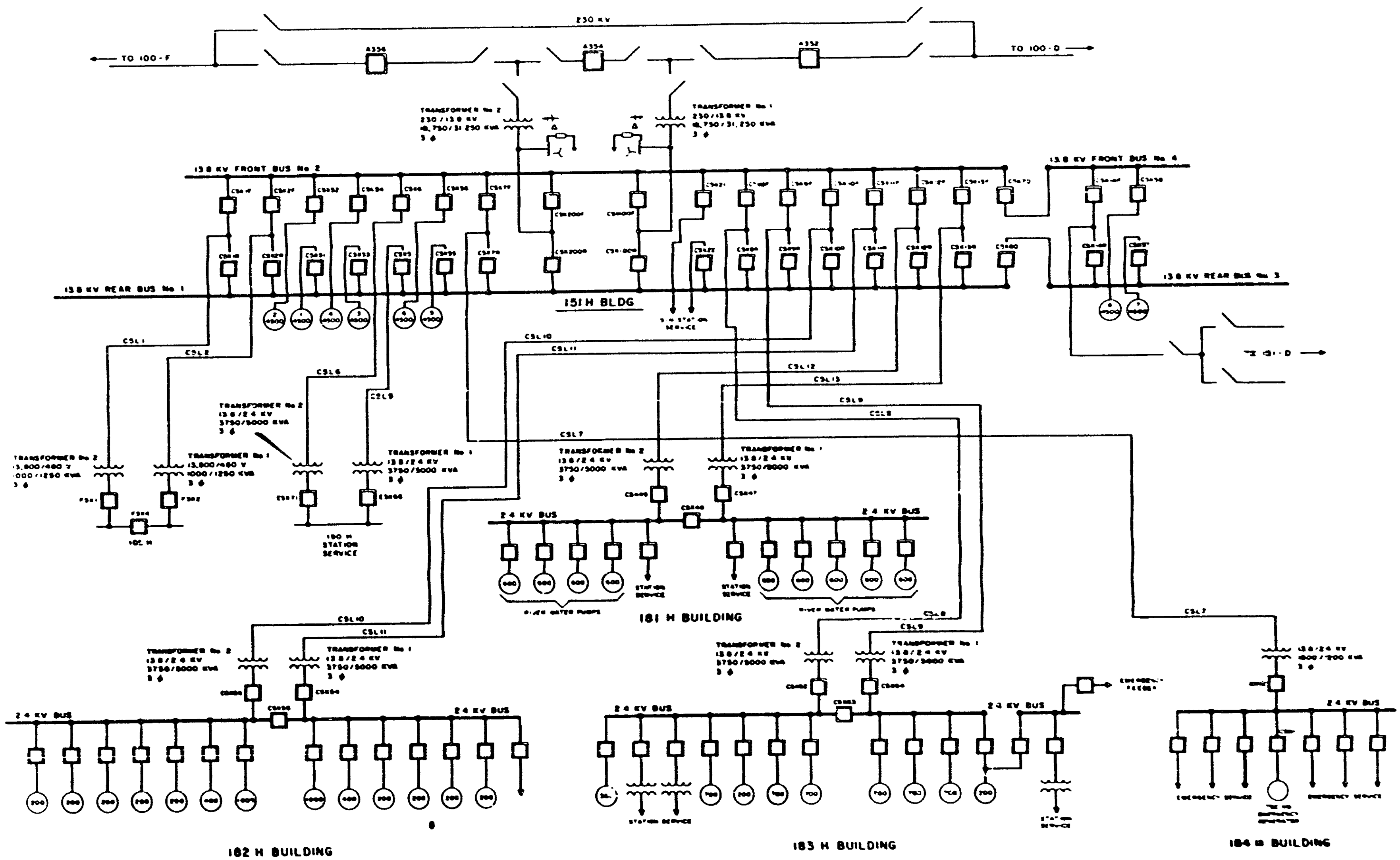

FIGURE 18

One Line Diagram of 100 H Area

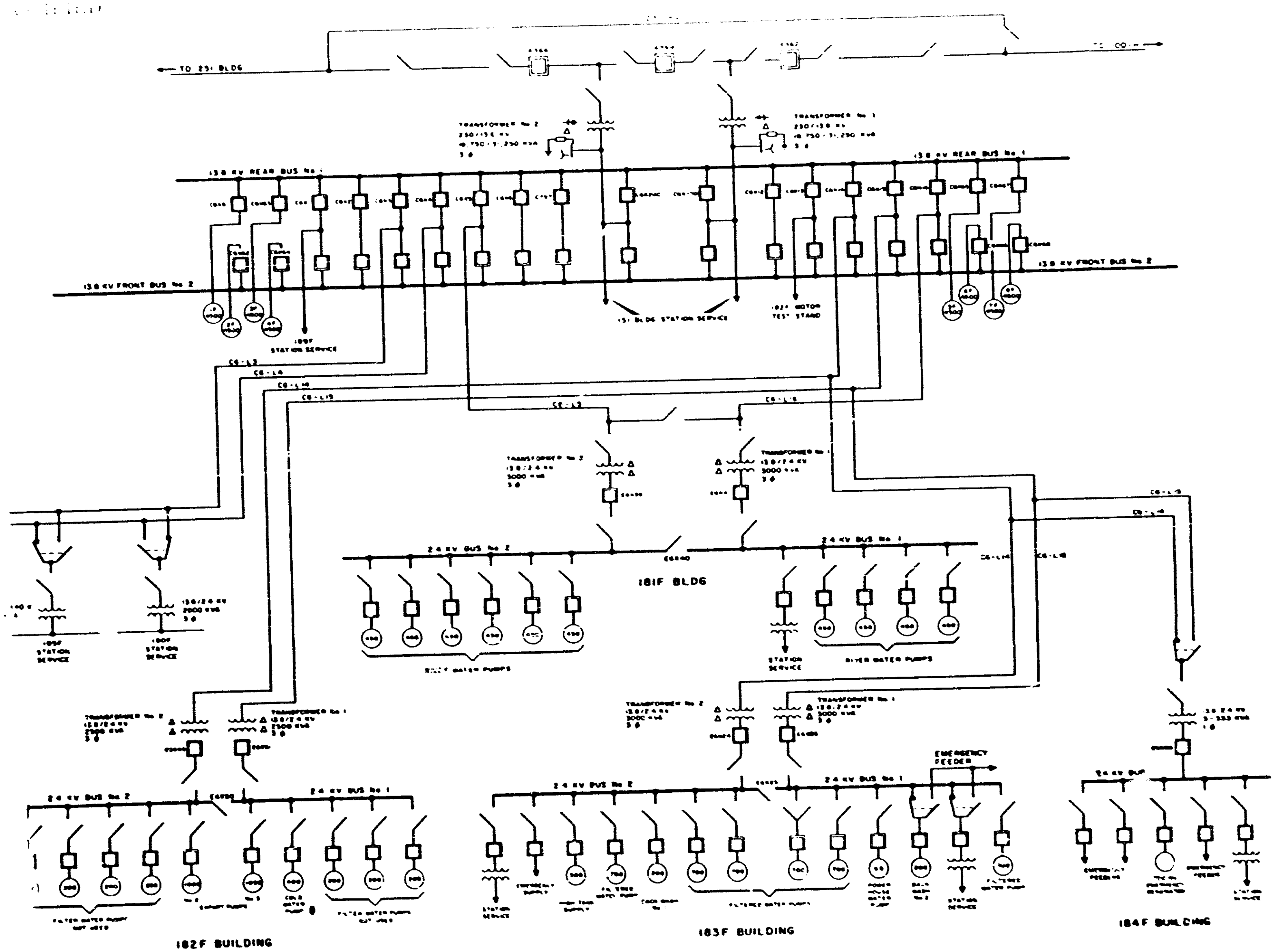

FIGURE 19

One Line Diagram of 100 F Area

UNCLASSIFIED

[redacted]

[redacted]

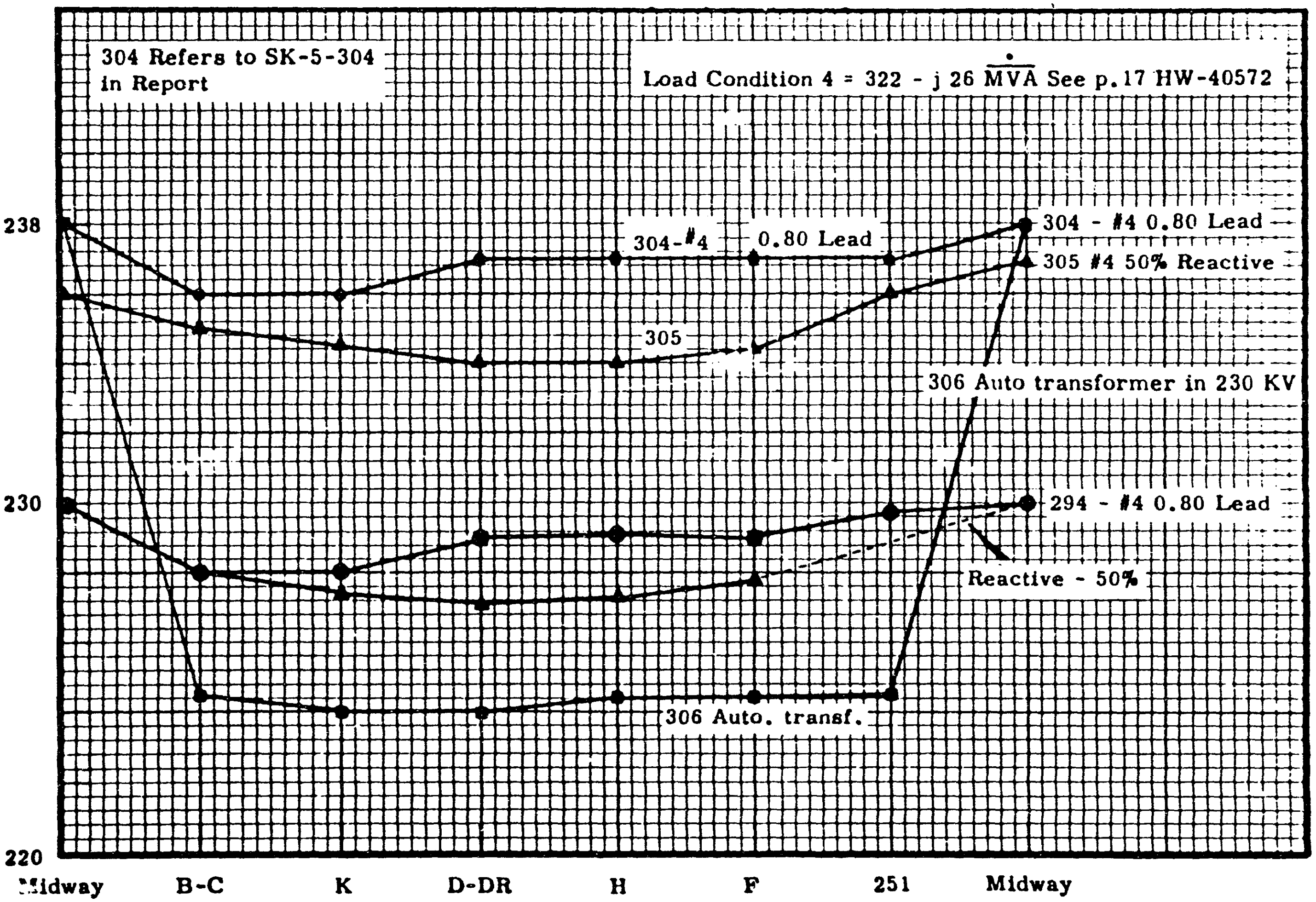

FIGURE 20

HAPO 230 KV Voltage Profile
(From HW-40512)

[redacted]

[redacted]

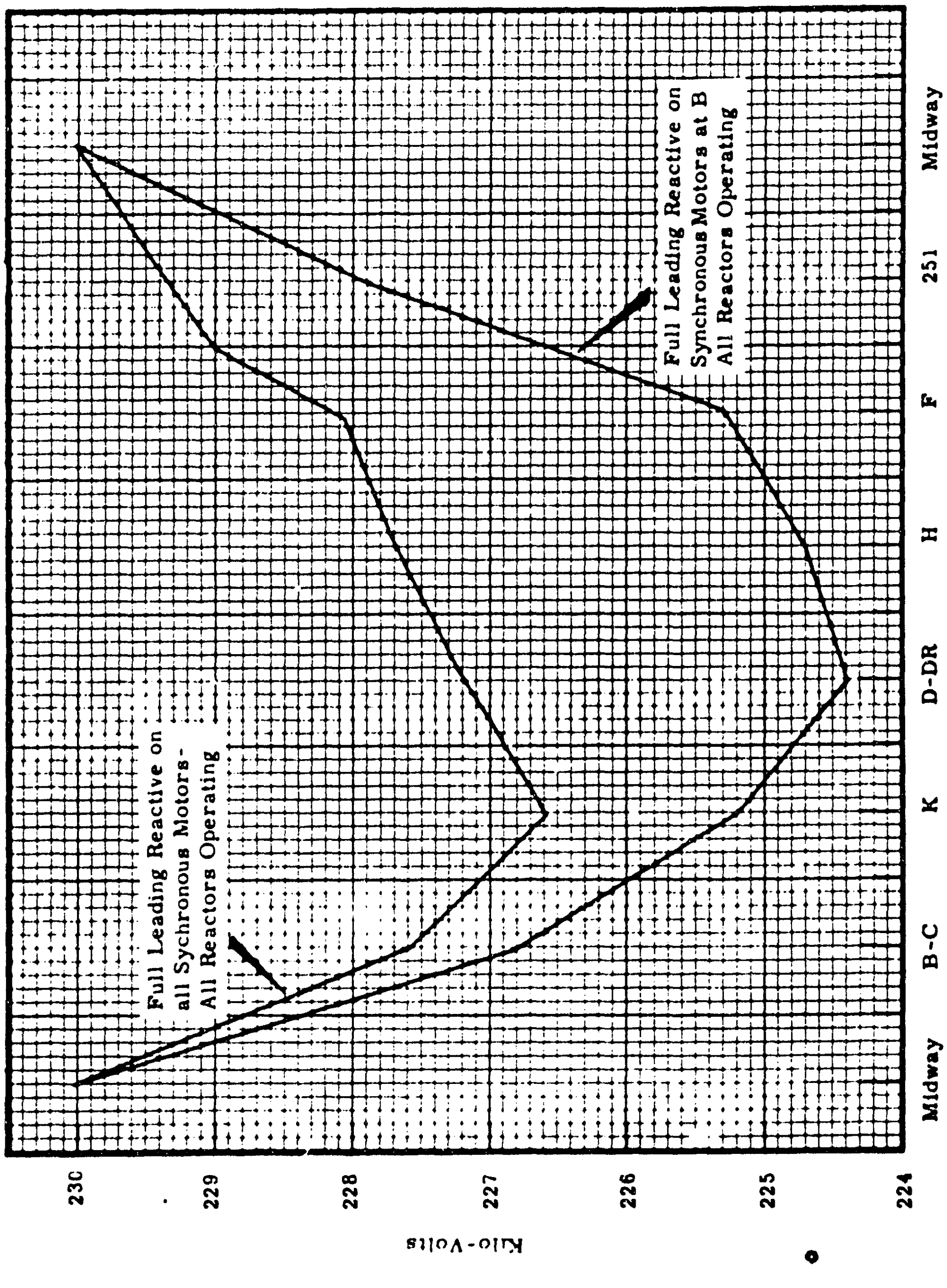

FIGURE 21

Voltage Profile HAPO 230 KV System
(From HW-63895 9-13-60)
MDH

[redacted]

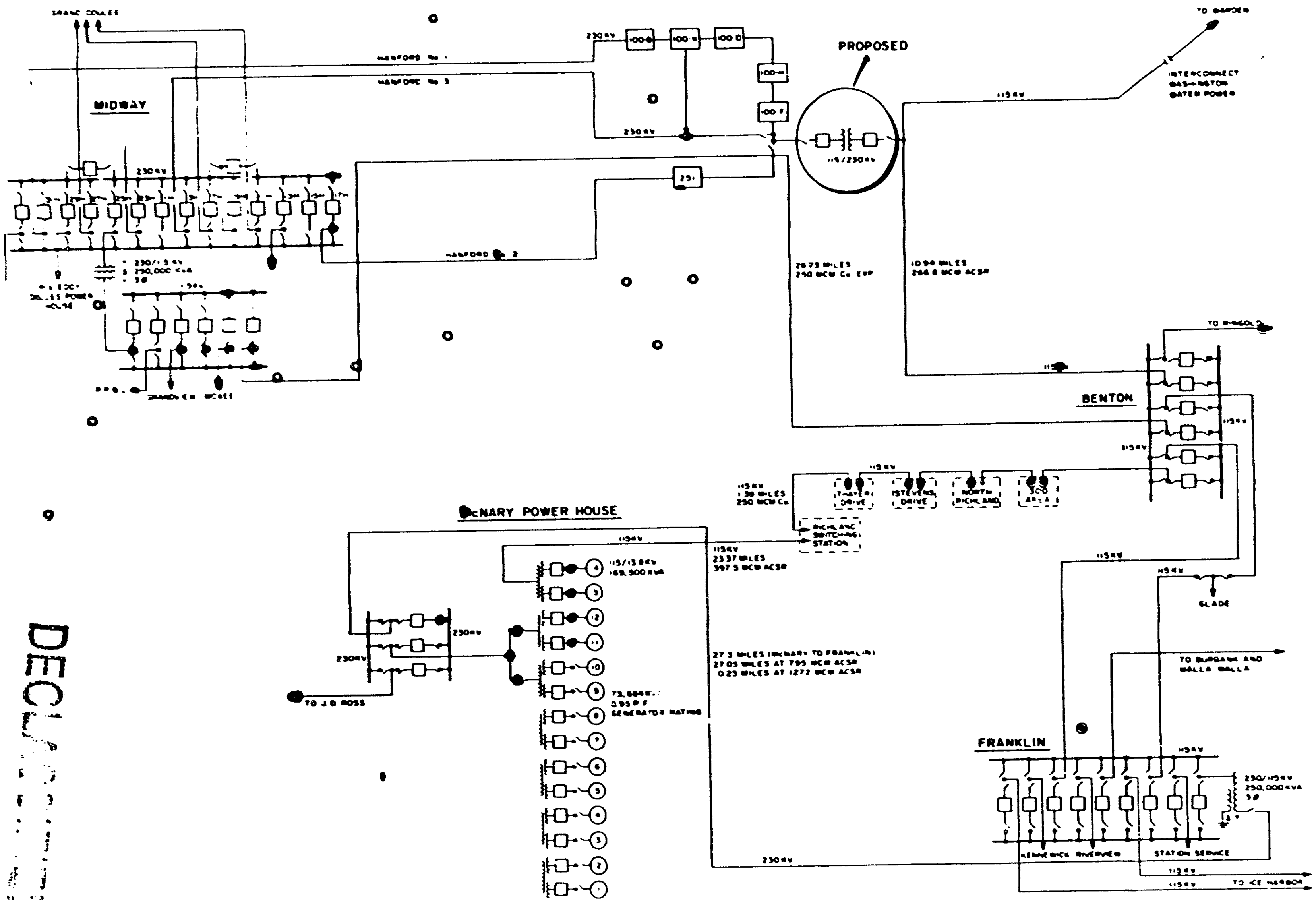

FIGURE 22

Simplified One Line Diagram of BPA System - McNary to Midway

[redacted]

[redacted]

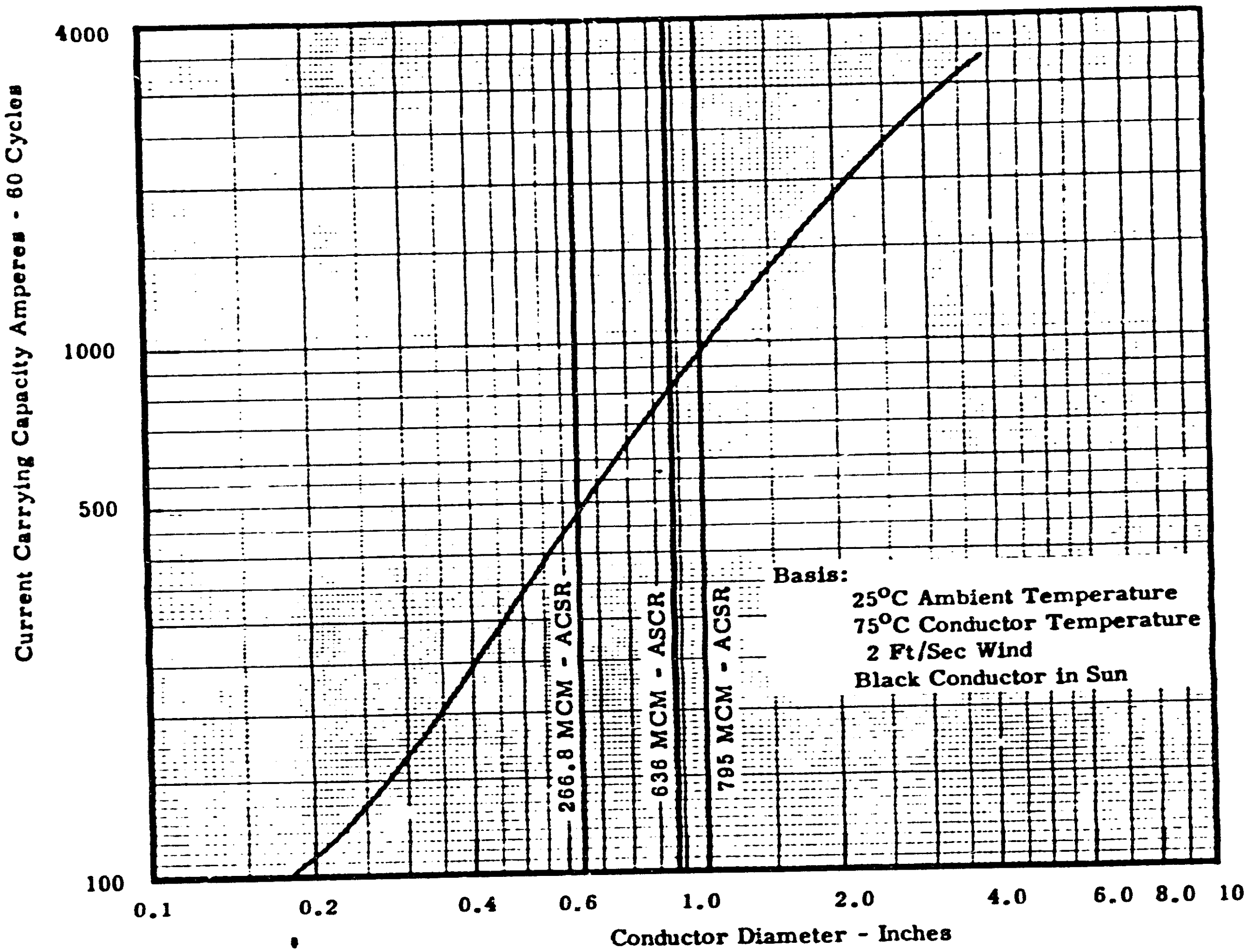

FIGURE 23

Current Carrying Capacity of Aluminum Cable Steel Reinforced - from AIEE Transactions 58-41
(8-6-60 MDH)

[redacted]

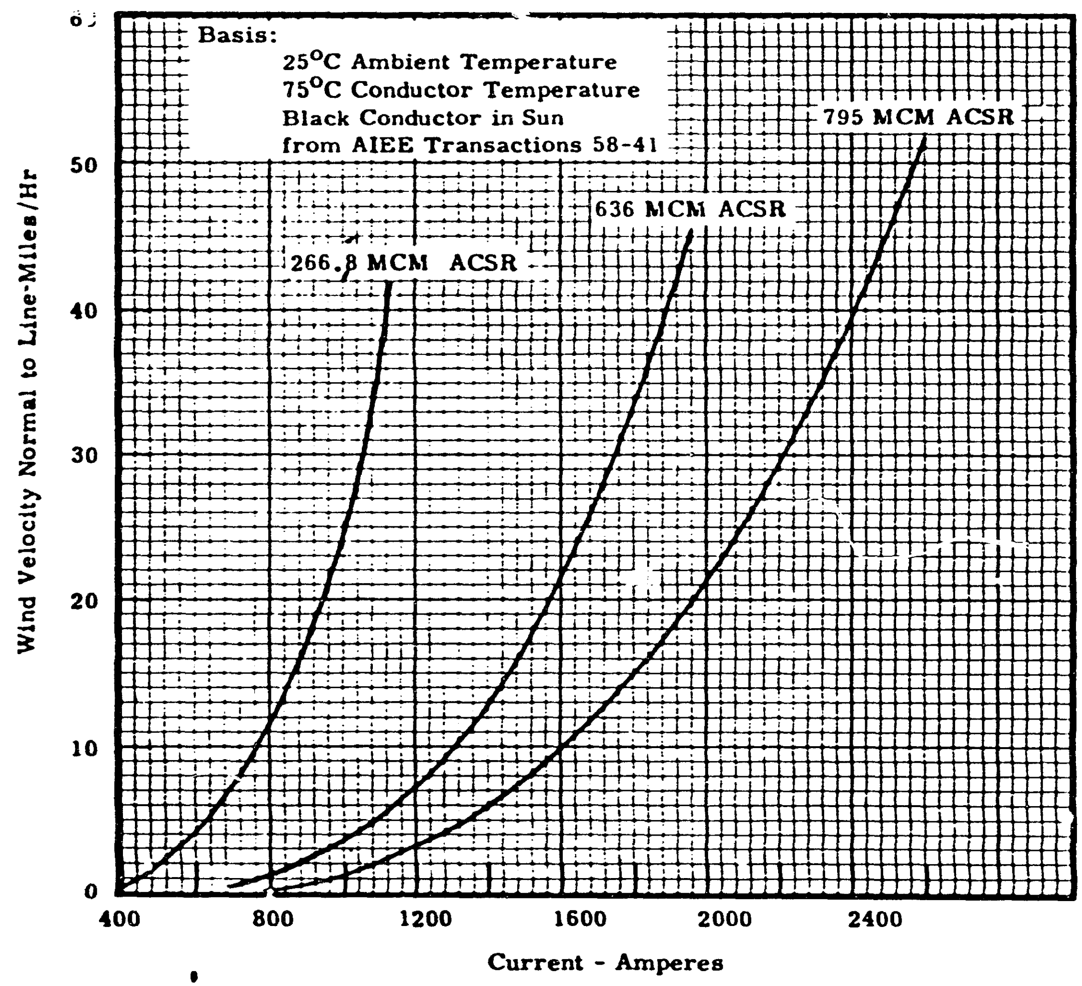

FIGURE 24

Effect of Wind Velocity on Current Carrying Capacity of ACSR Conductors
(8-6-60 MDH)

[redacted]

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[redacted]

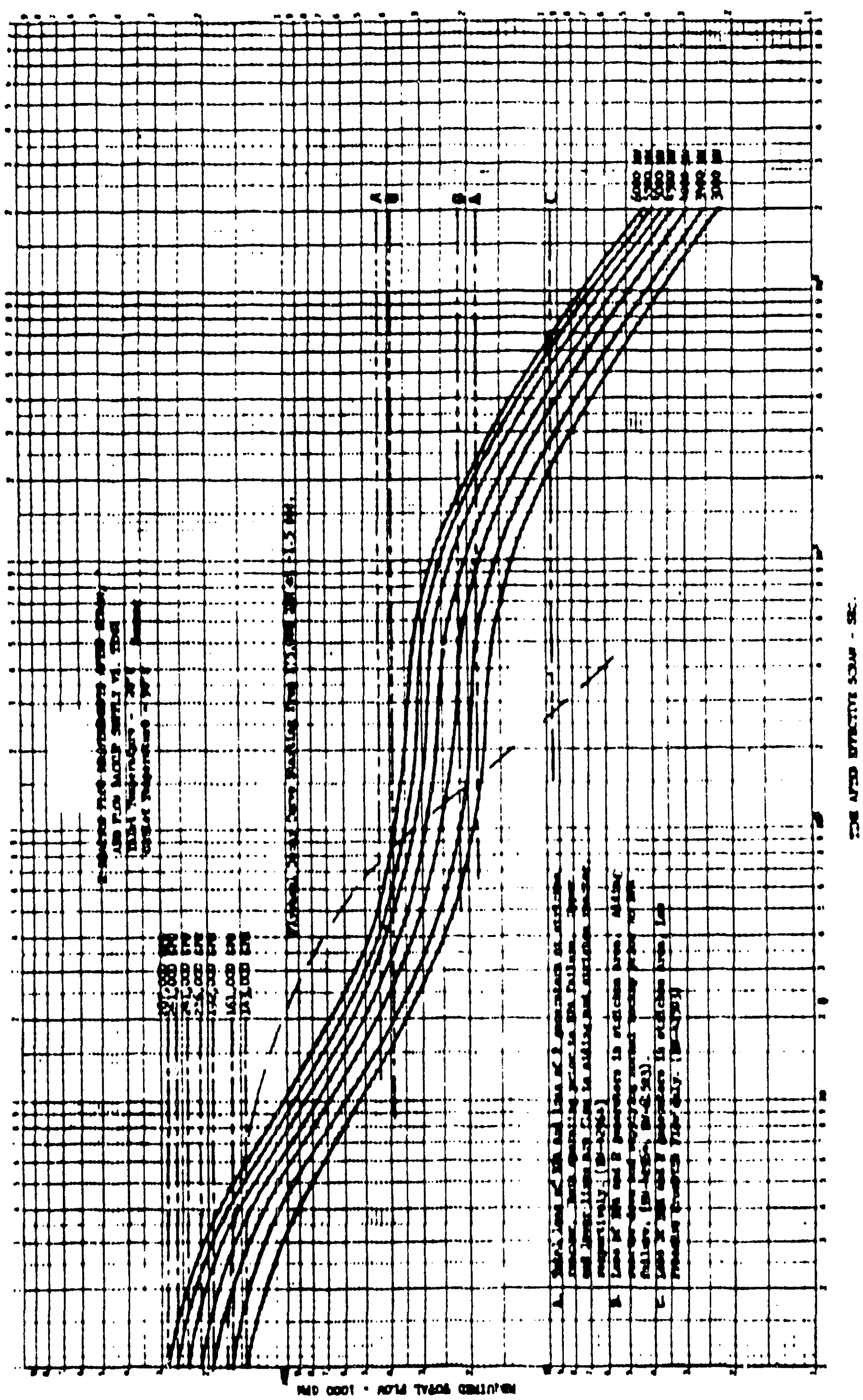


FIGURE 25

Flow Decay Following Loss of Power - K Reactor

[redacted]

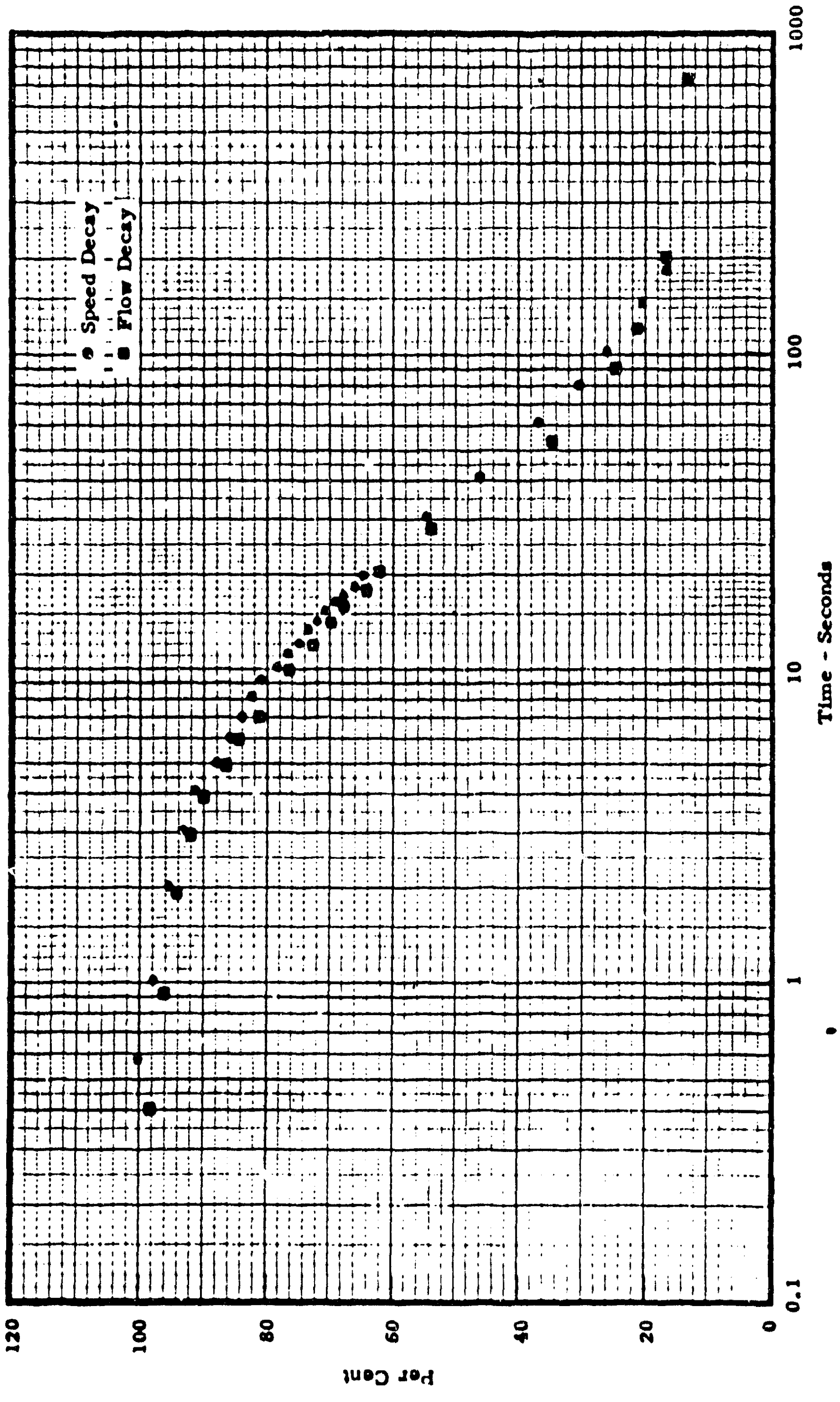
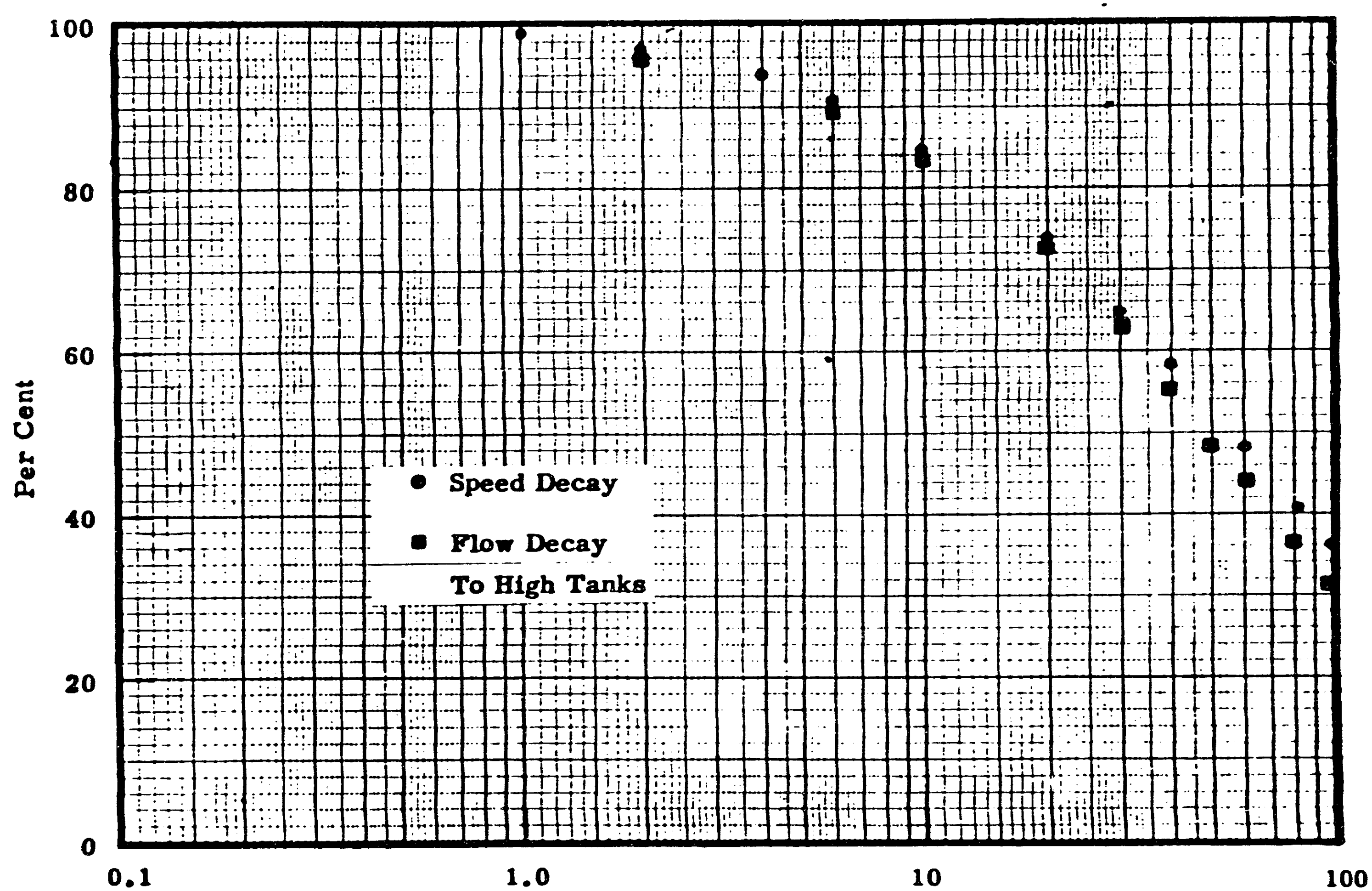


FIGURE 26

Speed & Flow Decay Following Loss of Power, H-Reactor 6 Pumps to Hi-Tanks

[redacted]

[redacted]



Time - Seconds

FIGURE 27

Speed and Flow Decay Following Loss of Power C-Reactor

[redacted]

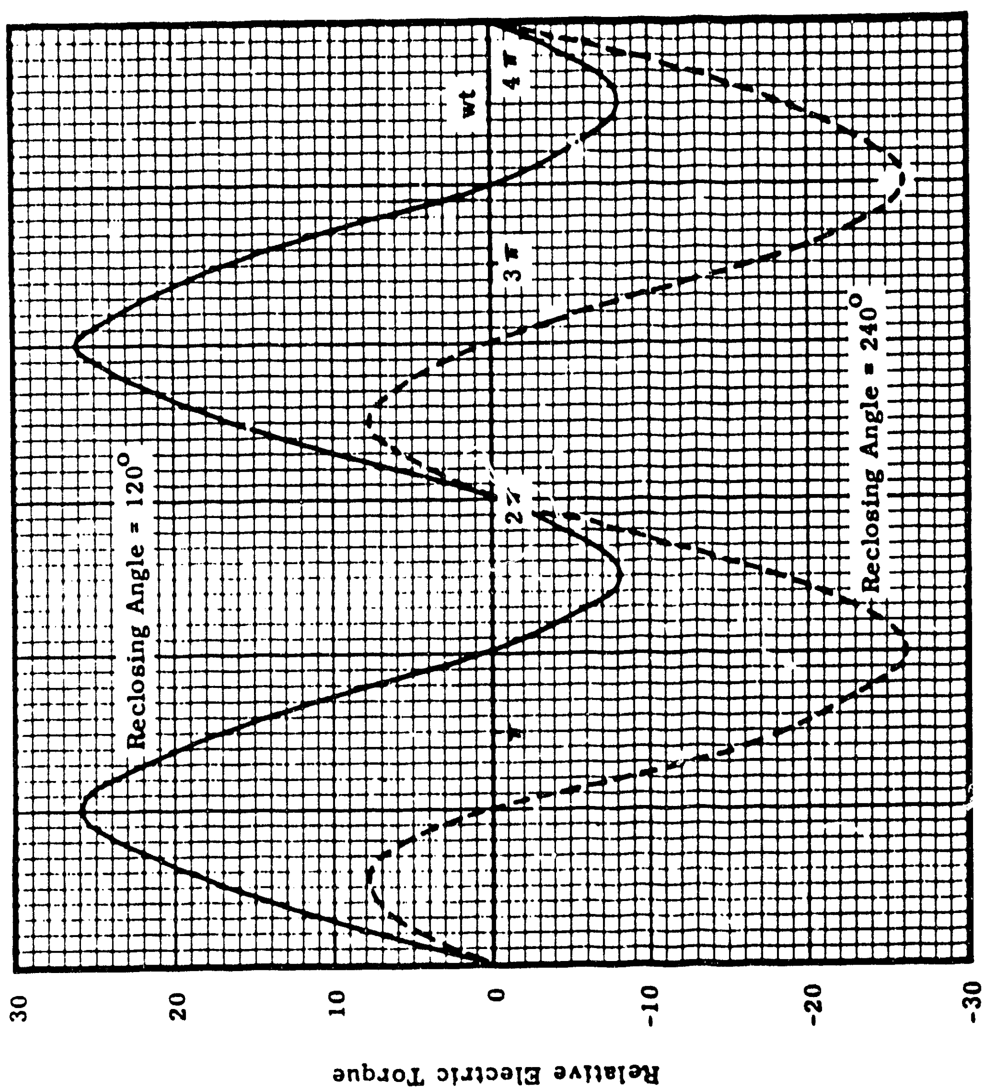


FIGURE 28

Variation in per Unit Electrical Torque Following Circuit Restoration

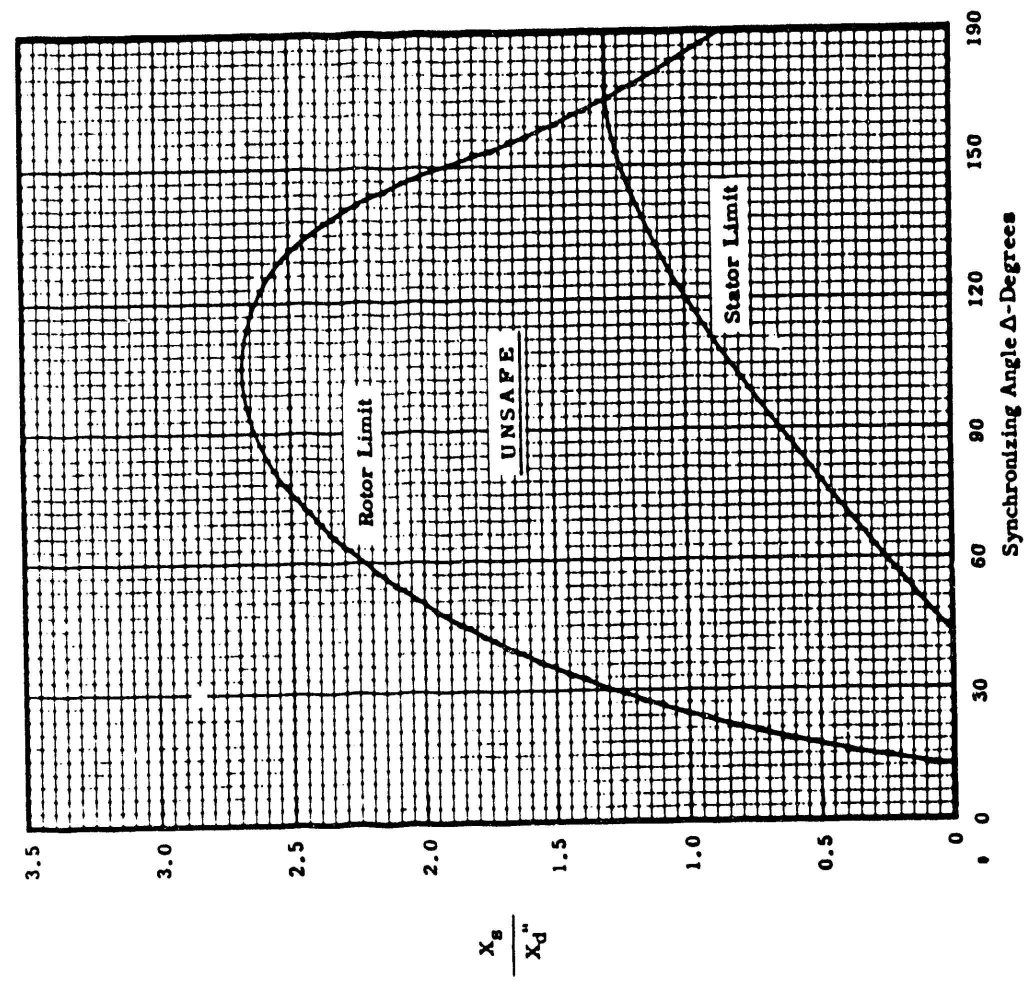


FIGURE 29

Safe Reclosing Angle

[redacted]

[redacted]

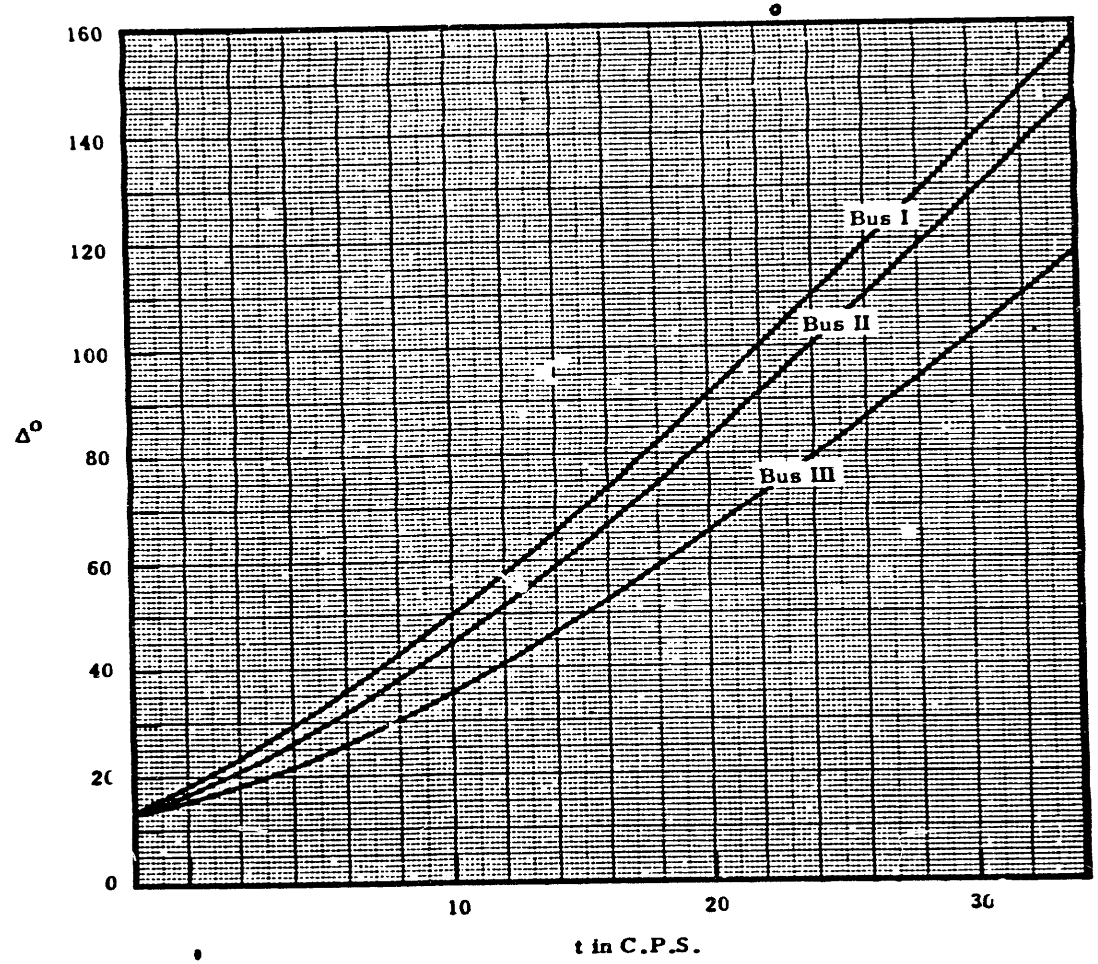


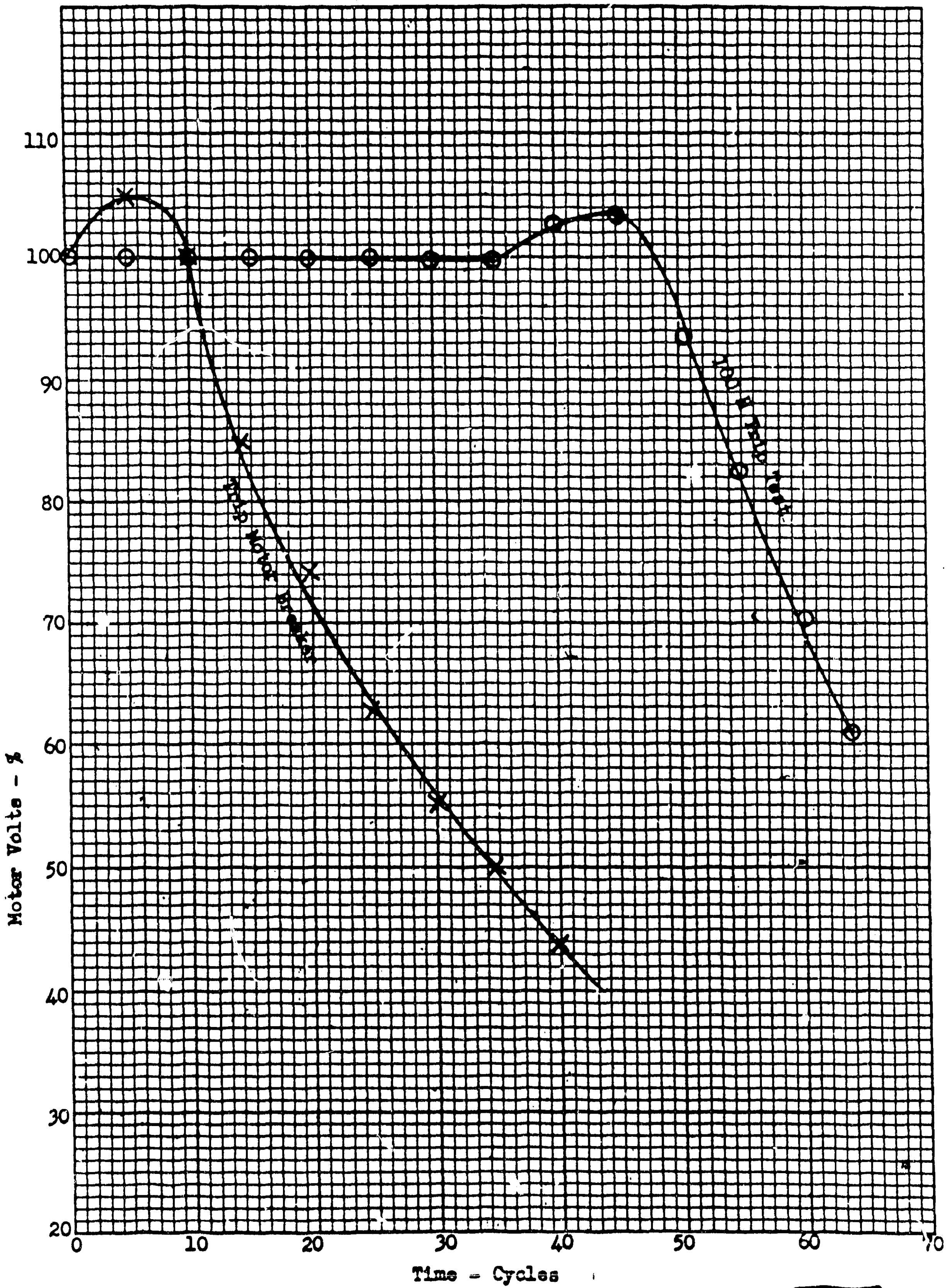
FIGURE 30

Angle Out of Phase Following Loss of Power to 13.8 KV Bus, D-DR Reactor
(FPR 7-12-60)

[redacted]

[redacted]

FIGURE 31
VOLTAGE ON 13.8 KV BUS FOLLOWING LOSS OF POWER



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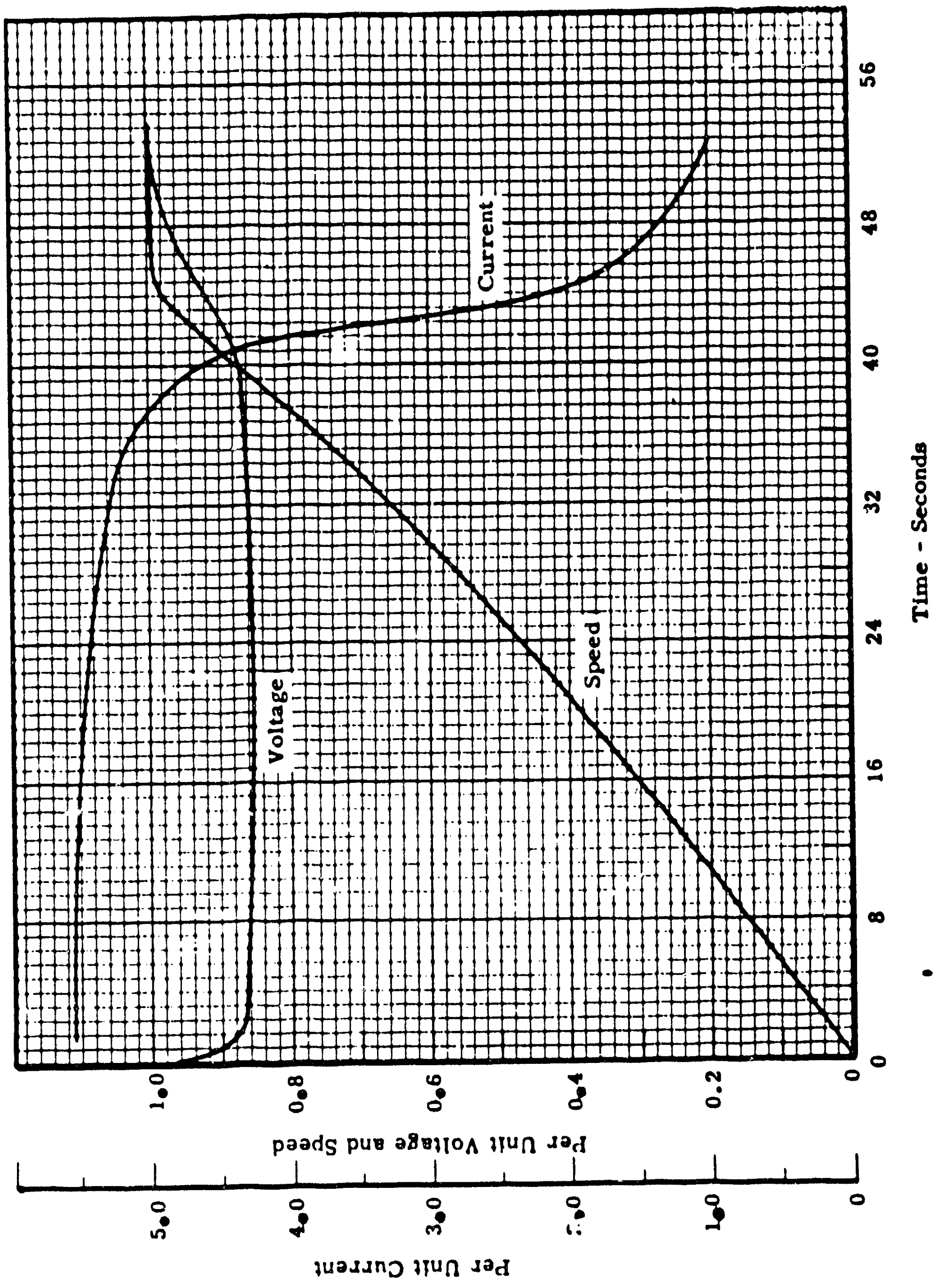

FIGURE 32

Per Unit Starting Transients - 4500 HP Synchronous Motor-Started on Single Bus (8-30-60 MDH)

[redacted]

[redacted]

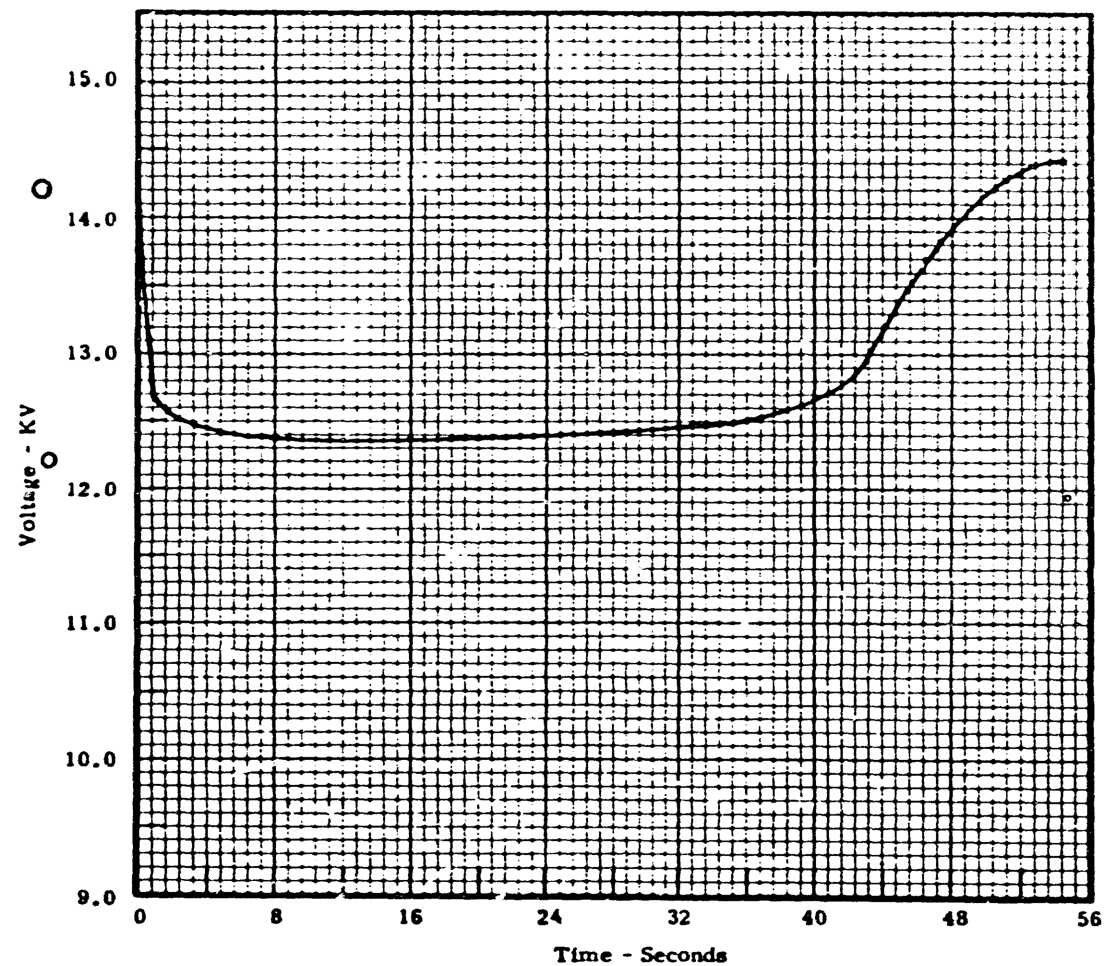

FIGURE 33

Starting Voltage Transients - 4500 HP Synchronous Motor-Started on Single Bus
(8-16-60 MDH)

[redacted]

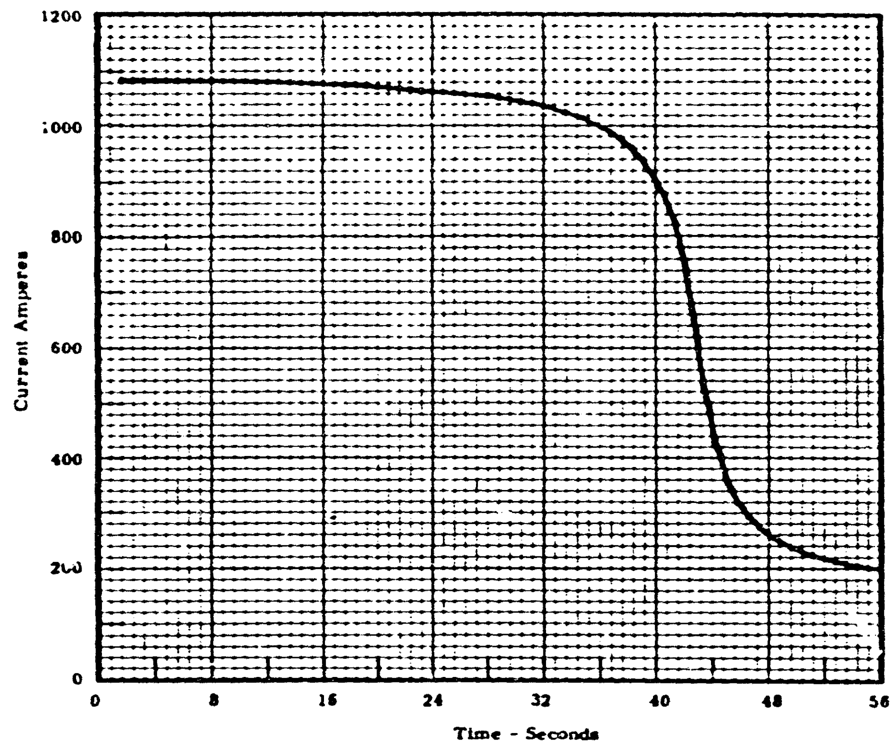

FIGURE 34

Starting Current Transient-4500 Synchronous Motors-Start on Single Bus
(8-4-60 MDH)

[redacted]

[redacted]

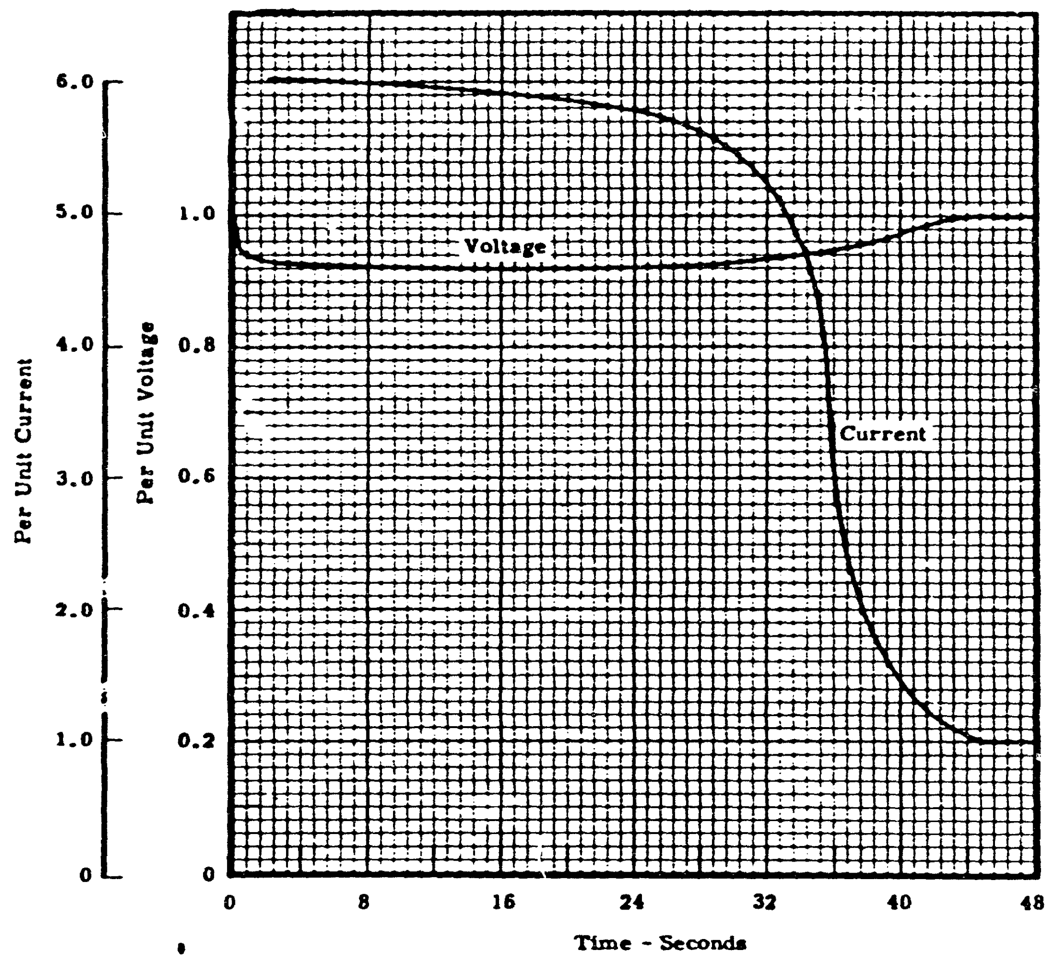

FIGURE 35

Starting Current and Voltage Transient - 4500 HP Synchronous Motors - Start on Paralleled Bus

(8-20-60 MDH)

[redacted]

APPENDIX C

TABLES

[redacted]

[redacted]

TABLE A

100 B-C ELECTRICAL EQUIPMENT LIST

Motor Function	Location	Number	Type	Horse Power Rating	Voltage	Current	Manufacturer
Process Water Pumps	190 B	8	Synchronous (Squirrel Cage Start)	4500	13,800	196	GE
Process Water	190 C	10	Induction	3500	4,160	406	Electric Machinery
Process Water	183 B	6	Induction	700	2,200	161	GE
High Tank	183 B	1	Induction	300	2,200		Fairbanks-Morse
Back Wash	183 B	2	Induction	200	2,200	48.9	Westinghouse
Fire & Senitary	183 B	2	Induction	20	440	25	A-C
Powerhouse	183 B	1	Induction	60	2,200	16	GE
High Tank	183 C	3	Induction	300	2,200	66.6	GE
Process Water and Back Wash	183 C	6	Induction	450	2,200	100	Westinghouse
Filtered Plant Supply	182 B	7	Induction	200	2,200	43.5	A-C
Condenser	182 B	1	Induction	400	2,200	97.3	Westinghouse
Export	182 B	3	Induction	1000	2,200	22.6	GE
River Water Pumps	181 B	8	Induction	600	2,200	143	Westinghouse
Export Pumps	181 B	2	Induction	450	2,200	106.8	Westinghouse
River Water Pumps	181 C	12	Induction	450	2,200	106.8	Westinghouse
River Water Pumps	181 C	2	Induction	900	2,200	107	Louis Allis

[redacted]

[redacted]

TABLE B

100 D-DR ELECTRICAL EQUIPMENT LIST

Motor Function	Location	Number	Type	Horse Power Rating	Voltage	Current	Manufacturer
Process Water Pumps	190 D	8	Synchronous (Squirrel Cage Start)	4500 (4820)	13,800	196	GE
Process Water Pumps	190 DR	8	Synchronous (Squirrel Cage Start)	4500 (4820)	13,800	196	GE
Process Water Pumps	183 D	6	Induction	700	2,300	161	GE
Backwash Pumps	183 D	3	Induction	200	2,300	48.9	Westinghouse
Powerhouse Pumps	183 D	1	Induction	60	2,300	16	GE
High Tank Pump	183 D	1	Induction	450	2,300	100	Fairbanks-Morse
Fire and Sanitary Water Pumps	183 D		Induction	20	440	25	AC
Filter Plant Supply Pumps	182 D	9	Induction	200	2,300	43.5	AC
Condenser Pump	182 D	1	Induction	400	2,300	97.3	Westinghouse
Export Pump	182 D	2	Induction	1000	2,300	226	GE
Export Pump	182 D	2	Induction	450	2,300	102	Westinghouse
Air Compressor	182 D	1	Induction	25	440	36	Westinghouse
River Water Pumps	181 D	14	Induction	900	2,300		Fairbanks-Morse
Emergency River Water Pump	181 D	1	Induction	450	2,300	100	Westinghouse

[redacted]

[redacted]

TABLE C

100 H ELECTRICAL EQUIPMENT LIST

Motor Function	Location	Number	Type	Horsepower Rating	Voltage	Current	Manufacturer
Process Water Pumps	190 H	8	Synchronous (Squirrel Cage Start)	4500 (4820)	13,800	196	GE
Process Water Pumps	183 H	1	Induction	700	2,300	153	GE
Process Water Pumps	183 H	5	Induction	700	2,300	153	Westinghouse
Fire and Sanitary Water Pumps	183 H	2	Induction	30	440	36	Fairbanks-Morse
Powerhouse Water Pumps	183 H	1	Induction	60	440	74.8	Westinghouse
Backwash Pumps	183 H	2	Induction	200	2,300	46.7	Westinghouse
High Tank Pump	183 H	1	Induction	300	2,300	64.6	Fairbanks-Morse
Filter Plant Supply Pump	182 H	2	Induction	200	2,300	145	Westinghouse
Export Pump	182 H	2	Induction	1000	2,300	212	Westinghouse
Condenser Water Pumps	182 H	4	Induction	400	2,300	87.3	Westinghouse
Air Compressor	182 H	1	Induction	25	440	36.5	Crocker-Wheeler
River Water Pumps	181 H	9	Induction	600	2,300	145	Westinghouse

[redacted]

[redacted]

TABLE D

100 F ELECTRICAL EQUIPMENT LIST

Motor Function	Location	Number	Type	Horsepower Rating	Voltage	Current	Manufacturer
Process Water Pumps	190 F	8	Synchronous (Squirrel Cage Start)	4500	13,800	196	GE
Process Water Pumps	183 F	6	Induction	700	2,300	161	GE
Powerhouse Pump	183 F	1	Induction	60	2,300	16	GE
Fire and Sanitary Water Pump	183 F	2	Induction	20	440	25	A-C
Backwash Pumps	183 F	2	Induction	200	2,300	48.9	Westinghouse
High Tank Pump	183 F	1	Induction	300	2,300	64.6	Fairbanks-Morse
Filter Plant Supply Pumps	182 F	7	Induction	200	2,300	43.5	A-C
Export Pumps	182 F	2	Induction	1000	2,300	226	GE
Condenser Water Pumps	182 F	1	Induction	400	2,300	91.3	Westinghouse
River Water Pumps	181 F	10	Induction	450	2,300	100	Westinghouse

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TABLE E

TRANSFORMER LOADING - BASED ON 1960 PEAK DEMANDS

AREA	TRANSFORMER NUMBER	TRANSFORMER LOAD COMPLEX MVA	TRANSFORMER LOAD POLAR MVA	TRANSFORMER RATING - MVA	PER UNIT LOADING
B-C	1	22.05 -j 8.69	23.7 ∠-21.5°	31.250	0.758
	2	24.49 -j 6.15	25.3 ∠-14.1°	31.250	0.810
	3	28.61 -j 5.16	29.1 ∠-10.2°	31.250	0.931
	Total	75.15 -j20.00	77.7 ∠-14.9°	93.750	0.329
KW	1	25.30 -j 13.3	28.6 ∠-27.8°	50.00	0.572
	2	25.20 -j 13.2	28.5 ∠-27.7°	50.00	0.570
	Total	50.50 -j 26.5	57.1 ∠-27.7°	100.00	0.571
KE	1	26.60 -j 13.7	29.9 ∠-27.4°	50.00	0.598
	2	26.50 -j 15.3	30.6 ∠-29.95°	50.00	0.612
	Total	53.00 -j 29.0	60.4 ∠-28.7°	100.00	0.604
D-DR	1	22.20 -j 00.00	22.2 ∠0	31.250	0.710
	2	23.80 -j 3.40	24.0 ∠-8.1°	31.250	0.768
	3	29.20 -j 9.20	30.6 ∠-17.55°	31.250	0.979
	Total	75.20 -j 12.60	76.1 ∠-9.54°	93.750	0.812

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TABLE E (CONT'D)

AREA	TRANSFORMER NUMBER	TRANSFORMER LOAD COMPLEX MVA	TRANSFORMER LOAD POLAR MVA	TRANSFORMER RATING - MVA	PER UNIT LOADING
H	1	19.86 -j 1.02	19.9 $\angle -2.94^\circ$	31.250	0.637
	2	18.53 -j 1.16	18.5 $\angle -3.59^\circ$	31.250	0.592
	Total	38.39 -j 2.18	38.4 $\angle -3.26^\circ$	62.500	0.614
F	1	17.82 -j 2.54	18.0 $\angle -8.1^\circ$	31.250	0.576
	2	19.14 -j 2.73	19.33 $\angle -8.1^\circ$	31.250	0.619
	Total	36.96 -j 5.26	37.4 $\angle -8.1^\circ$	62.500	0.598
251	1	5.81 -j 4.33	7.24 $\angle -36.7^\circ$		
	2	6.04 -j 4.33	7.40 $\angle -35.8^\circ$		
	Total	11.85 -j 8.66	14.71 $\angle -36.15^\circ$		

[redacted]

TABLE F

TRANSFORMER LOADING - BASED ON ROBBINS AND BLANCHETTE PROPOSED INCREASE

AREA	TRANSFORMER NUMBER	TRANSFORMER LOAD COMPLEX MVA	TRANSFORMER LOAD POLAR MVA	TRANSFORMER RATING MVA	PER UNIT LOADING
B-C	1	26.4 -j 4.7	26.8 /-10.1°	31.250	0.858
	2	29.4 -j 3.4	30.9 /-6.6°	31.250	0.989
	3	34.3 -j 2.8	34.3 /-4.7°	31.250	1.098
	Total	90.1 -j 10.9	90.8 /-6.9°	93.750	0.969
KW	1	36.8 -j 17.7	40.8 /-25.7°	50.00	0.816
	2	36.7 -j 17.5	40.7 /-25.5°	50.00	0.814
	Total	73.5 -j 35.2	81.5 /-25.6°	100.00	0.815
KE	1	39.2 -j 20.2	44.0 /-27.3°	50.00	0.880
	2	38.8 -j 22.5	44.9 /-30.1°	50.00	0.898
	Total	78.0 -j 42.7	88.9 /-28.7°	100.00	0.889
D-DR	1	26.7 -j 0	26.7 /0	31.250	0.854
	2	28.6 -j 4.4	28.9 /-8.75°	31.250	0.925
	3	35.1 -j 11.8	37 /-18.6°	31.250	1.184
	Total	90.4 -j 16.2	91.6 /-10.2°	93.750	0.977

[redacted]

TABLE F (CONT'D)

AREA	TRANSFORMER NUMBER	TRANSFORMER LOAD COMPLEX MVA	TRANSFORMER LOAD POLAR MVA	TRANSFORMER RATING MVA	PER UNIT LOADING
H	1	23.6 -j 1.21	23.6 $\angle -2.94^\circ$	31.250	0.755
	2	22.1 -j 1.38	22.1 $\angle -3.58^\circ$	31.250	0.707
	Total	45.7 -j 2.59	45.7 $\angle -3.25^\circ$	62.500	0.731
F	1	20.7 -j 3.84	21.1 $\angle -10.5^\circ$	31.250	0.675
	2	22.3 -j 4.11	22.7 $\angle -10.45^\circ$	31.250	0.726
	Total	43.0 -j 7.95	43.7 $\angle 10.5^\circ$	62.500	0.699
251	1	7.35 -j 5.3	9.05 $\angle -35.8^\circ$		
	2	7.65 -j 5.3	9.33 $\angle -34.7^\circ$		
	Total	15.0 -j 10.6	18.38 $\angle -35.3^\circ$		

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TABLE G

TRANSFORMER LOADING - BASED ON PREDICTED LOAD OF 415.6 -j 110.8

AREA	TRANSFORMER NUMBER	TRANSFORMER LOAD COMPLEX MVA	TRANSFORMER LOAD POLAR MVA	TRANSFORMER RATING MVA	PER UNIT LOADING
B-C	1	23.44 -j 7.16	24.5 /-17°	31.250	0.784
	2	26.08 -j 5.08	26.5 /-11.05°	31.250	0.848
	3	30.48 -j 4.26	30.7 /-8°	31.250	0.982
	Total	80.00 -j 16.5	81.6 /-11.18°	93.750	0.870
KW	1	36.22 -j 29.8	46.8 /-39.5°	50.00	0.936
	2	36.08 -j 29.6	46.7 /-39.3°	50.00	0.934
	Total	72.3 -j 59.4	93.6 /-39.4°	100.00	0.936
KE	1	36.29 -j 28.0	45.8 /-37.7°	50.00	0.916
	2	36.01 -j 31.4	47.8 /-41.1°	50.00	0.956
	Total	72.3 -j 59.4	93.6 /-39.4°	100.00	0.936
D-DR	1	24.43 + j 0	24.4 / 0	31.250	0.781
	2	26.16 + j 3.4	26.2 / 0.74°	31.250	0.838
	3	32.31 + j13.6	35.0 /22.9°	31.250	1.120
	Total	[illegible] + j17.0	[illegible]4.5 /11.61°	93.750	[illegible]

[redacted]

TABLE G (CONT'D)

AREA	TRANSFORMER NUMBER	TRANSFORMER LOAD COMPLEX MVA	TRANSFORMER LOAD POLAR MVA	TRANSFORMER RATING MVA	PER UNIT LOADING
H	1	19.65 +j 5.34	$20.3 \angle 15.2^\circ$	31.250	0.650
	2	18.35 +j 6.06	$19.6 \angle 18^\circ$	31.250	0.627
	Total	38.00 +j 11.4	$39.7 \angle 16.7^\circ$	62.500	0.635
F	1	17.83 +j 6.33	$18.9 \angle 19.55^\circ$	31.250	0.605
	2	19.17 +j 6.77	$20.3 \angle 19.45^\circ$	31.250	0.650
	Total	37.00 +j 13.1	$39.3 \angle 19.5^\circ$	62.500	0.629
251	1	7.35 -j 5.3	$9.06 \angle -35.8^\circ$		
	2	7.65 -j 5.3	$9.32 \angle -34.7^\circ$		
	Total	15.00 -j 10.6	$18.35 \angle -31.2^\circ$		

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TABLE H

230 KV TRANSMISSION LINE LOADINGS
PER UNIT OF CAPABILITY (1.4 MPH WIND)

CASE II	CAPABILITY MVA	#1 OUT	#2 OUT	#3 OUT	#1&2 OUT	#1&3 OUT	#2&3 OUT
Line #1	326.7	0.0	0.609	0.722	0.0	0.0	1.093
2	326.7	0.421	0.0	0.377	0.0	1.093	0.0
3	378.4	0.579	0.416	0.0	0.943	0.0	0.0
CASE III							
Line #1	326.7	0.0	0.730	0.878	0.0	0.0	1.313
2	326.7	0.493	0.0	0.441	0.0	1.313	0.0
3	378.4	0.714	0.505	0.0	1.134	0.0	0.0
CASE IV							
Line #1	326.7	0.0	0.799	0.960	0.0	0.0	1.445
2	326.7	0.539	0.0	0.483	0.0	1.445	0.0
3	378.4	0.760	0.554	0.0	1.247	0.0	0.0

[redacted]

TABLE I

230 KV TRANSMISSION LINE LOADINGS PER UNIT OF CAPABILITY (2.5 MPH WIND)

CASE II	CAPABILITY MVA	#1 OUT	#2 OUT	#3 OUT	#1&2 OUT	#1&3 OUT	#2&3 OUT
Line #1	371.5	0.0	0.535	0.679	0.0	0.0	0.961
2	371.5	0.370	0.0	0.332	0.0	0.961	0.0
3	450.0	0.487	0.350	0.0	0.793	0.0	0.0
CASE III							
Line #1	371.5	0.0	0.642	0.773	0.0	0.0	1.155
2	371.5	0.433	0.0	0.388	0.0	1.155	0.0
3	450.0	0.600	0.425	0.0	0.953	0.0	0.0
CASE IV							
Line #1	371.5	0.0	[illegible].703	0.844	0.0	0.0	1.271
2	371.5	0.474	[illegible]	0.425	0.0	1.271	0.0
3	450.0	0.656	[illegible].456	0.0	1.049	0.0	0.0

[redacted]

TABLE J

AREA	TEST NO.	BUS	TIME AFTER BPA SEPARATION (CYCLES)	ANGLE OUT OF △
D-DR	I	I	1	18.9°
			10	53.5°
			20	85.3°
			30	154.3°
D-DR	I	II	1	18.9°
			10	43.8°
			20	80.5°
			30	140.3°
D-DR	I	III	1	18.9°
			10	43.8°
			20	61.6°
			30	102.9°
D-DR	II	I	1	28.1°
			10	52.°
			20	90.°
			30	148.4°
D-DR	II	II	1	22.5°
			10	47.7°
			20	81.8°
			30	137.3°
D-DR	II	III	1	16.9°
			10	43.4°
			20	65.5°
			30	103.9°
D-DR	III	I	1	13.8°
			10	41.5°
			20	82.0°
			30	136.7°
D-DR	III	II	1	13.8°
			10	46.2°
			20	82.0°
			30	136.7°
D-DR	III	III	1	000.0°
			10	36.9°
			20	54.7°
			30	91.1°

END

DATE
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