ELECTRIC POWER SYSTEMS

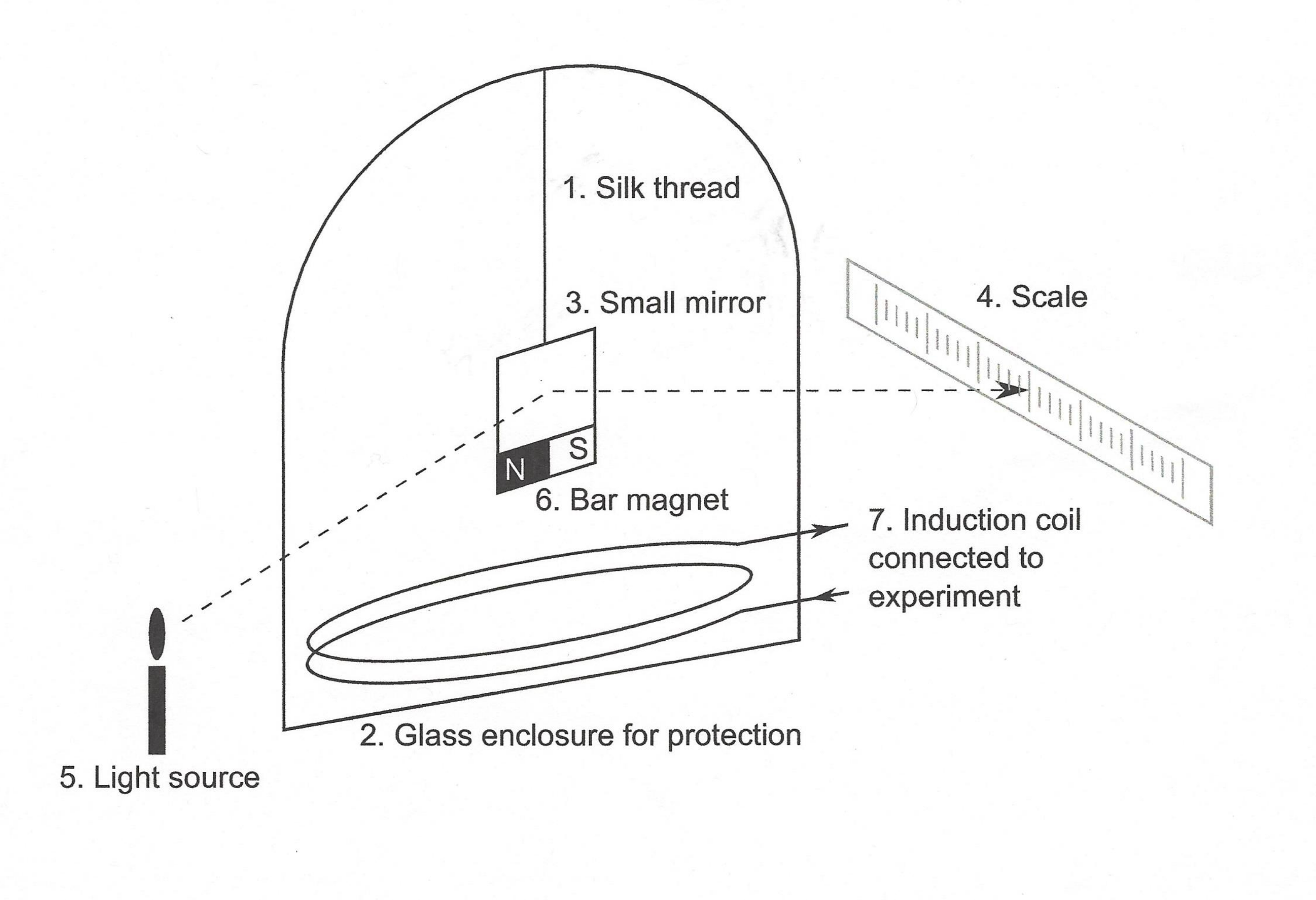
- A BRIEF HISTORY -
- ANCIENT AND MODERN.

PRINCIPAL ACTORS

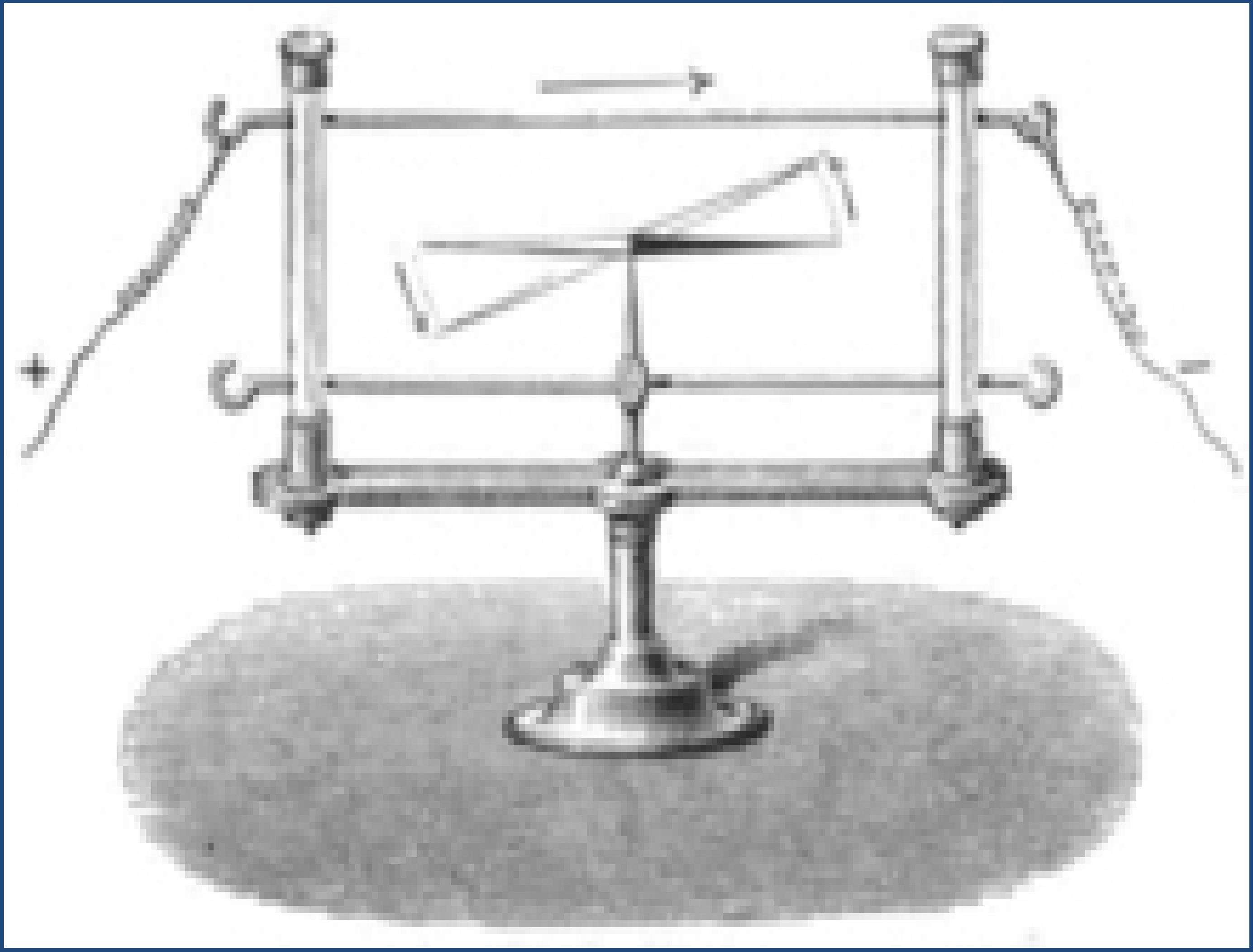
- FRANKLIN 1706 - 1790 (84)
- GALVANI 1739 - 1798 (59)
- VOLTA 1745 - 1827 (82)
- OERSTED 1777 – 1851 (80)
- FARADAY 1791 – 1867 (76)
- MAXWELL 1831 – 1879 (44)
- HEAVISIDE 1850 - 1925 (75)
- LODGE 1851 – 1940 (91)
- HERTZ 1857 – 1894 (37)
- WESTINGHOUSE 1846 – 1914 (68)
- EDISON 1847 – 1931 (84)
- TESLA 1856 - 1943 (87)
- AND MANY MORE.

WHERE IT ALL BEGAN
THE ORIGINAL VOLTAIC PILE. CIRC 1800.

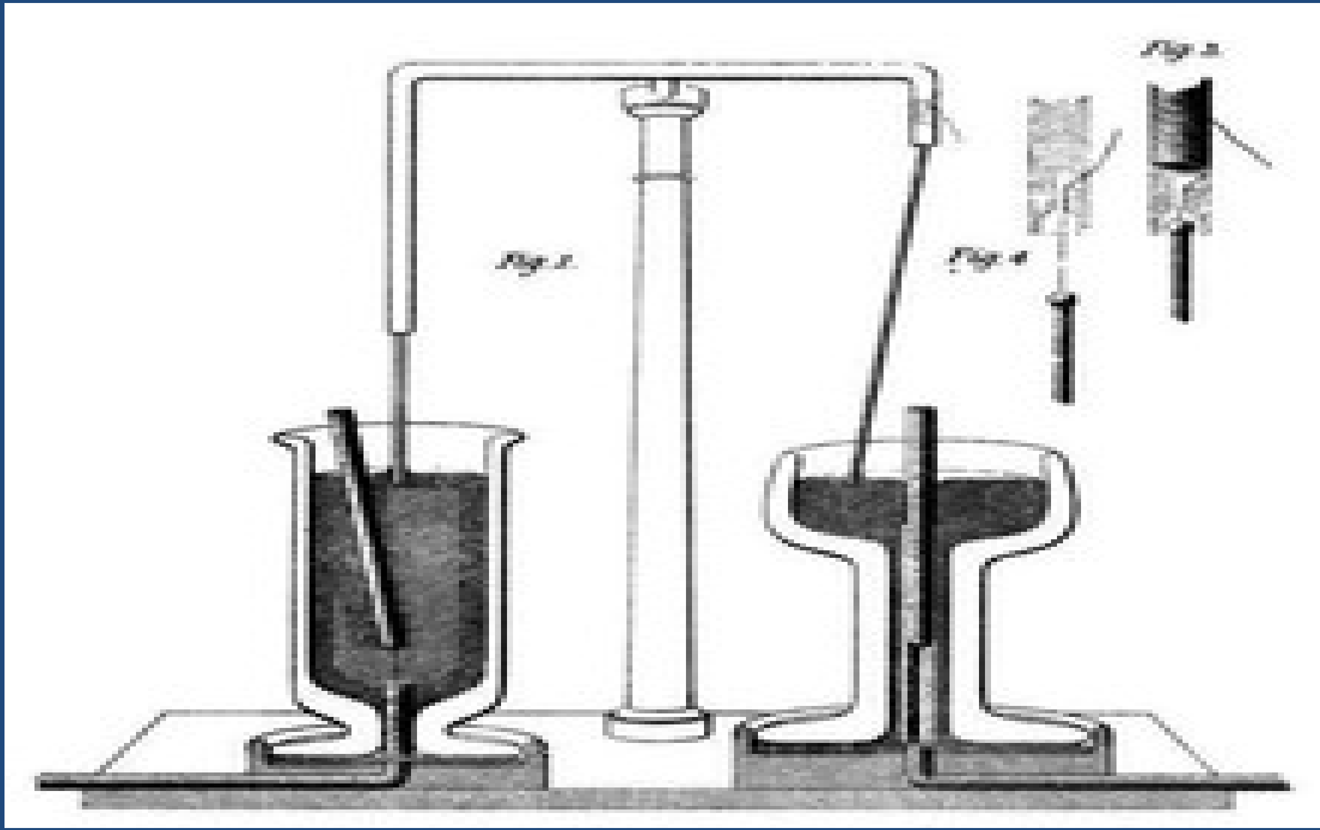
MIRROR GALVANOMETER
CIRC. 1795



OERSTED AND COMPASS DEFLECTION

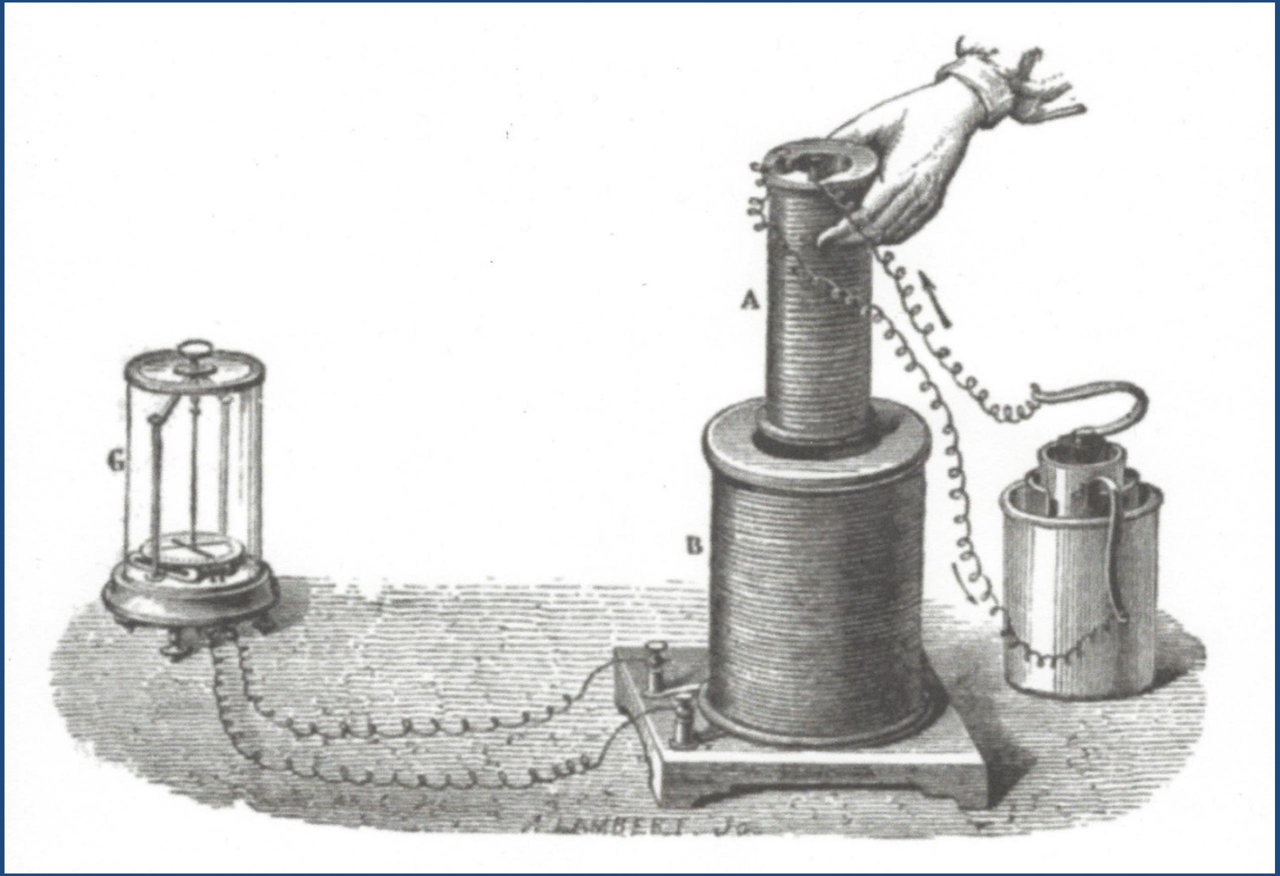


FARADAY AND ROTARY MOTION 1820



FARADAY & ELECTRIC INDUCTION, CIRC 1831

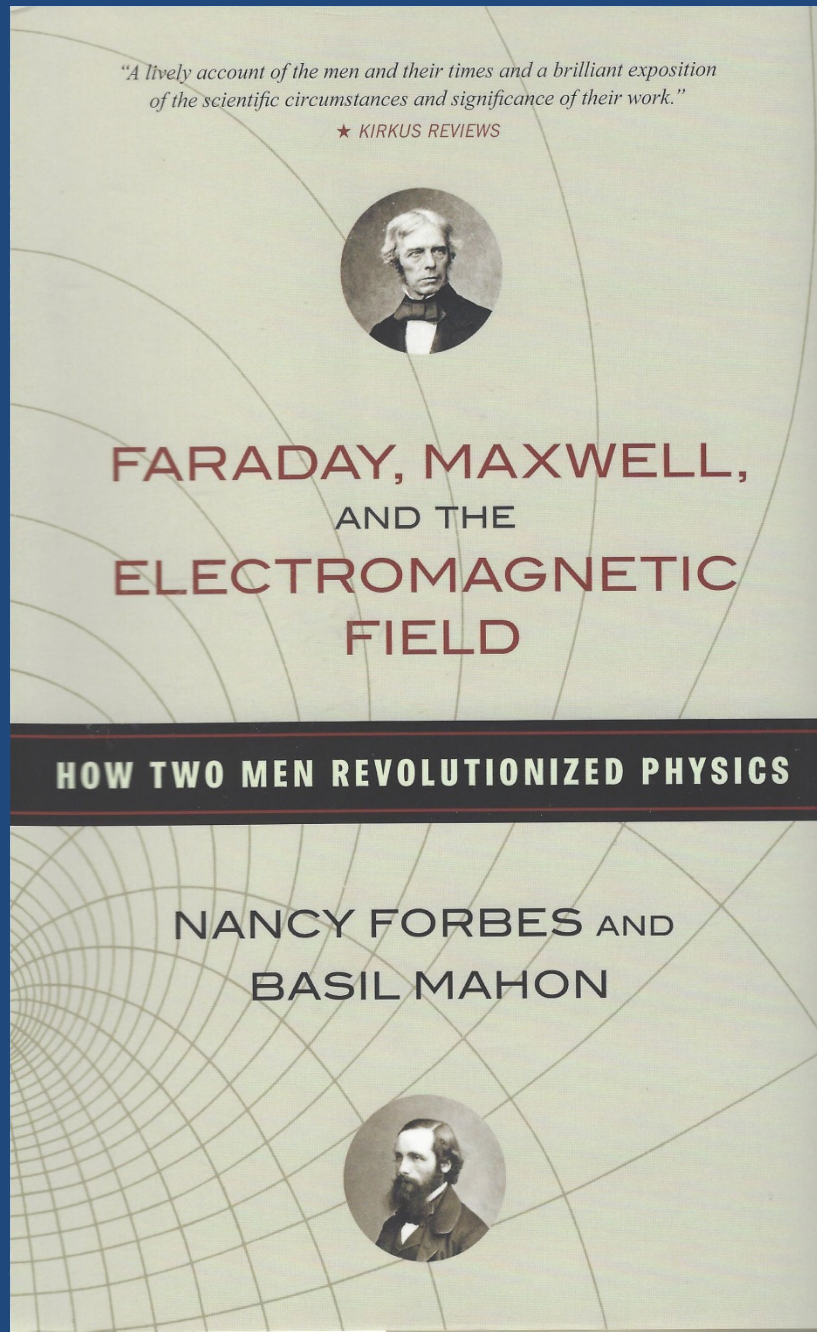
ALL YOU REALLY NEED TO KNOW ABOUT AC ELECTRICITY.
ANY CHANGE IN THE LINKAGE BETWEEN MAGNET FLUX AND A COIL OF WIRE WILL RESULT IN A VOLTAGE OF SOME SORT.



BUT FARADAY WAS PUZZLED.

- WHY COULD MAGNETISM PASS THRU A VACUUM, BUT ELECTRICITY COULD NOT. WHY DID MAGNETISM WORK AT A RIGHT ANGLE TO CURRENT FLOW? FARADAY WAS ALONE. ALL OTHERS VISUALIZED ELECTRICITY AS BEING LIKE A FLUID. THE DEBATE LASTED 20 YEARS.
- MEANWHILE OTHERS MEASURED THE SPEED OF LIGHT MECHANICALLY. 300,000 km/sec.
- 1865, MAXWELL SUCCEEDED IN PUTTING FARADAY'S FINDINGS ONTO A MATHEMATICAL BASIS. MORE IMPORTANTLY HE CALCULATED THAT THE SPEED OF ELECTRICITY WAS ASLO 300,000 km/sec. WAS THAT A COINCIDENCE? EVENTUALLY HE PROVED THAT LIGHT AND MAGNETISM WERE BOTH ELECTRIC EMISSIONS. THIS PROVED THAT FARADAY HAD BEEN RIGHT. BUT MAXWELL'S 20 EQUATIONS WERE AGONIZINGLY COMPLEX. (THREE VOLUMES OF TEXT).
- MAXWELL DID NO EXPERIMENTS. HIS WORK WAS ALL ANALYTICAL – BUT CONVINCING.
- 1884, HEAVISIDE "SIMPLIFIED" MAXWELLS' EQUATIONS. BUT STILL 4 EQUATIONS AND TWO VOLUMES OF TEXT.
- 1888, LODGE & HERTZ SHOWED ELECTRICITY COULD PASS THRU THE AIR UNSEEN AND BE RE-ESTABLISHED ON THE OTHER SIDE. IT COULD ALSO BE REFLECTED LIKE LIGHT. IN EFFECT THEY HAD DISCOVERED RADIO EMISSIONS.
- EVEN EINSTEIN READ UP ON MAXWELL.

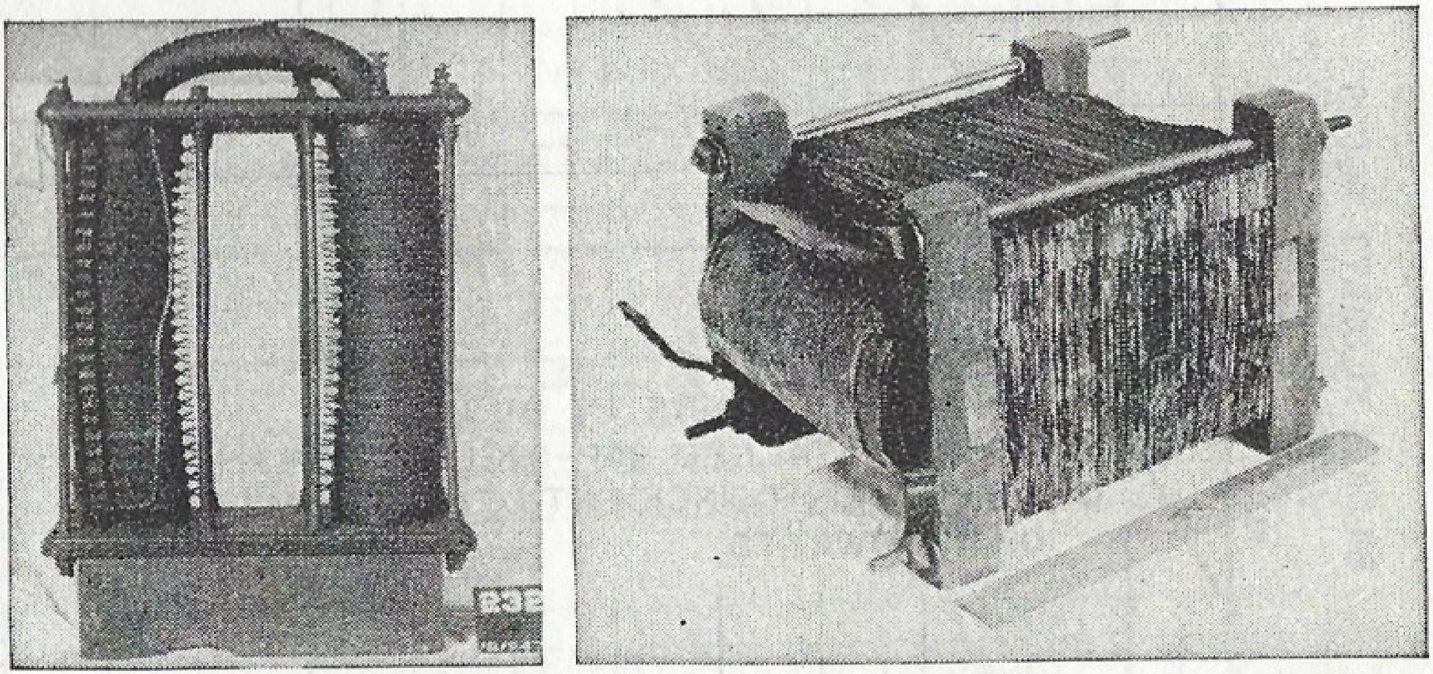
A MUST-READ. 2014 ISBN 978-1-61614-942-0



BUT SIMULTANEOUSLY, OTHERS WERE MAKING PRACTICAL PROGRESS.

- **ALTERNATING CURRENT BEGAN TO DEVELOP.**
- **1881, GAULARD (FRANCE) PATENTED A TRANSFORMER, SOLD THE PATENT TO GEORGE WESTINGHOUSE.**
- **1883-84, FERRANTI (UK) AND STANLEY (USA) BOTH DEVELOPED TRANSFORMERS.**
- **1885. GAULARD LOST HIS PATENT IN A LEGAL ACTION WITH FERRANTI AND STANLEY.**
- **RIGHT OR WRONG, IEEE RECOGNIZES STANLEY AS THE INVENTOR.**
- **EDISON, OF COURSE, RESISTED AC CURRENT RUTHLESSLY.**

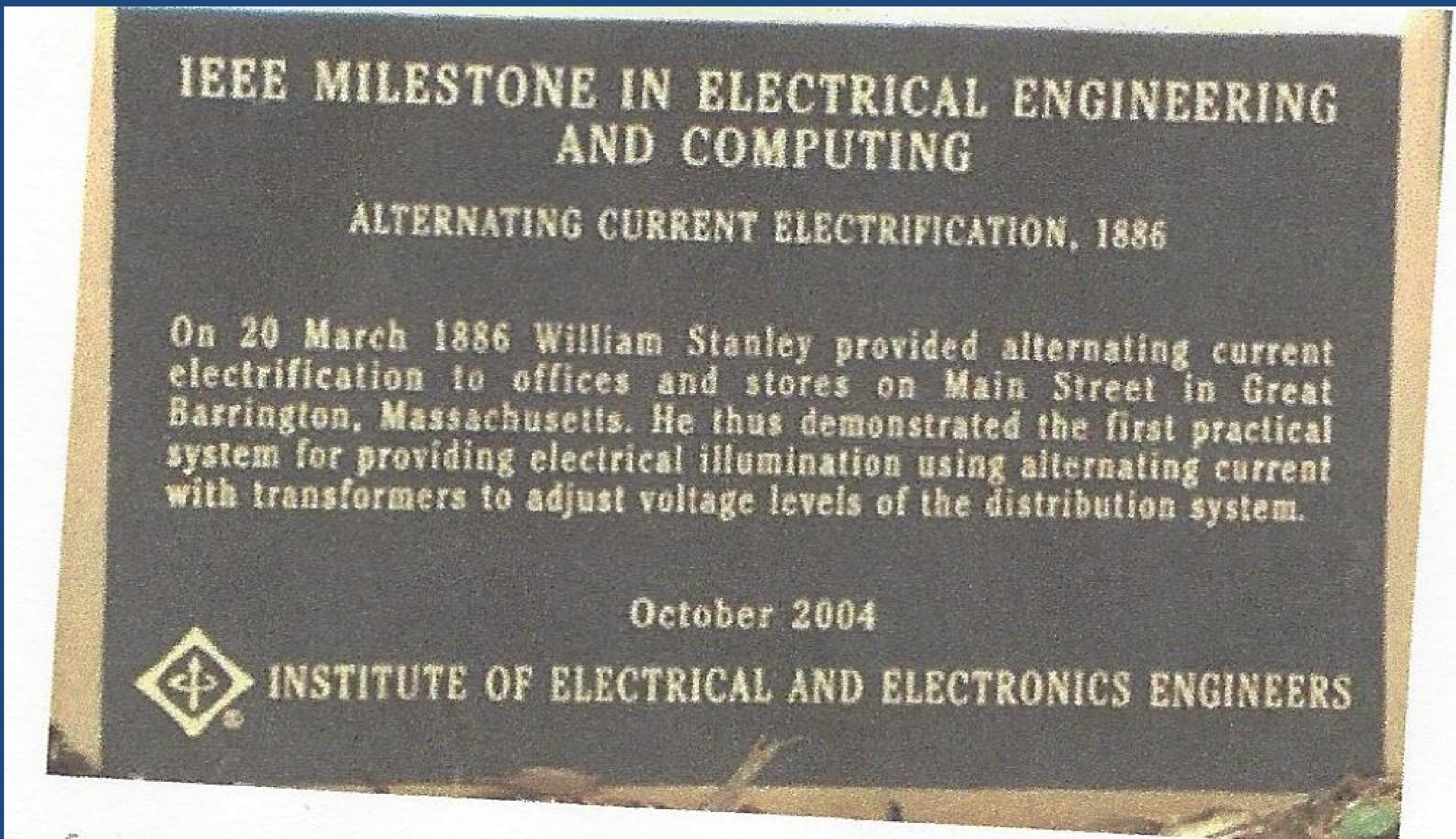
GAULARD 1881 & STANLEY 1885



(a) (b)

Fig. 1—(a) Gaulard and Gibbs transformer for which George Westinghouse had secured all rights in the United States. (b) First transformer designed by William Stanley. The prototype of all transformers since built, it definitely established the commercial feasibility of the alternating-current system, 1884–1886.

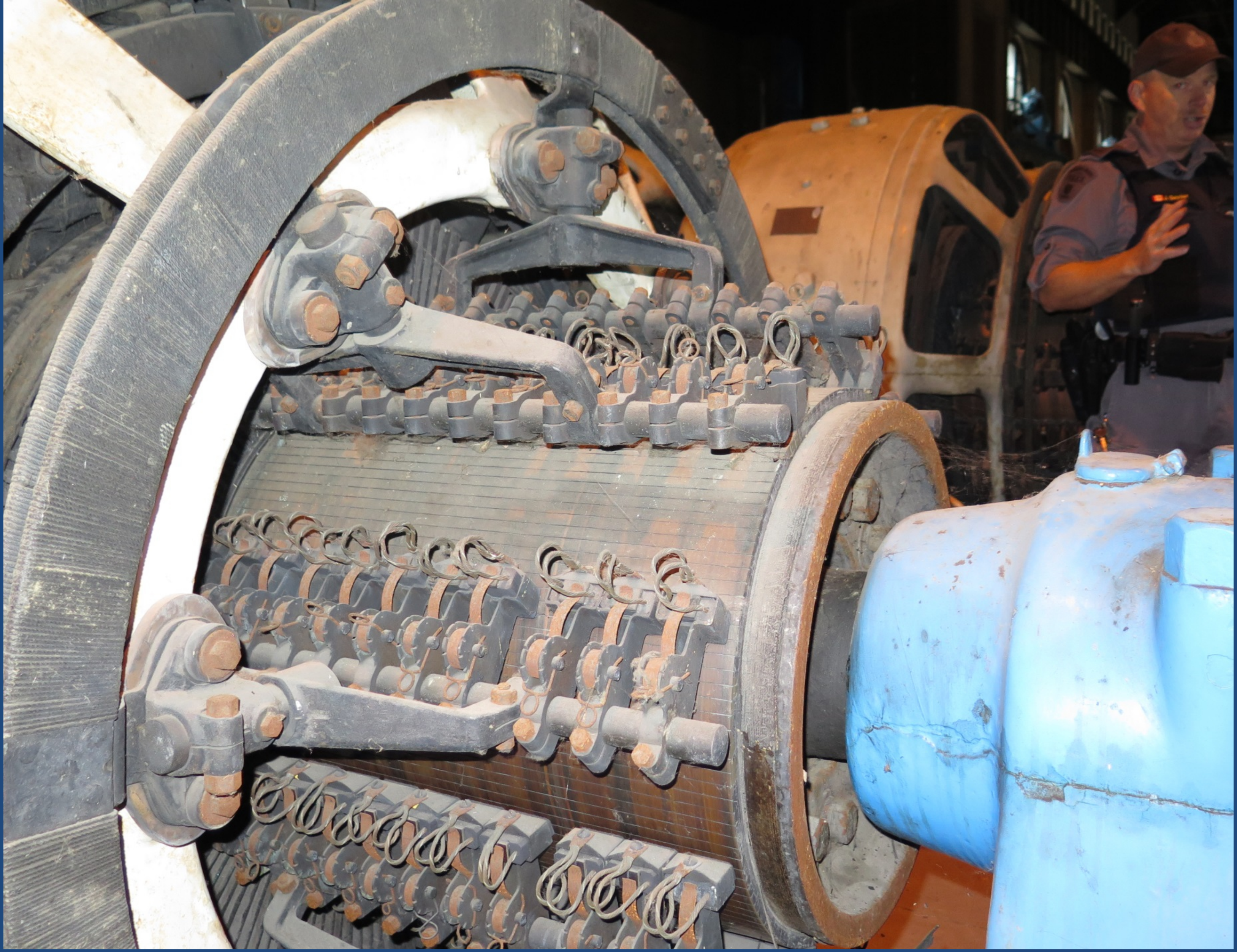
2004, STANLEY WON OUT



MEANWHILE:-

DC ELECTRIC MOTORS BECAME EXTREMELY LARGE (SEVERAL THOUSAND HP).

AND THE COMMUTATORS BECAME A MAJOR MAINTENANCE PROBLEM



THIS IS A COMMUTATOR AT THE RANKINE PLANT
1905 (Sorry about the dust)

FURTHERMORE:-

- **THE USE OF DIRECT CURRENT SEVERELY LIMITED THE LONG-DISTANCE TRANSMISSION OF POWER.**
- **EDISON DEVELOPED SEVERAL PLANS TO CONNECT TWO OR MORE LARGE, 2,000 VOLT, GENERATORS IN CASCADE AT ONE END, AND SIMILAR MOTORS AT THE OTHER.**
- **BUT THIS WAS OBVIOUSLY EXPENSIVE AND GAVE TROUBLE WITH INSULATION TO GROUND.**
- **EDISON WAS ALSO CURIOUSLY BLIND TO EDDY CURRENTS IN HIS EARLY MACHINES. MANY PARTS WERE NOT LAMINATED AND RAN QUITE HOT.**

MEANWHILE, IN SERBIA …..

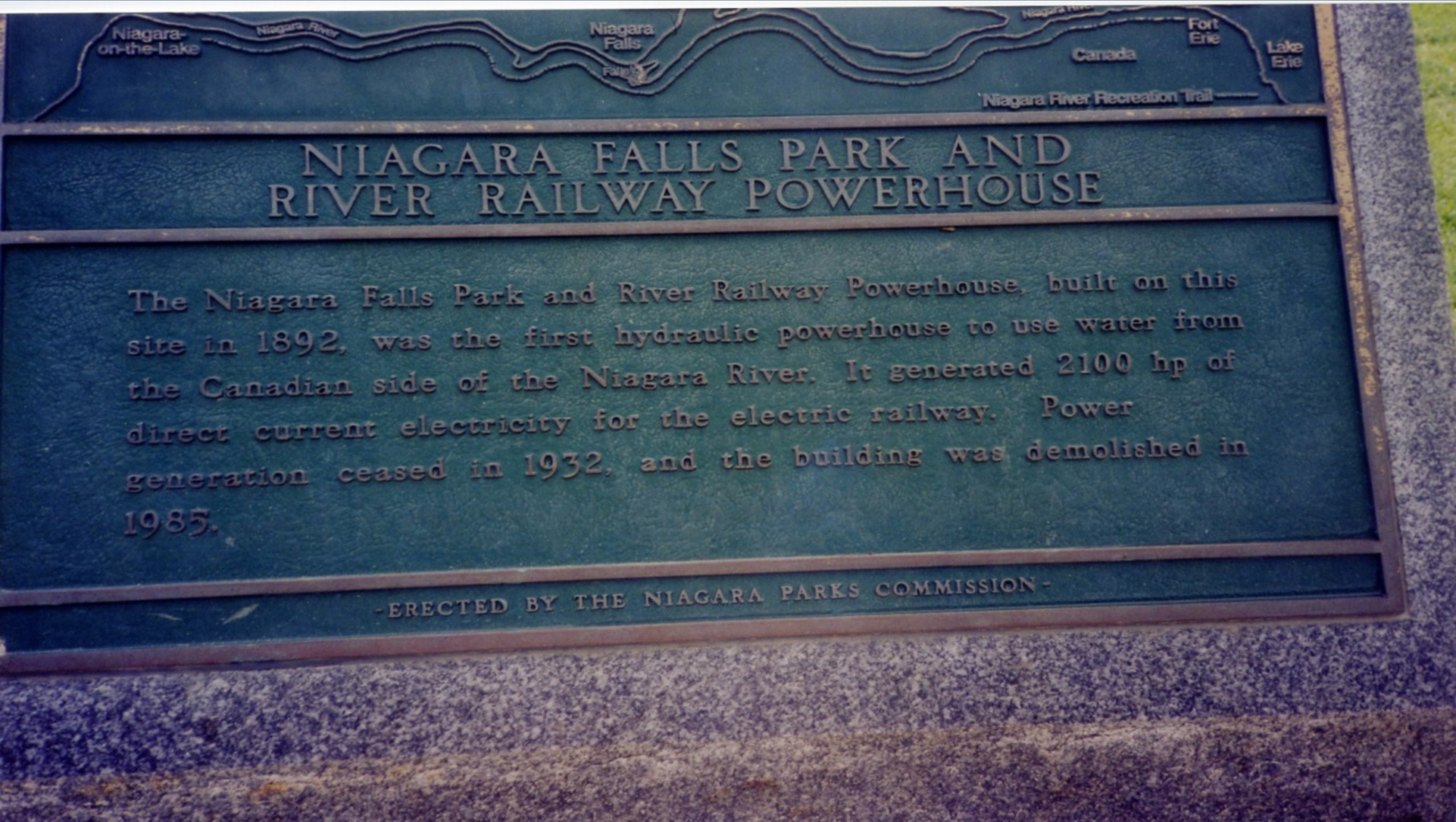
- **IN 1883 , IN SERBIA, TESLA BECAME DISENCHANTED WITH COMMUTATORS AND FOUND A WAY TO DISPENSE WITH THEM BY USING AN AC "INDUCTION" MOTOR. BUT STARTING IT WAS DIFFICULT.**
- **IN 1885 HE DEVELOPED HIS 2-PHASE SYSTEM. BOTH AS GENERATORS AND MOTORS. LOOK UP THE "TELLURIDE GOLD MINE SYSTEM". IT IS REALLY HILLAROIUS.**
-
- **IN 1887, TESLA SOLD HIS PATENT TO GEORGE WESTINGHOUSE FOR $150,000. A HUGE SUM THEN. BUT ALL WESTINGHOUSE GOT WAS THE PATENT. SEE SLIDE xxx. IT WAS THE WESTINGHOUSE ENGINEERS WHO STRUGGLED FOR SEVERAL YEARS TO DEVELOP A WORKABLE SYSTEM.**
- **FOR SOME YEARS BOTH GENERATORS AND MOTORS WERE ACTUALLY TWO SEPARATE SINGLE PHASE MACHINES BOLTED TOGETHER, WITH A 90 DEGREE ELECTRIC PHASE DISPOSITION BETWEEN THE TWO STATORS. (I PRESUME THE ROTOR POLES WERE COMMON TO BOTH. ANY COMMENTS?)**
- **AND THE OUTGOING LINES WERE TWO SEPARATE 2-WIRE SYSTEMS, 4 WIRES TOTAL.**
- **IT WAS ONLY ABOUT 1900, THAT THE ECONOMIES AND SMOOTH BALANCE OF A 3-PHASE, "Wye CONNECTED" SYSTEM. SEE BELOW.**

THE PACE PICKED UP……

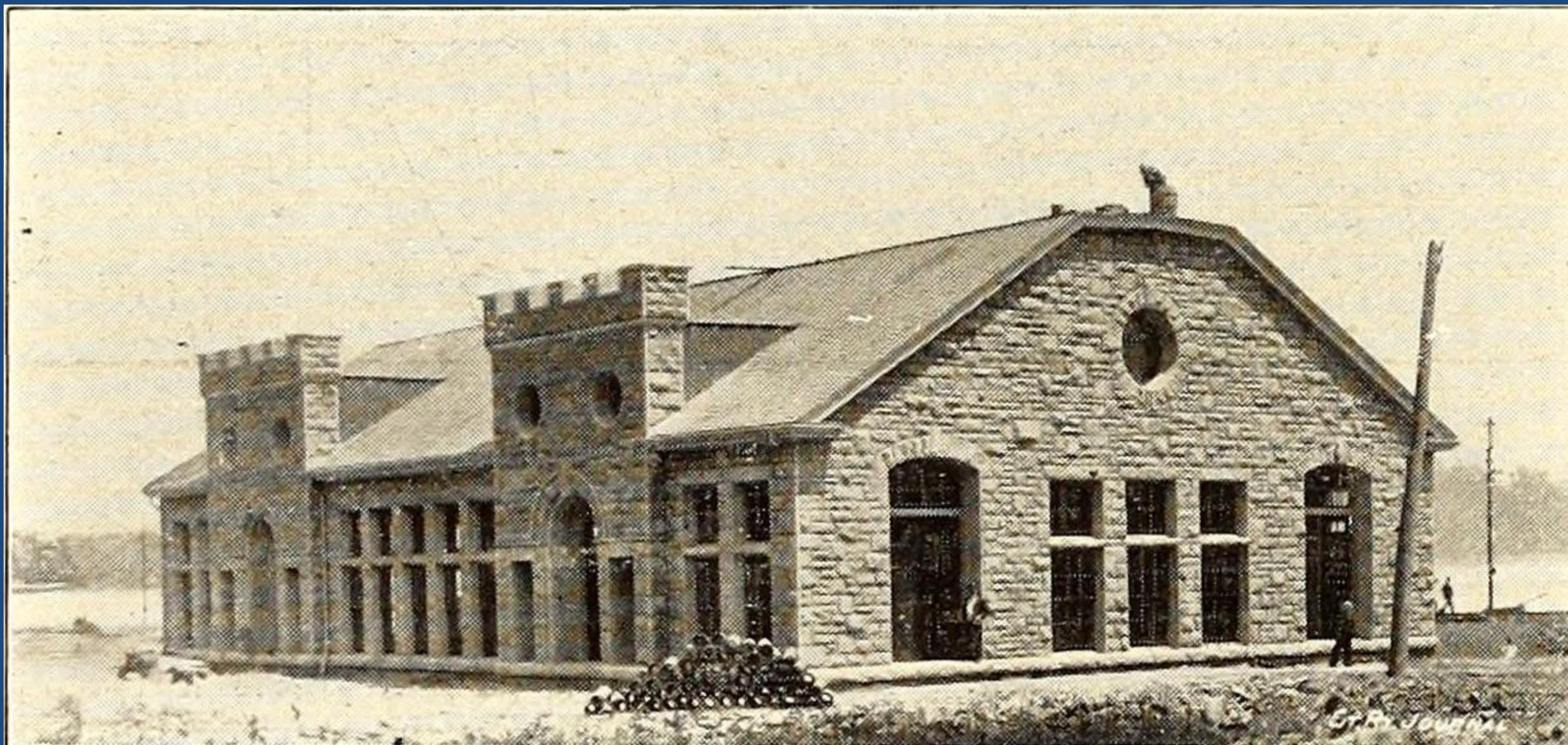
- 1892. IN NIAGARA FALLS, THE ELECTRIC STREET RAILROAD WAS BUILT. THIS WAS 2,100 HP, DC.
- VOLTAGE UNKNOWN BUT PROBABLY BETWEEN 400 & 800 VOLTS.

THE FIRST ELECTRICITY IN NIAGARA FALLS, CANADA, WAS IN 1892.

D C FOR THE ELECTRIC RAILWAY

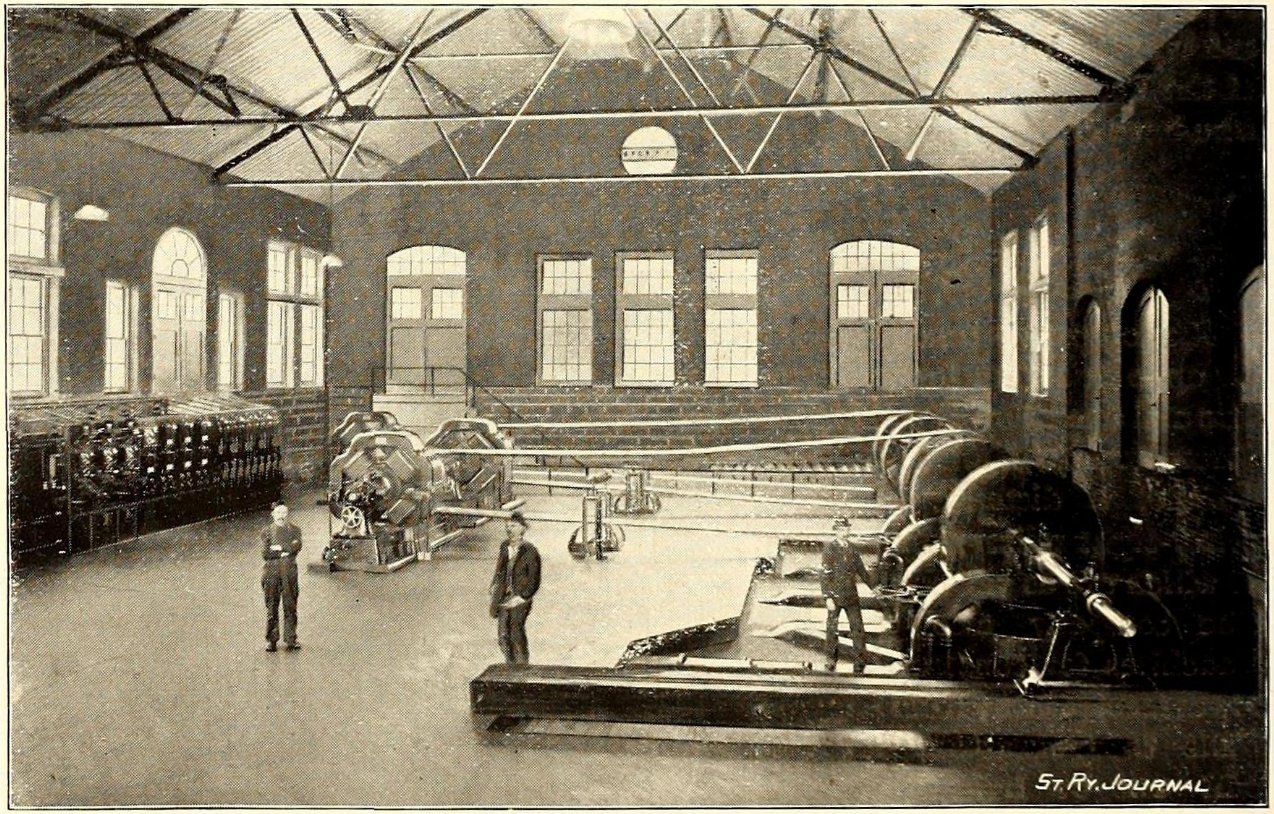


THE 1892 ELECTRIC TROLLY CAR.
POWER HOUSE WAS NEAR WHERE TABLE ROCK RESTAURANT IS NOW.



THE POWER STATION—N. F. P. & R. RAILWAY.

2,100 HP OR 1,575 Kw, DC.



INTERIOR OF POWER STATION.
NIAGARA FALLS PARK AND RIVER RAILWAY.

- 1893. WESTINGHOUSE & TESLA ELECTRIFIED THE CHICAGO EXHIBITION WITH A.C.. BUT MAINLY LIGHTING.

- ALTHOUGH THE POTENTIAL OF NIAGARA FALLS WAS KNOWN, NO ONE KNEW HOW TO DEVELOP IT. THE REASON FOR THE "PIT" WAS PARTLY BECAUSE ONE ALTERNATIVE MIGHT HAVE BEEN COMPRESSED AIR. THERE WAS EVEN A SCHEME FOR A PLANT DIRECTLY UNDER THE RIVER.

- THERE WERE 4 BASICALLY SIMILAR PLANTS – ADAMS # 1, 1896, ADAMS # 2, 1902, RANKINE, 1905, AND TORONTO POWER, 1906. AS FAR AS I KNOW, THERE ARE NO OTHER PLANTS BUILT ANYWHERE IN THE WORLD, WITH A "WHEEL PIT".

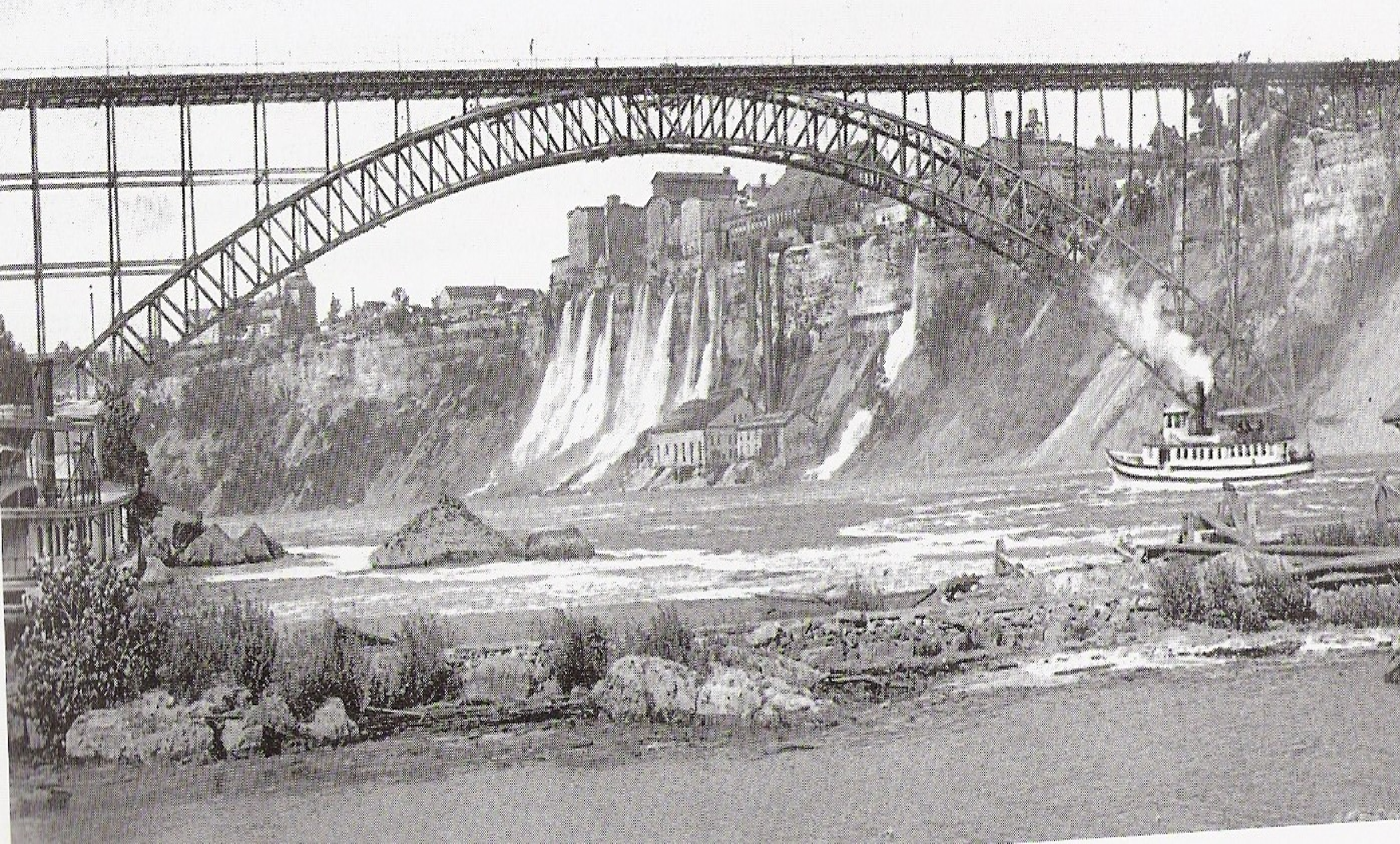
- ADAMS WAS THE FINANCIAL MAN BEHIND THE FIRST THREE SCHEMES. HE EVENTUALLY BUILT TWO PLANTS, ADAMS #1 AND ADAMS #2 IN THE U.S. AND THE 1905 RANKINE PLANT. (THE TORONTO POWER PLANT WAS SIMILAR, BUT FUNDED WITH CANADIAN MONEY.

- THE WESTINGHOUSE BID FOR 4,000 Kw, 2,000 V, AC MACHINES, 2-PHASE, 25 HZ WAS ACCEPTED. TRANSMISSION WAS ONLY 11 MILES TO NIAGARA FALLS, SO NO STEP-UP TRANSFORMERS REQUIRED.

- BY THAT TIME TESLA HAD LEFT WESTINGHOUSE, LEAVING WESTINGHOUSE STAFF TO FINALIZE THE DESIGN OF WORKABLE 2-PHASE MACHINES, (GENERATORS AND MOTORS).

-

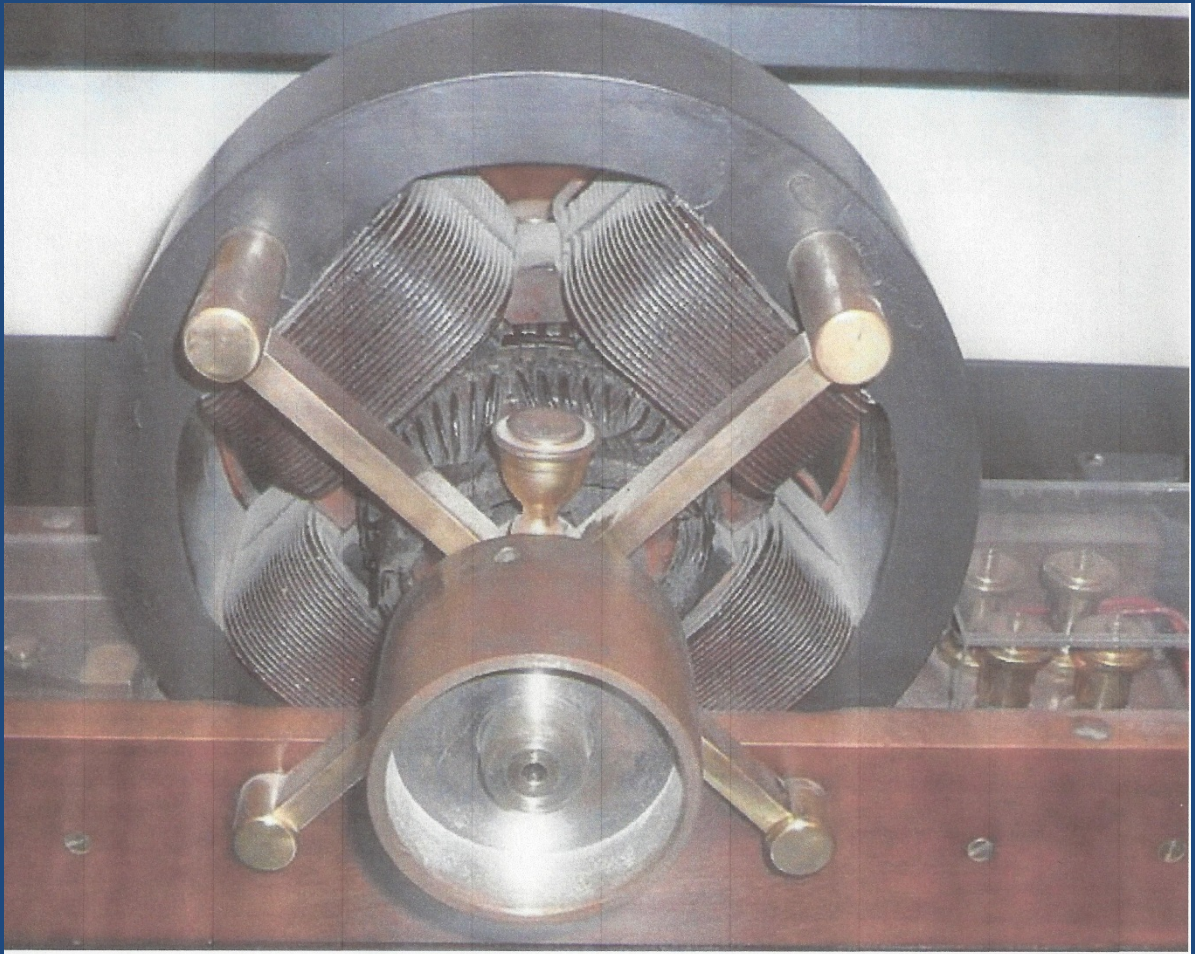
SUMMER CIRCA 1890
NOT PRETTY



REPLICA OF TESLA'S ORIGINAL 1885 INDUCTION MOTOR. USED FOR APPLICATION FOR U.S. PATENT 1887.

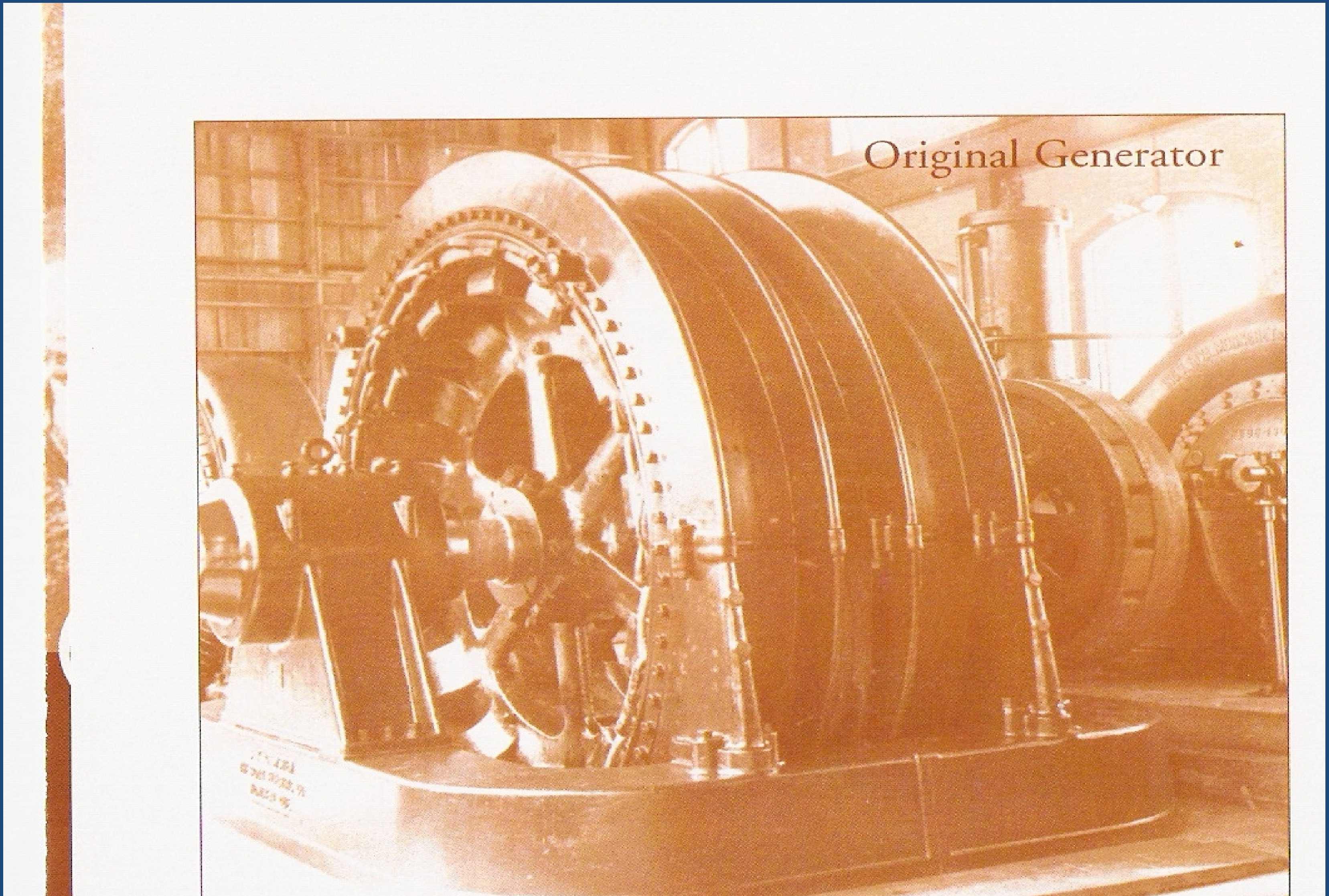
PATENT EXPIRED MAY 1905

MOTOR OR GENERATOR?



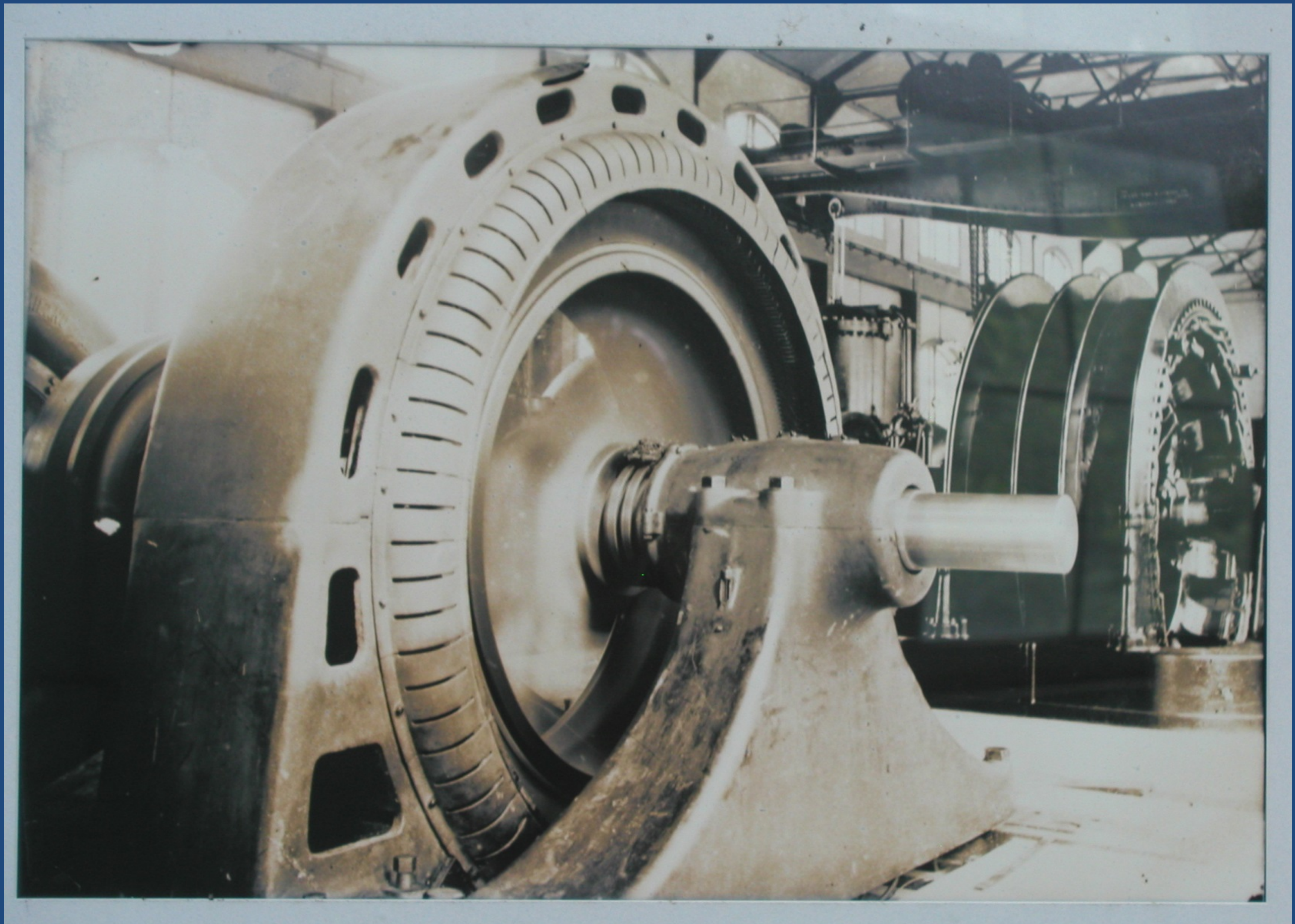
A TWO-PHASE GENERATOR, 1896 (DECEW).1,000 kW, 66-2/3 Hz, 2.2 Kv.
NOTE DOUBLE STATOR AND FLYWHEEL. WERE ROTOR POLES ALSO DUPLICATED??

TESLA ALSO DESIGNED A MACHINE WITH 3 SEPARATE PHASES AND 6 WIRES.

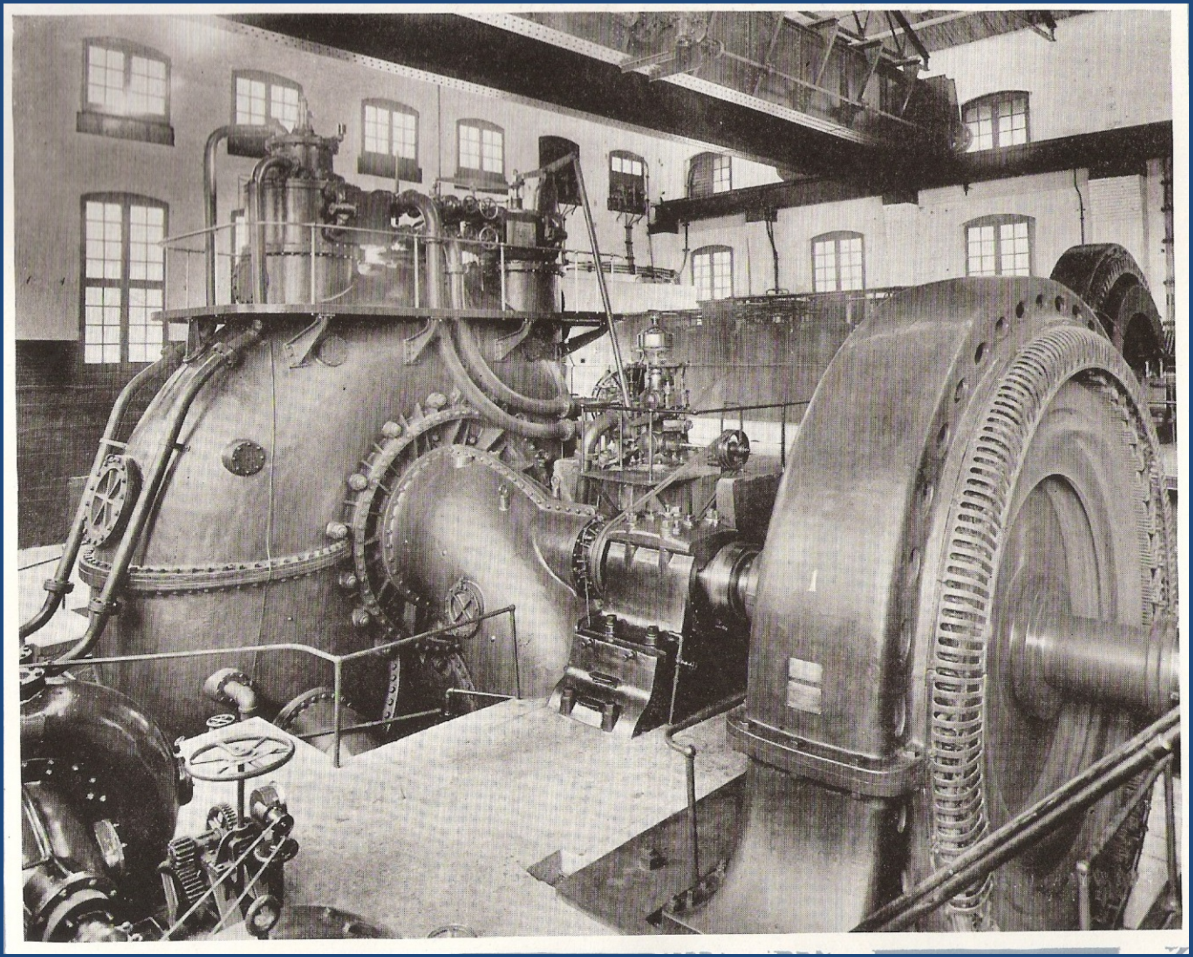


ANOTHER VIEW OF UNIT #2 AT DECEW.
NOTE ALSO UNIT #3 (1900). 2,000 kW. MUCH MORE MODERN,
BUT STILL HAS A FLYWHEEL.

Source - OPG



BY 1902, DESIGNS HAD BEGUN TO STABILIZE. THIS IS UNIT #1 AT SHAWINIGAN. 3,730 kW, 30 Hz, BUT STILL 2-PHASE. TRANSMISSION TO MONTREAL, 60 kV, 100 MILES. PROGRESS!



1900. STEAM TURBINE DRIVEN
6-POLE, 1,200 RPM, TWO PHASE.

Westinghouse

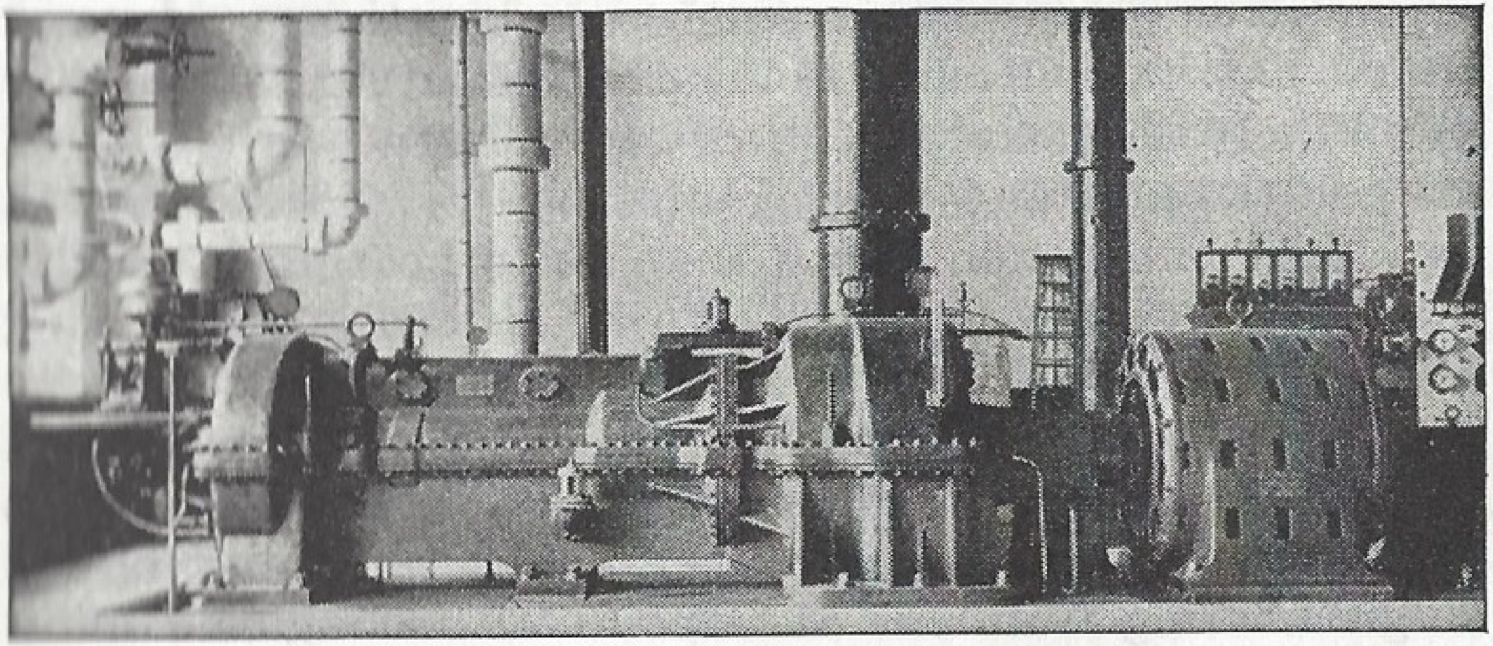


Fig. 3—The first central-station turbo-alternator installation in the United States—a 2000-kw turbine coupled to a 60-cycle generator, 2000 kw, 2400 volts, two-phase, 1200 rpm—at the Hartford Electric Light Company, Hartford, Connecticut, 1900. This turbine was about four times as large as any one built before that time and caused much comment the world over.

TESLA ALSO PATENTED A 3-PHASE SYSTEM USING SIX WIRES, BUT NEVER FOLLOWED UP ON IT. MAY NEVER HAVE REALIZED THE COST SAVING OF A COMMON NEUTRAL

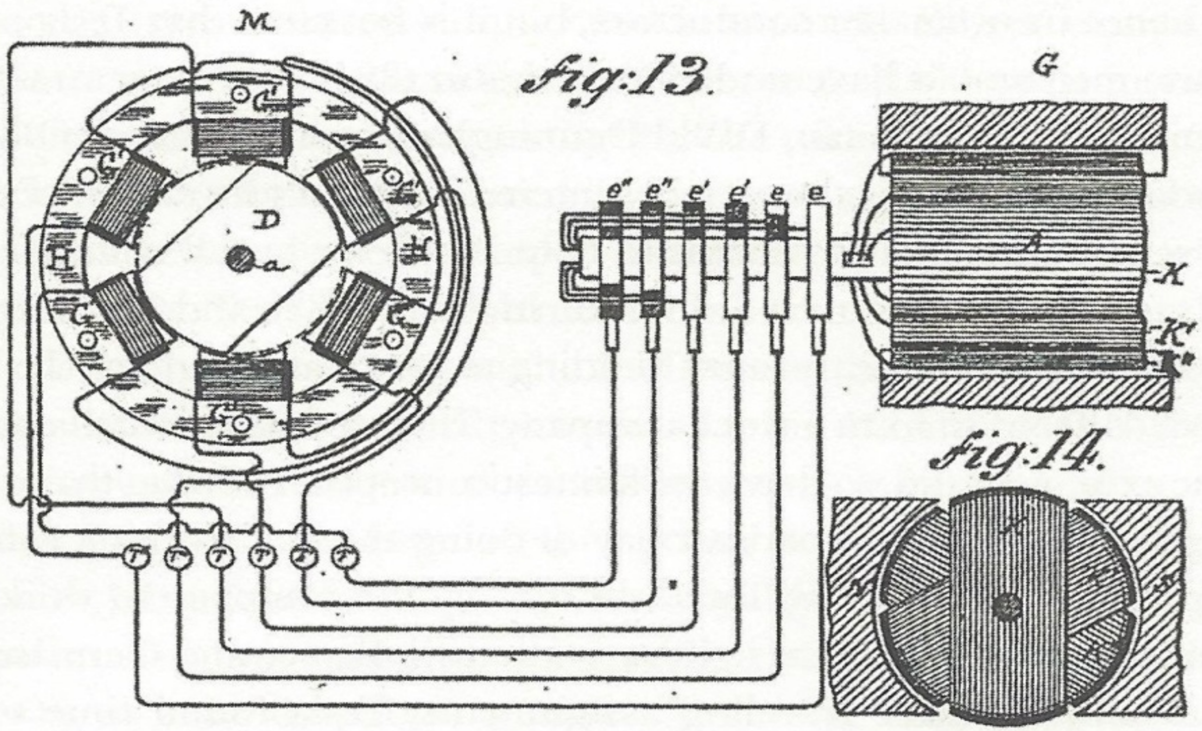
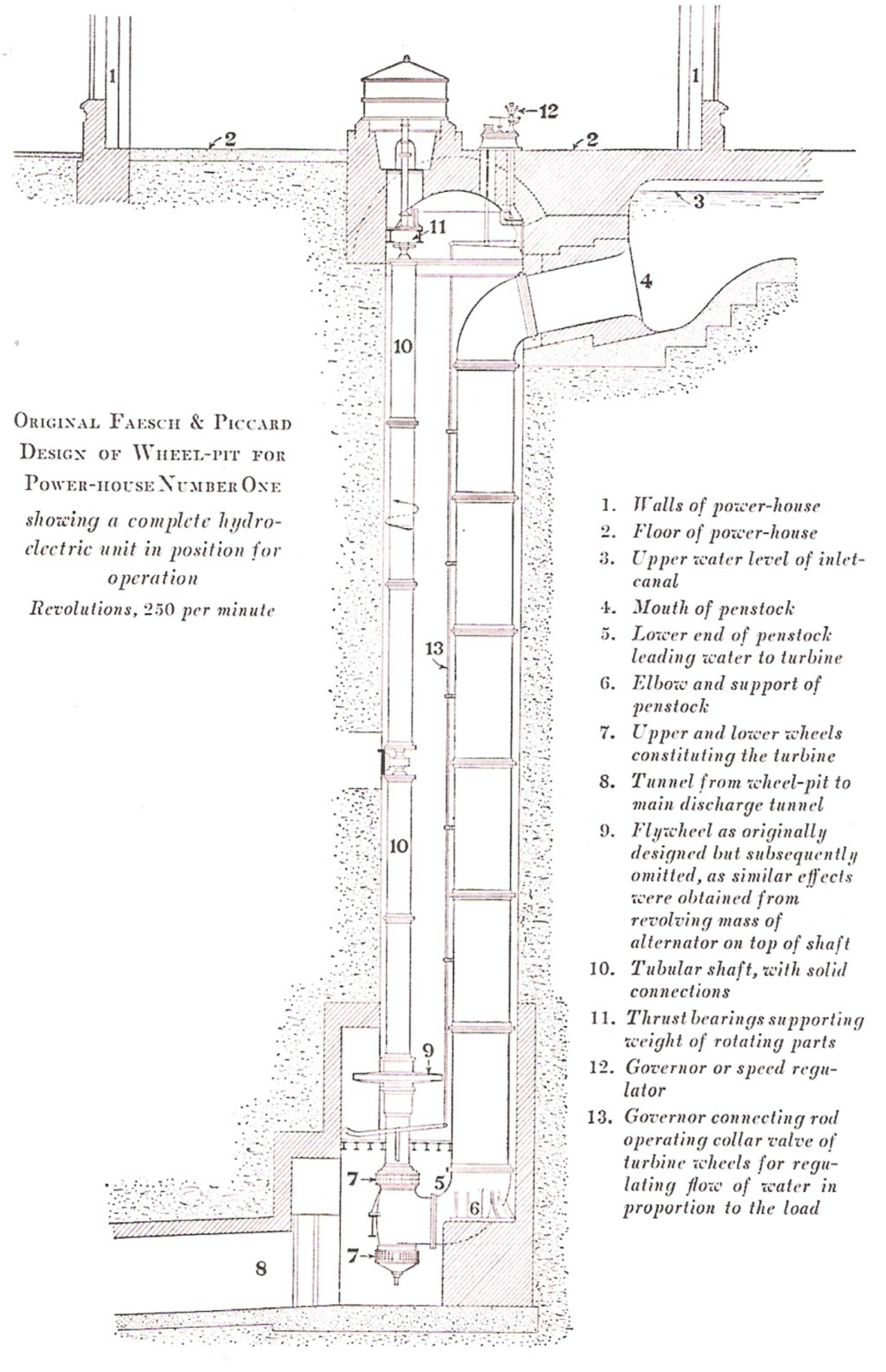


FIGURE 3.3. Diagram from later Tesla patent showing his system in which the generator produced three separate alternating currents that were delivered to the motor over six different wires.

Figure 13 in U.S. Patent 381,968, "Electric Magnetic Motor," (granted 1 May 1888).

A LITTLE MORE HISTORY

EARLY CONCEPTUAL DESIGN FOR ADAMS #1
NOTE THE FLYWHEEL AT BOTTOM
AND THRUST BEARING AT TOP



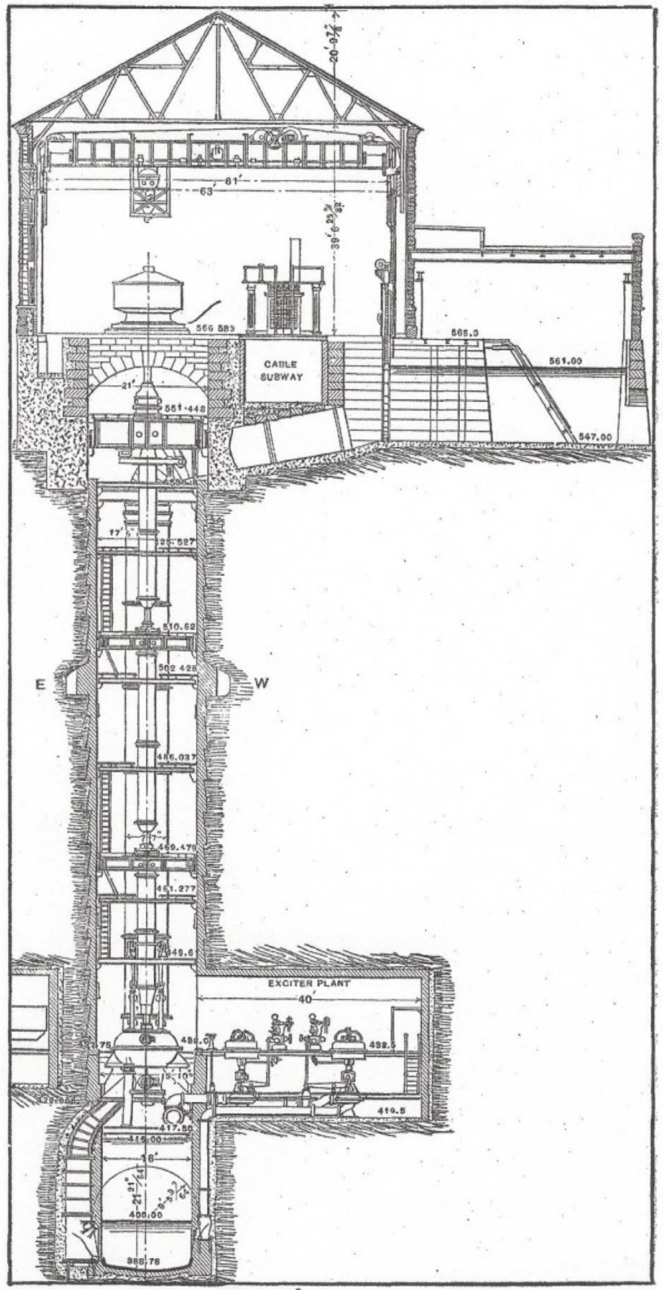
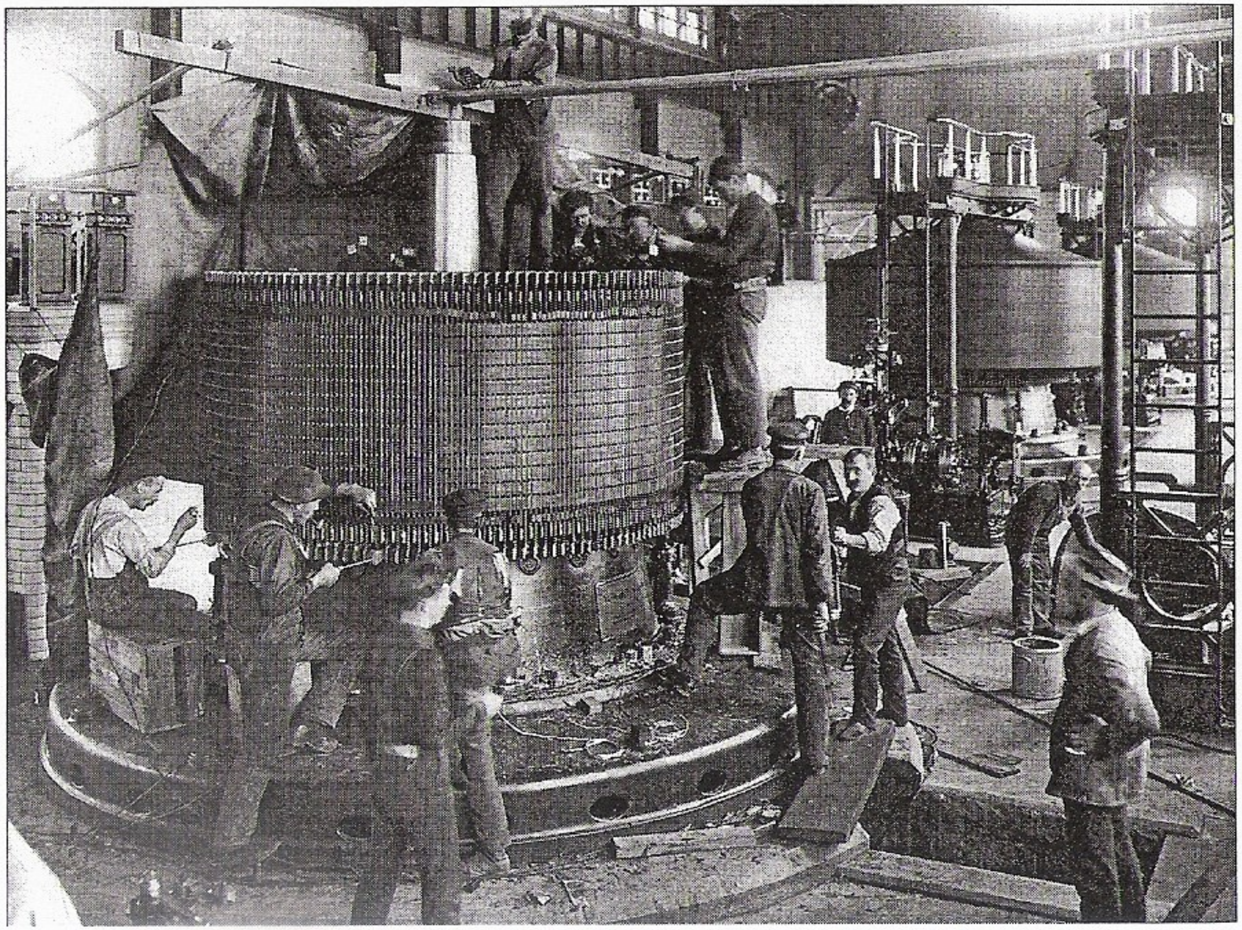


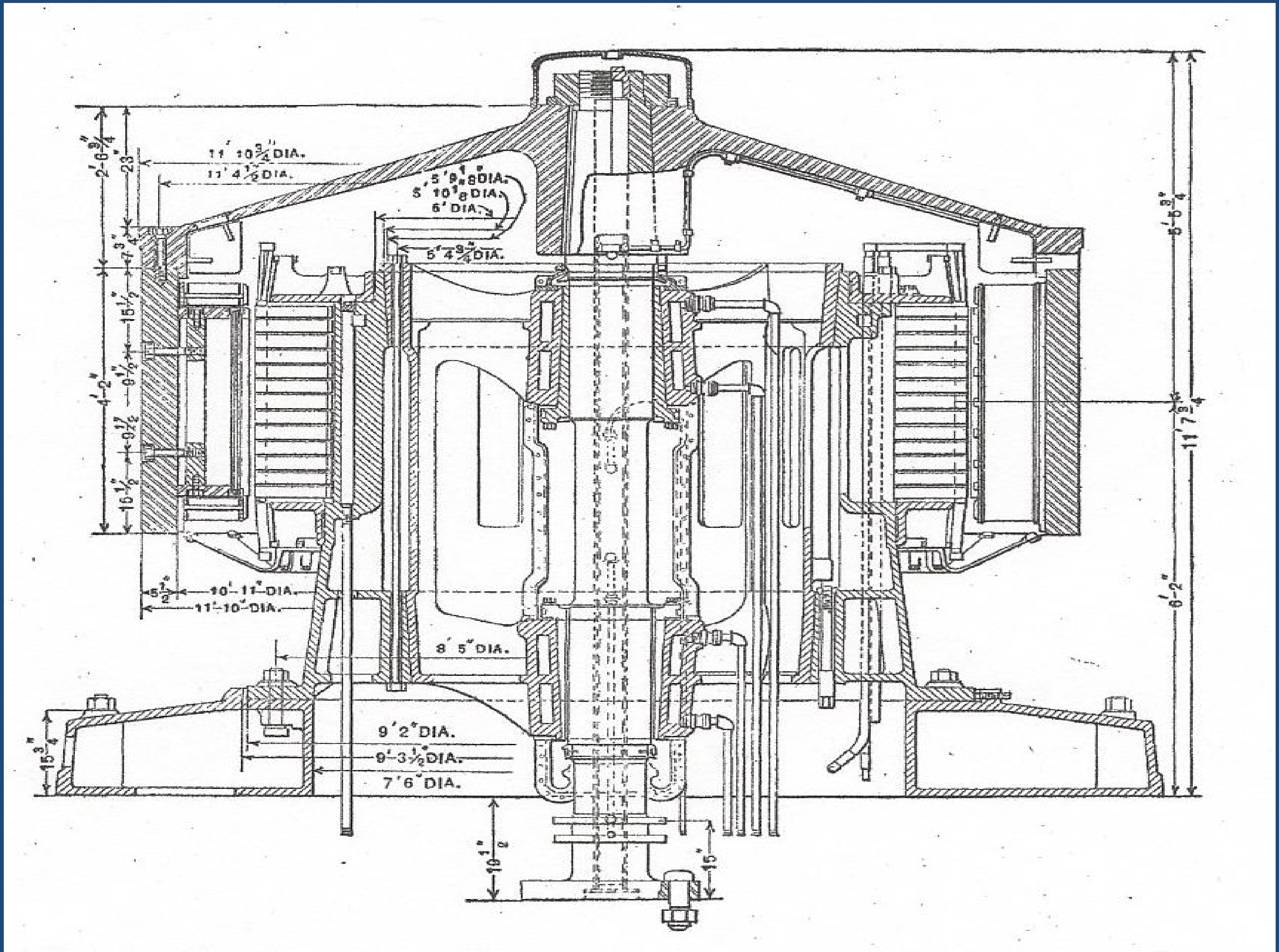
Fig. 1.—Section of Power-House No. 2.

ADAMS #1, 1896. 4,000 kW, 25 HZ. 2 PHASE. STRANGE DESIGN, WITH ROTOR OUTSIDE STATOR.



COURTESY OF NIAGARA MOHAWK, NATIONAL GRID USA SERVICE COMPANY, INC.

OLD STYLE. OUTSIDE ROTOR



"NEW" STYLE. ROTOR INSIDE

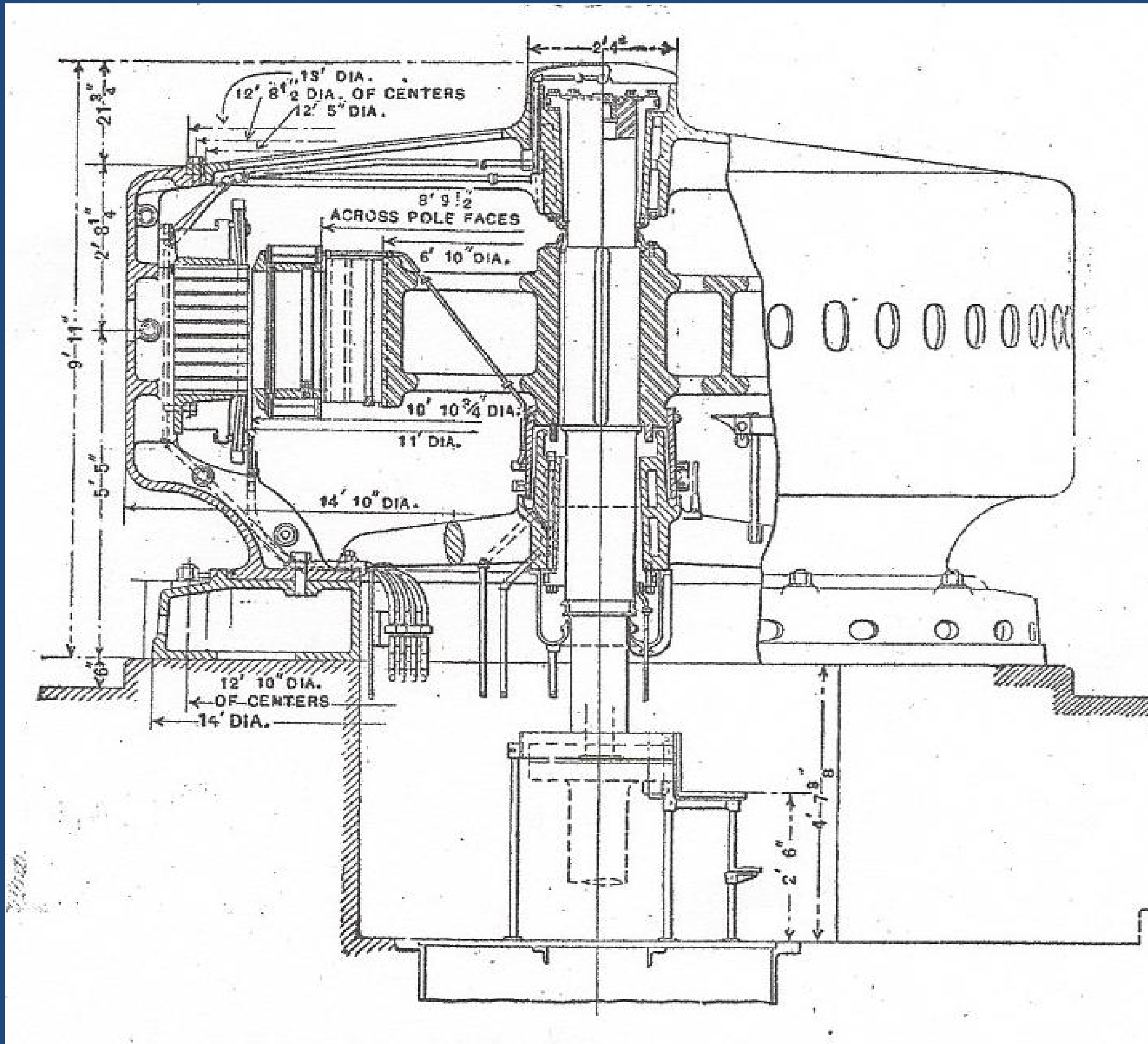
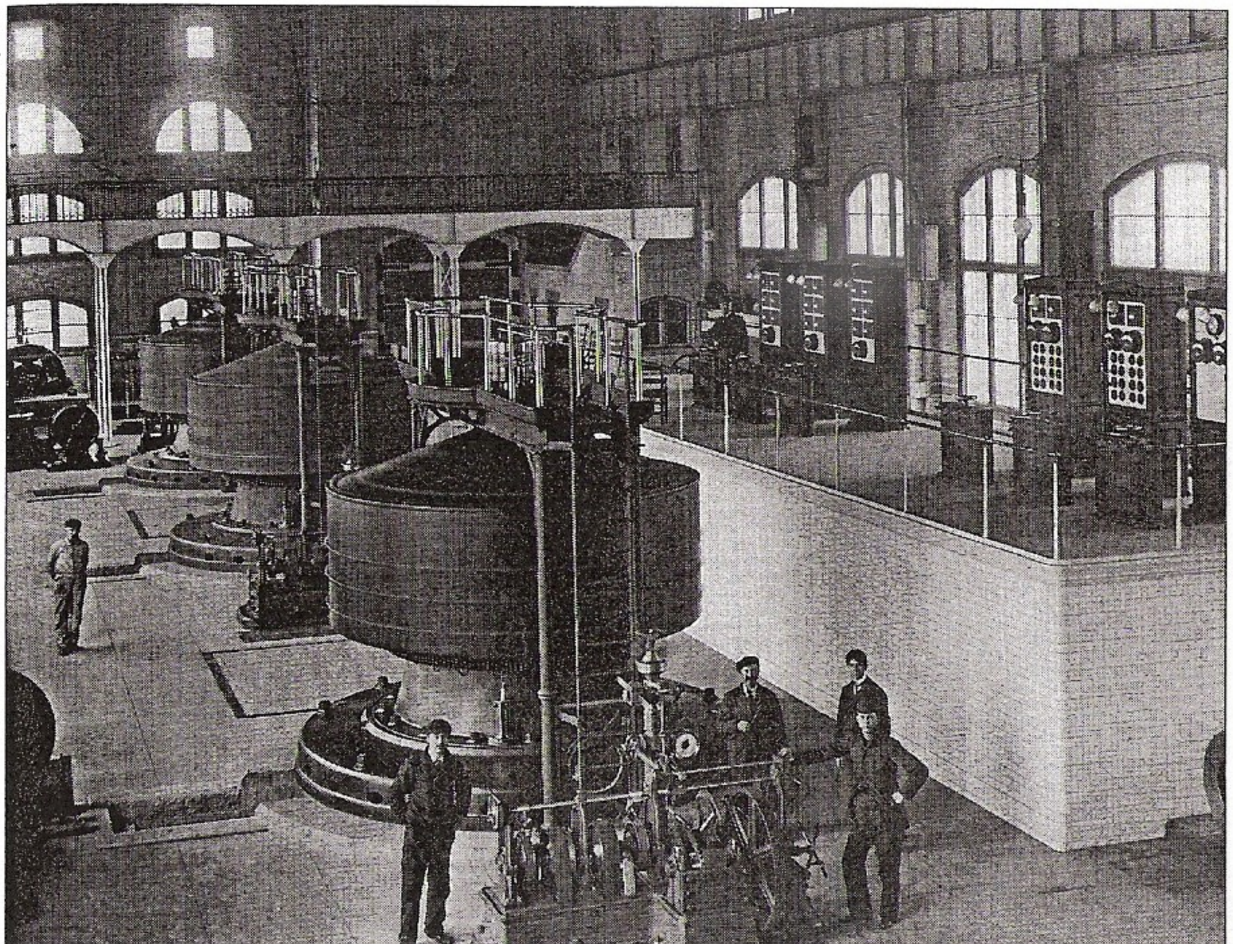


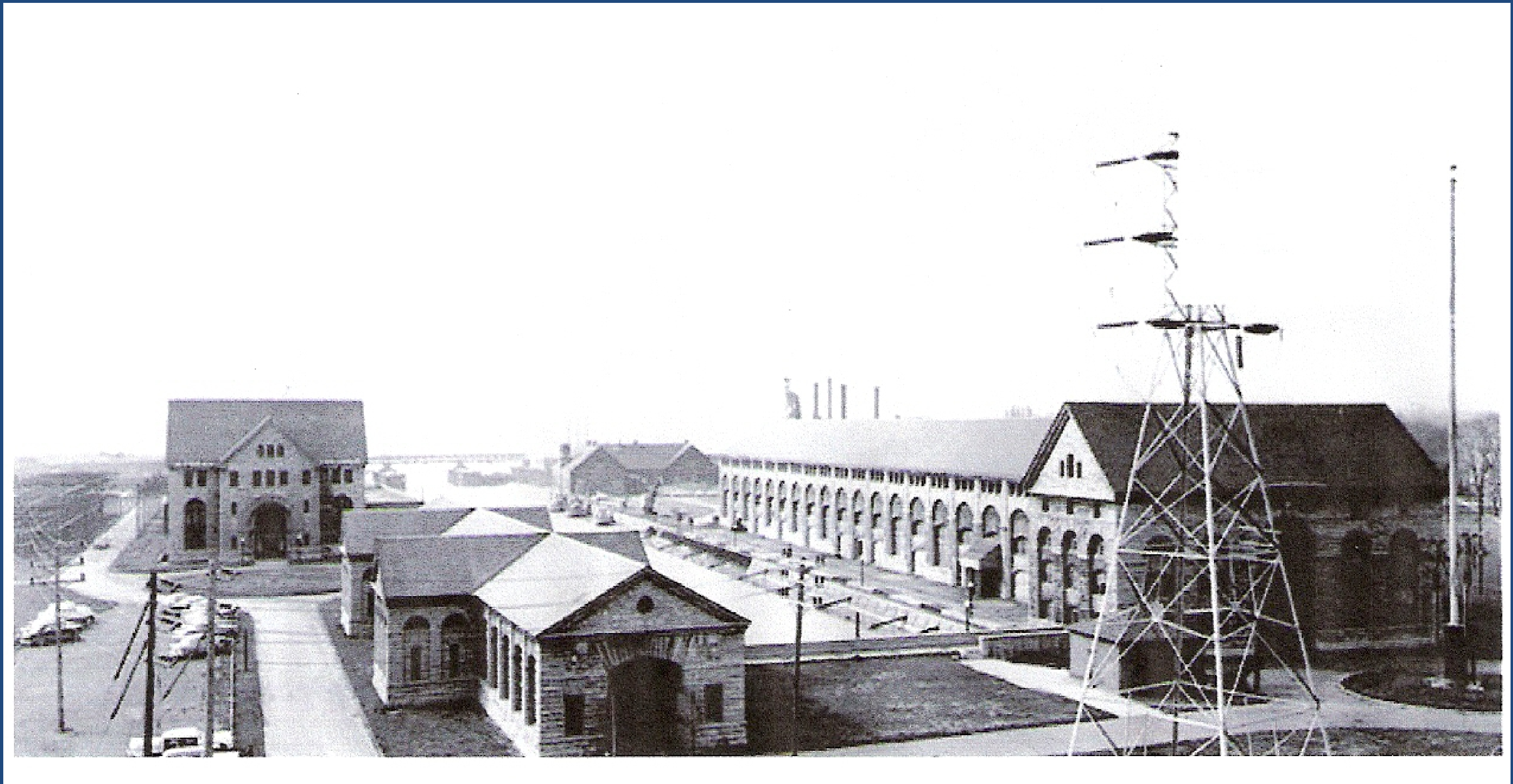
Fig. 3—Internal Field 5000 H. P. Generator, Power-House No.

ADAMS #1, 1896
FIRST 3 UNITS COMPLETED

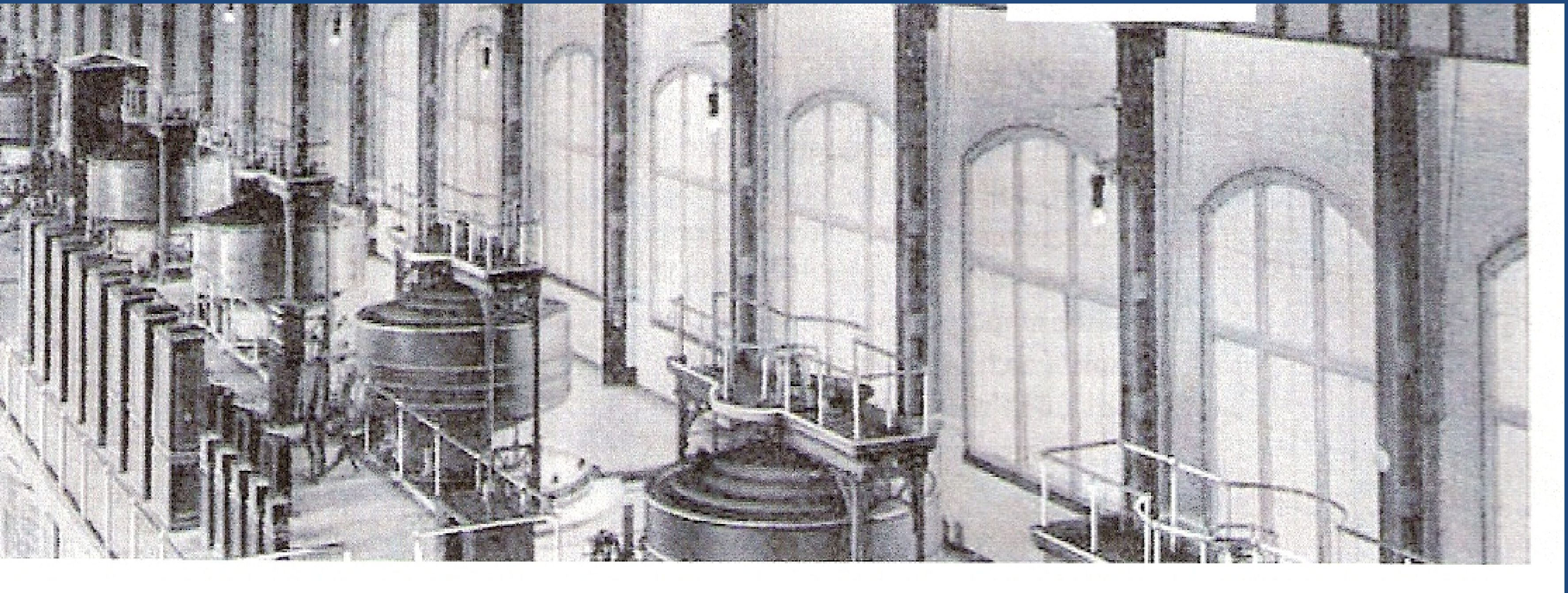


The first three Westinghouse dynamos in Stanford White's "Cathedral of Power" at Niagara Falls in a photo taken April 6, 1896.

EXTERIOR OF ADAMS #1 1896



INSIDE ADAMS #1. CIRCA 1898



SOME MORE NOTES

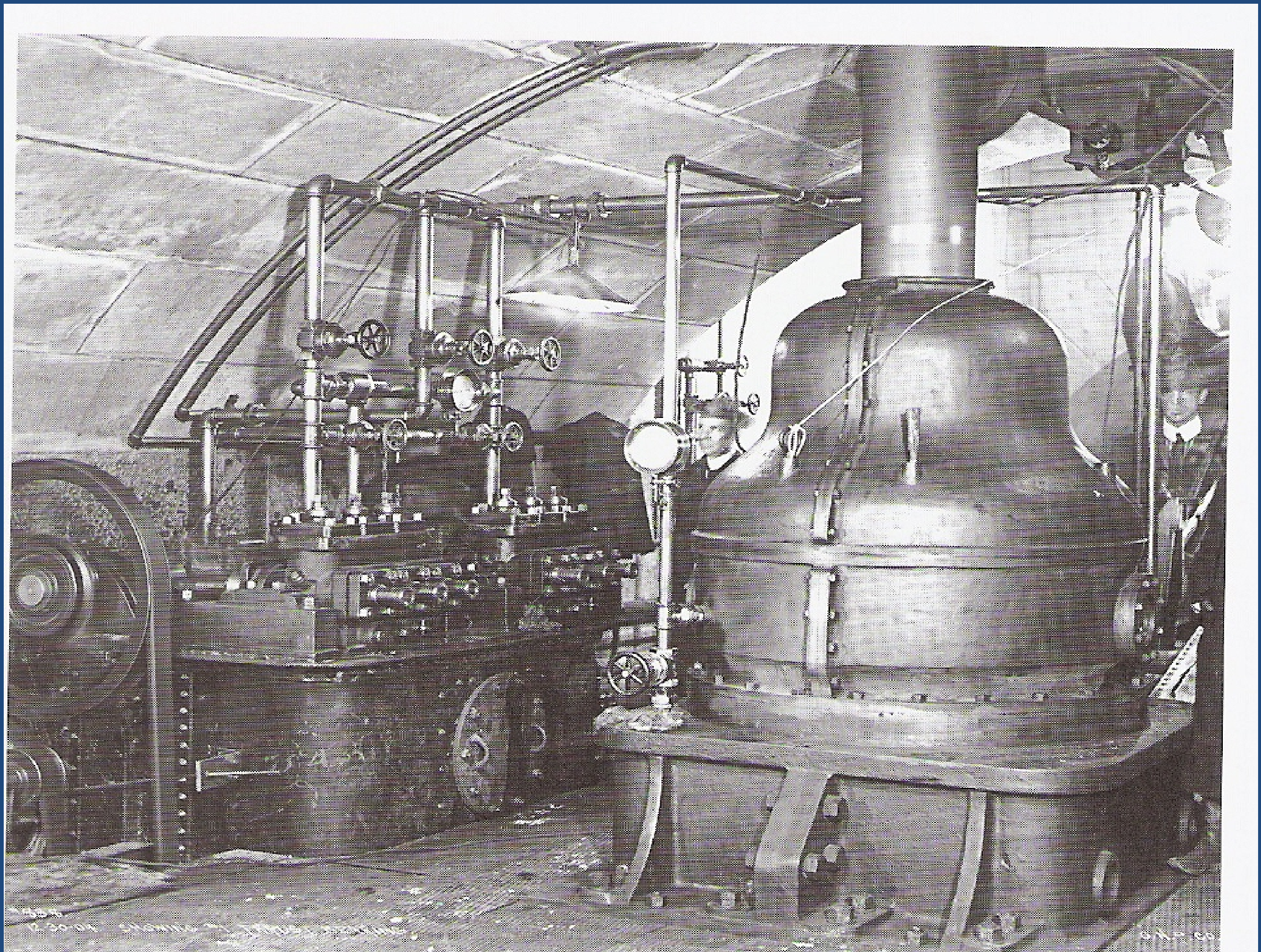
- **ADAMS #1 WAS THE FIRST MAJOR “CENTRAL” POWER PLANT IN THE WORLD.**
-
- **THE FIRST GENERATORS AT ADAMS #1 WERE BUILT ABOUT 1895, THEY WERE TWO-PHASE, VERTICAL. HEAD WAS 140 FT. UNITS WERE 7 x 5 MW, 25 HZ, AND 2,200 VOLTS, BECAUSE THE TRANSMISSION WAS ONLY 11 MILES TO NIAGARA FALLS. (BUFFALO CAME LETTER).**

- **VERY STRANGE DESIGN WITH THE DC ROTOR OUTSIDE THE STATOR. THERE IS ONE AT THE NATIONAL MUSEUM OF TECHNOLOGY IN OTTAWA. EVERYTHING ELSE WAS SCRAPPED CIRCA 1955. BARBARIANS!**

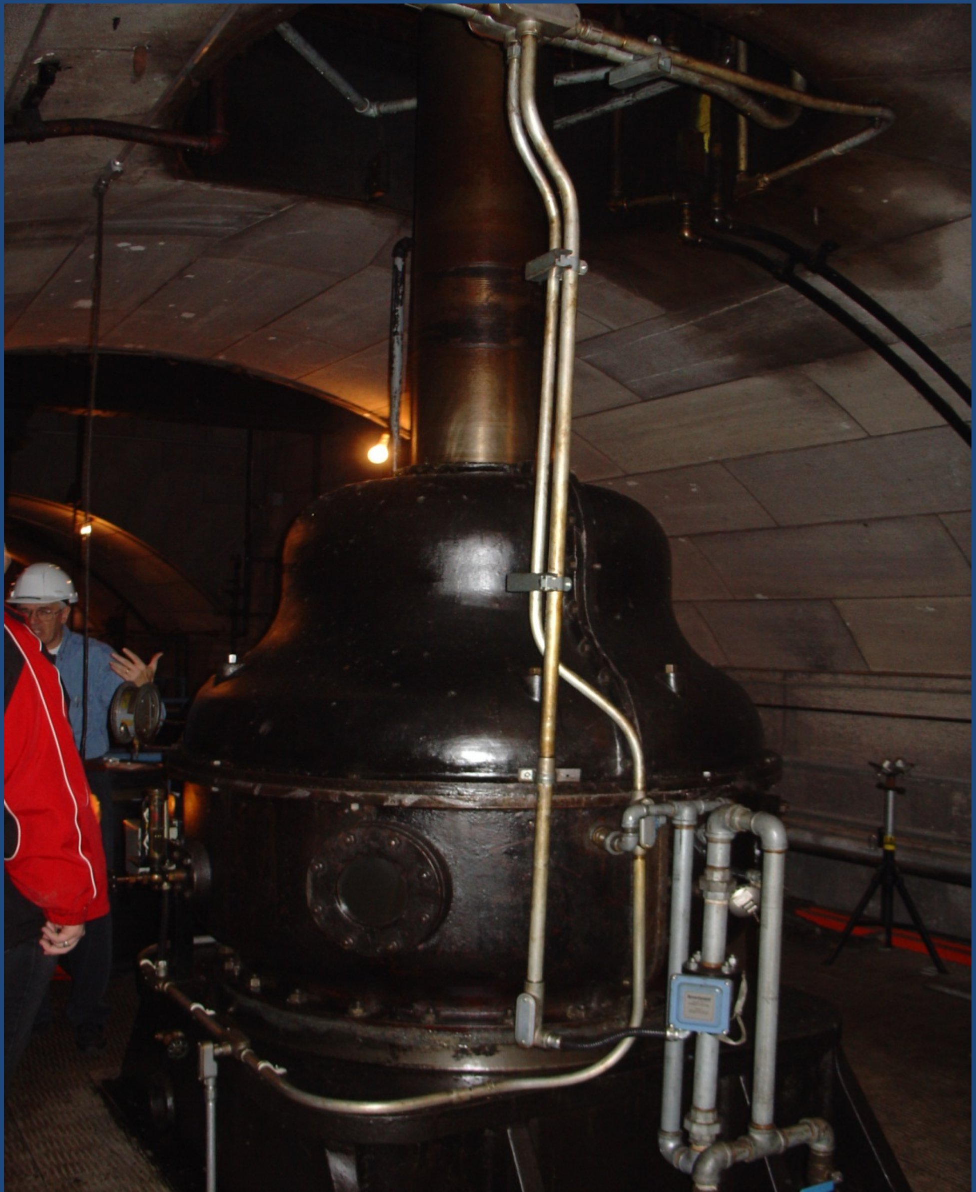
- **FIRST UNITS AT DECEW IN 1898, WERE 2 X 1 MW, 66.66 HZ. HEAD WAS 275 FT, WHICH WAS THE PRINCIPAL CHALLENGE THERE. TRANSMISSION WAS 34 MILES (55 KM) 2 PHASE, AT 22,500 VOLTS, ALSO A CHALLENGE AND SUBJECT OF MUCH DEBATE. ALSO BASIS OF IEEE HISTORIC MARKER.**

THE "WHEEL PIT" DANGEROUS?

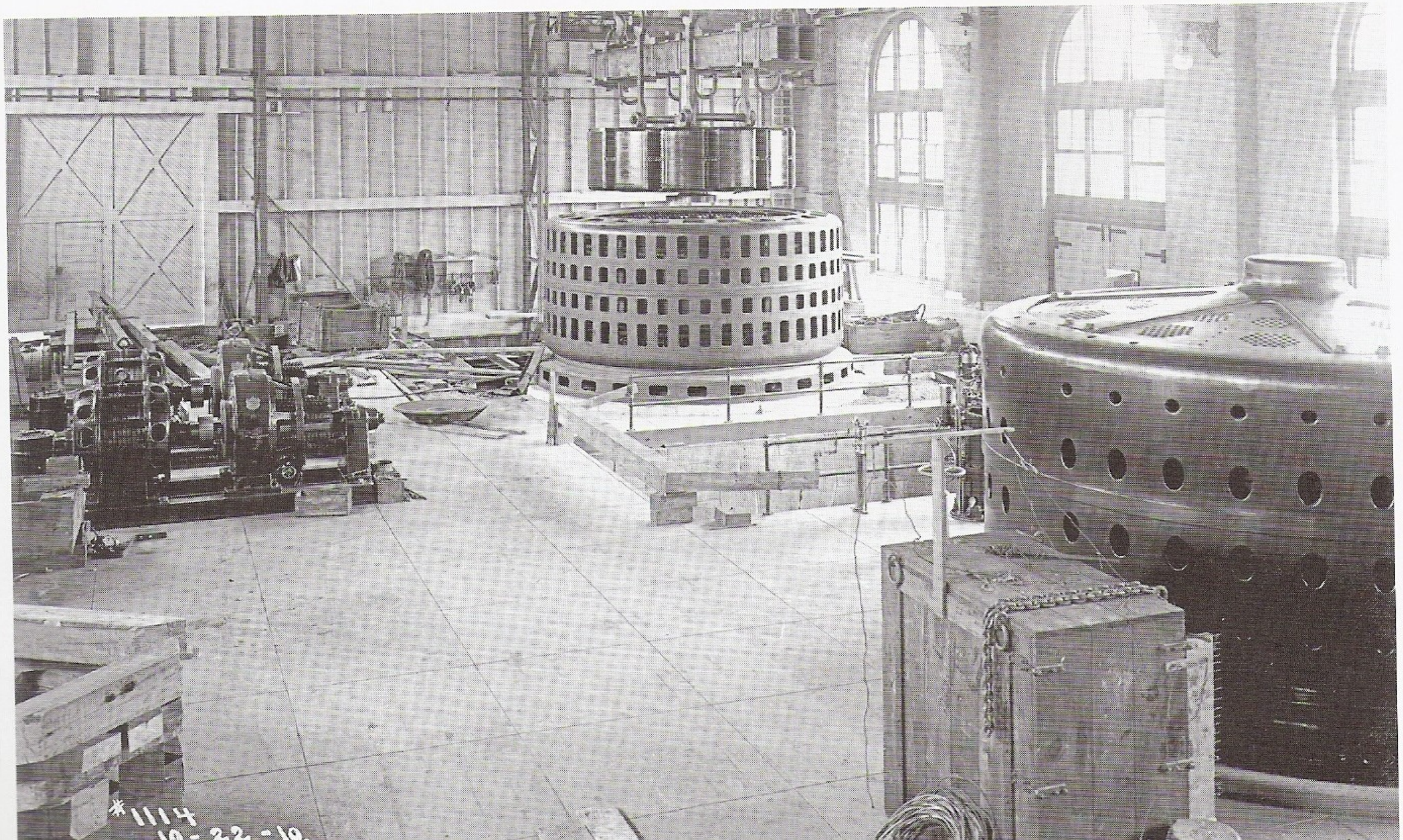
THRUST BEARING AT BOTTOM OF SHAFT. TAKES FULL WEIGHT OF TURBINE, SHAFT & ROTOR. MAYBE 50 TONS.



THRUST BEARING TODAY



NOTE DIFFERENT COOLING VENTS. CIRCA 1910 ALSO TWO EXCITERS AWAITING INSTALLATION.

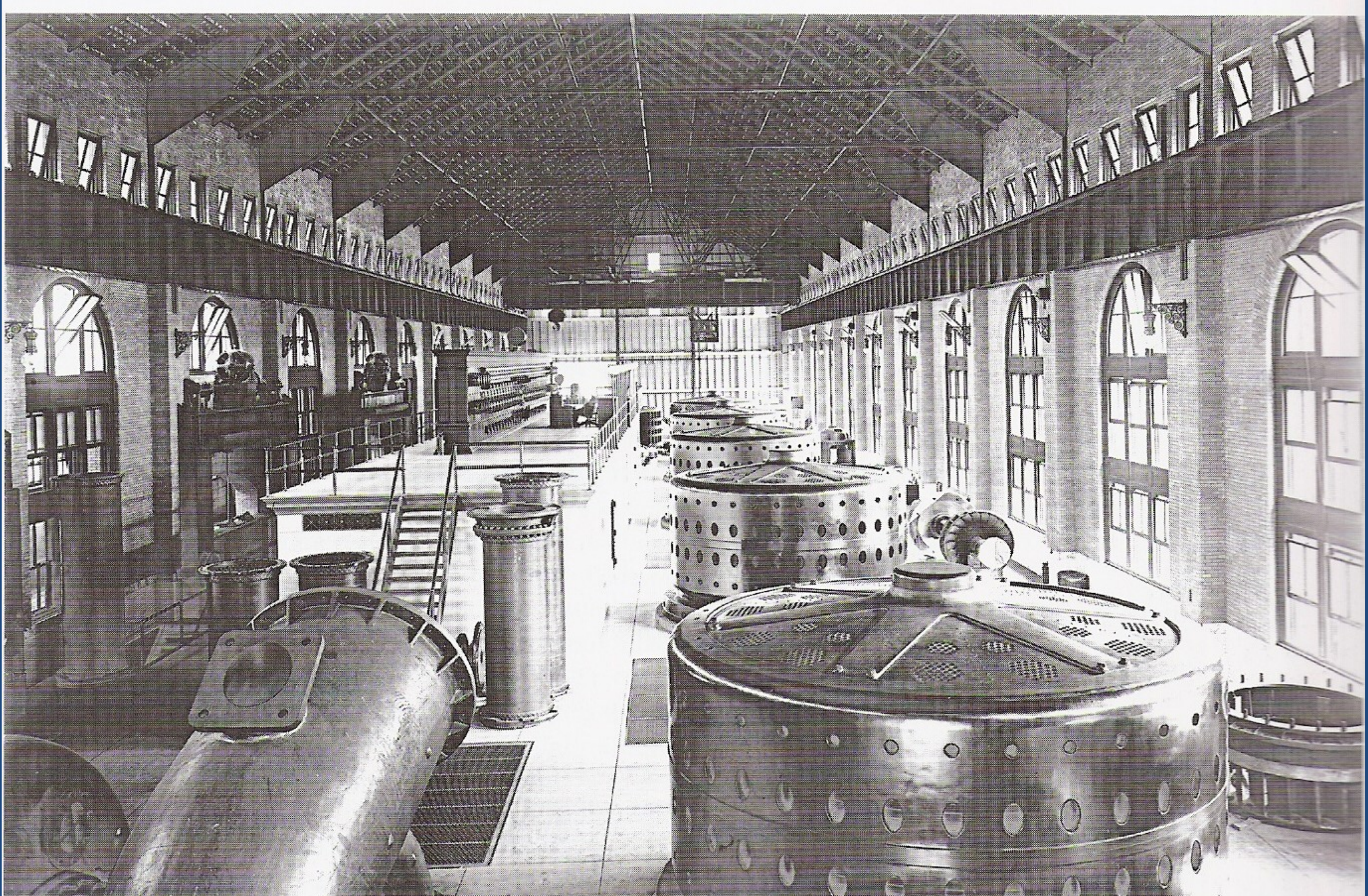


De CEW. FIRST PHASE.

HOW DOES A HYDRO TURBINE WORK? THESE ARE KNOWN AS "WICKET GATES". I WILL EXPLAIN.

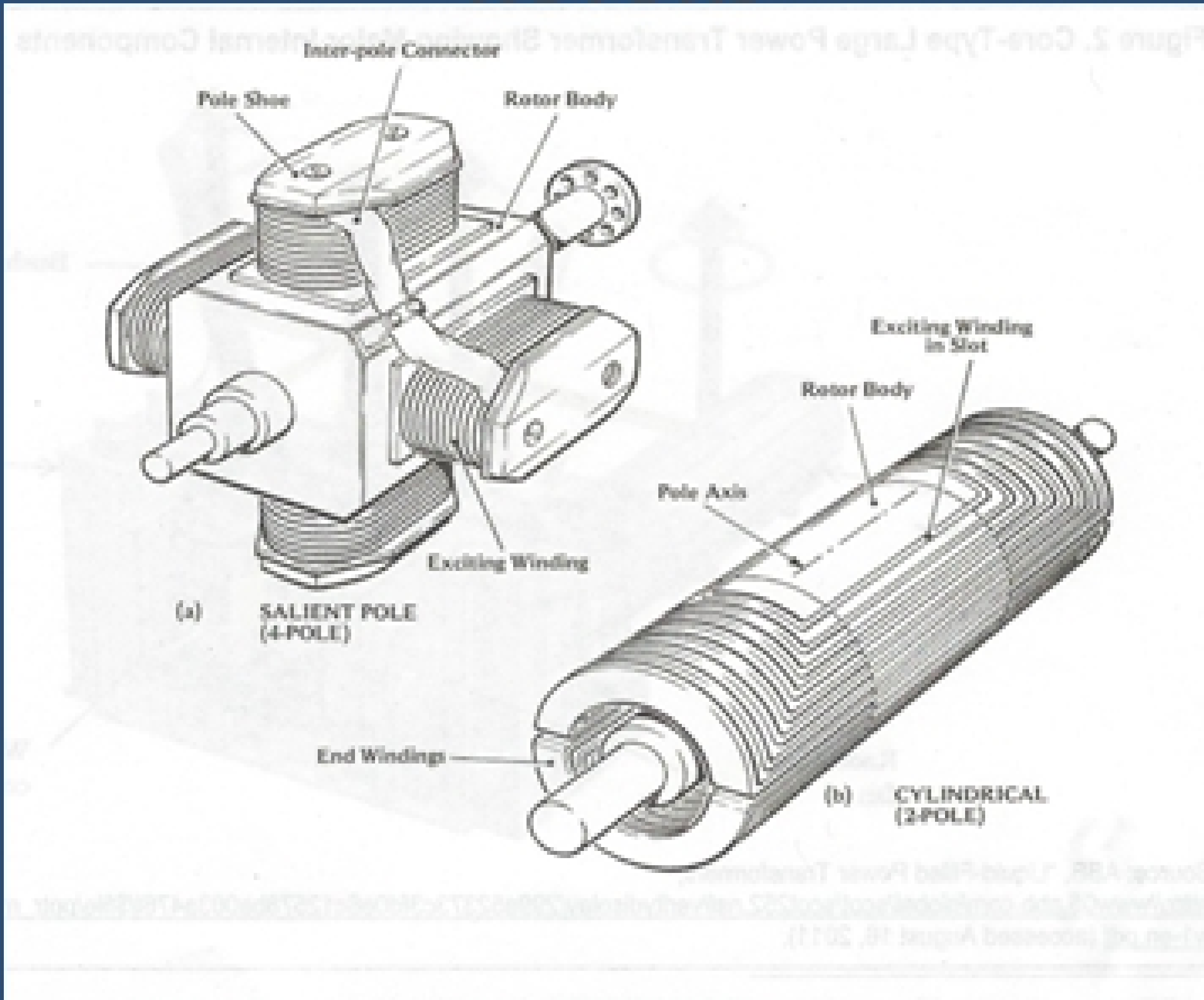
WICKET GATE MECHANISM
1903 DE CEW PLANT. SAME TODAY.

FIRST 5 UNITS ARE 7.5 MW.
FOLLOWED BY 7 x 9.3 MW, TOTAL IS 102.5 MW.
PRIMITIVE OIL CIRCUIT BREAKERS IN CENTER. STRICTLY NOT ALLOWED TODAY. NOTE TURBINE RUNNER CR. RT.

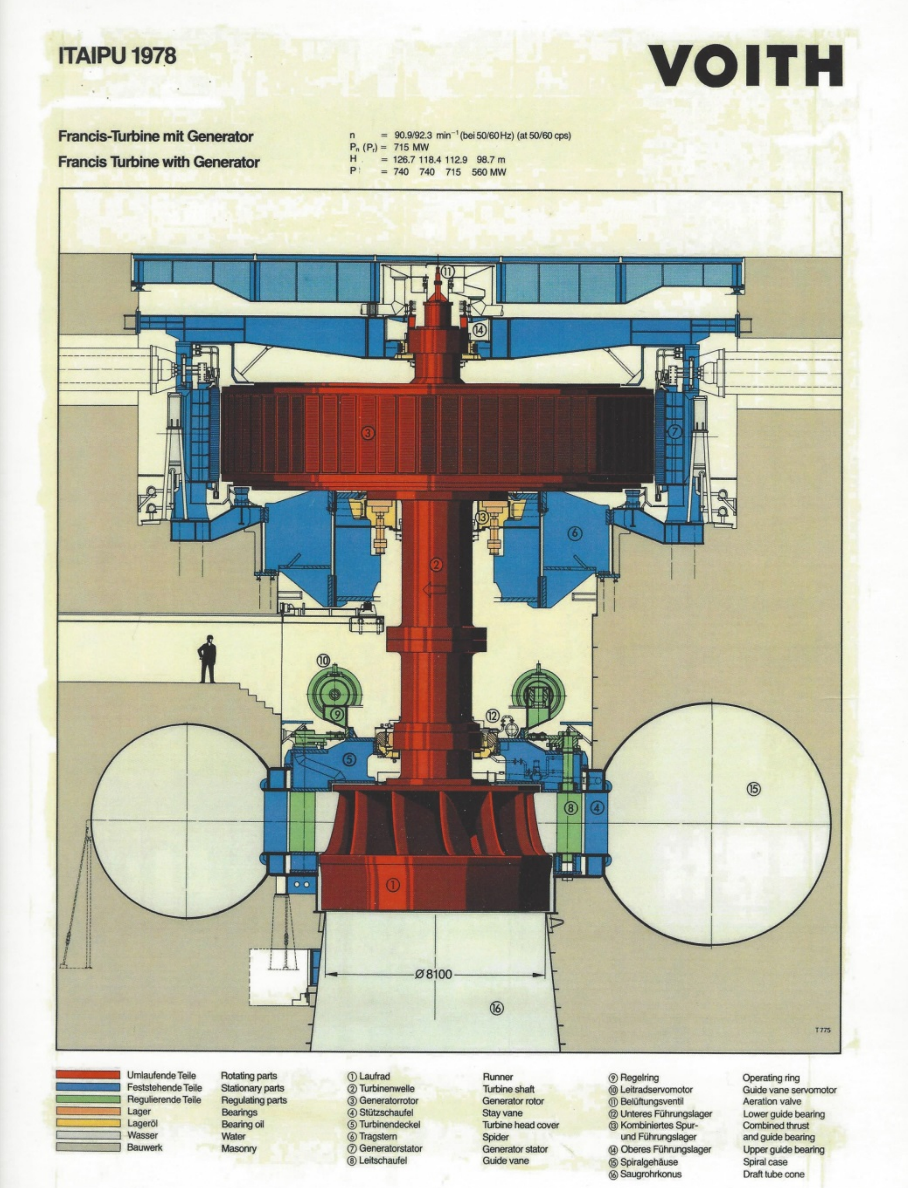


MODERN STUFF

SALIENT POLE AND CYLINDRICAL ROTORS



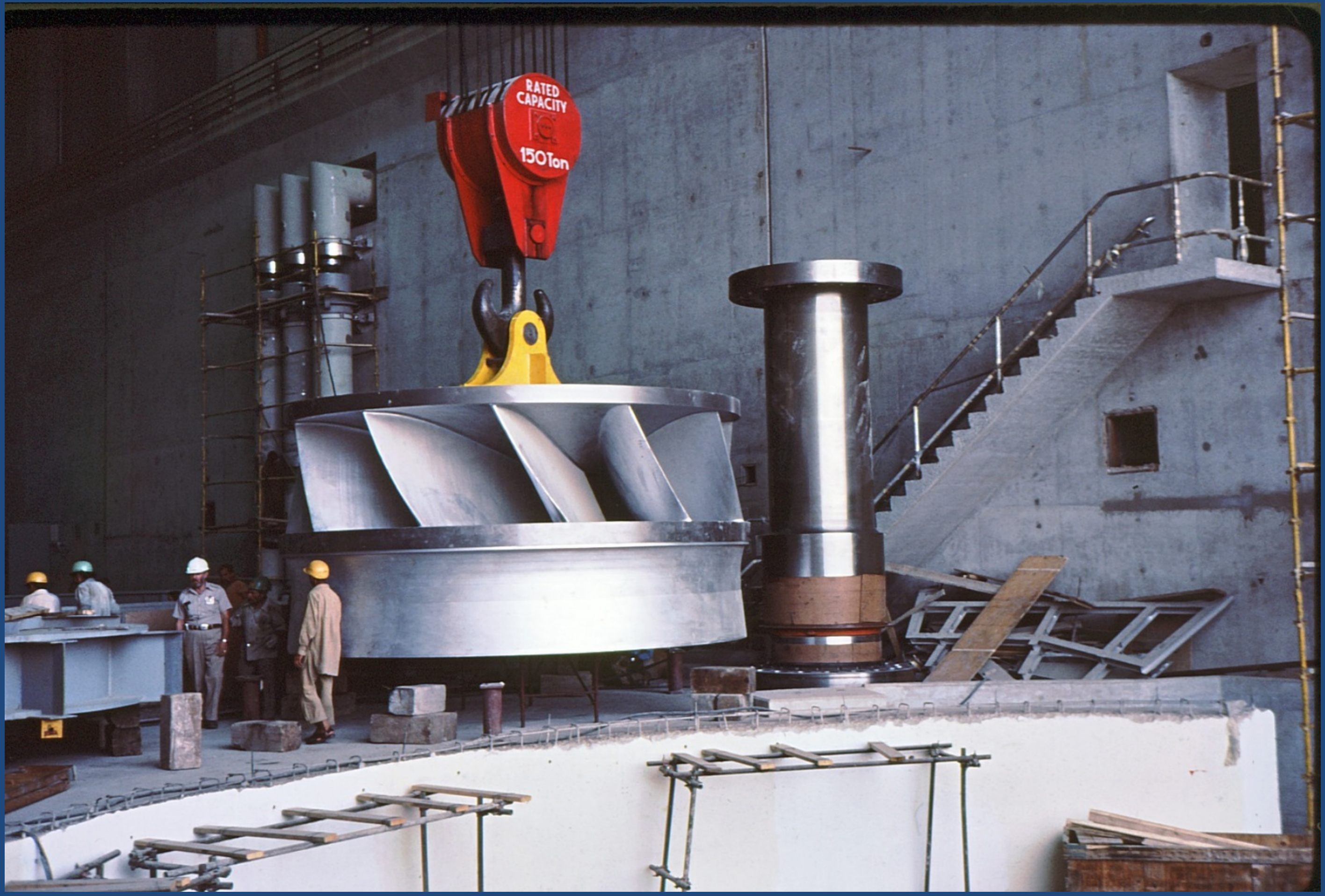
LARGE ROTOR, 715 MW, 125 M HEAD.



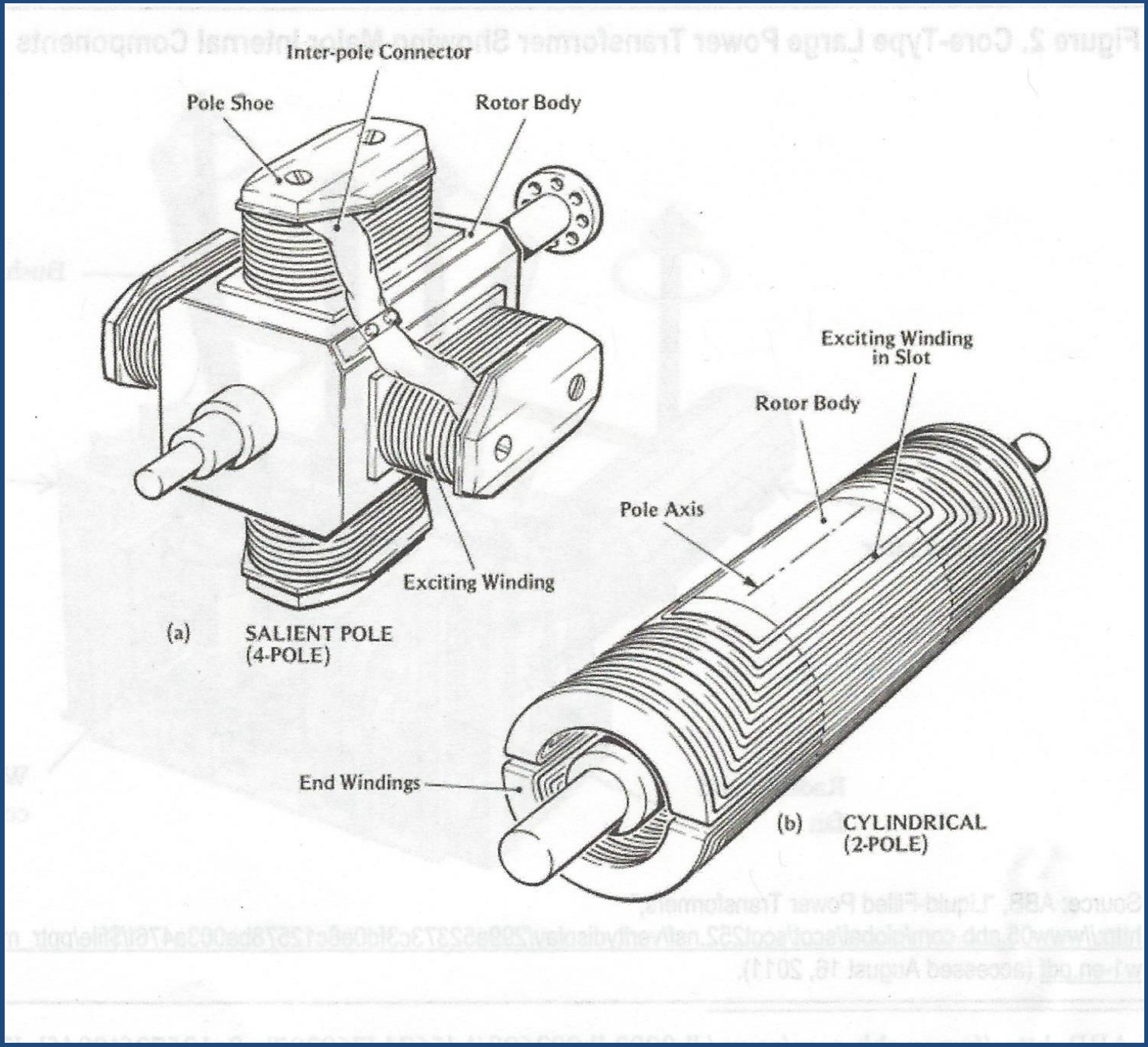
VERY LARGE HYDRO ROTOR. PROBABLY THREE GORGES. 32 x 700 MW, 110 M HEAD (360 FT).

Wikipedia

MEDIUM SIZE RUNNER.
TARBELA, 175 MW, 450 FT HEAD.

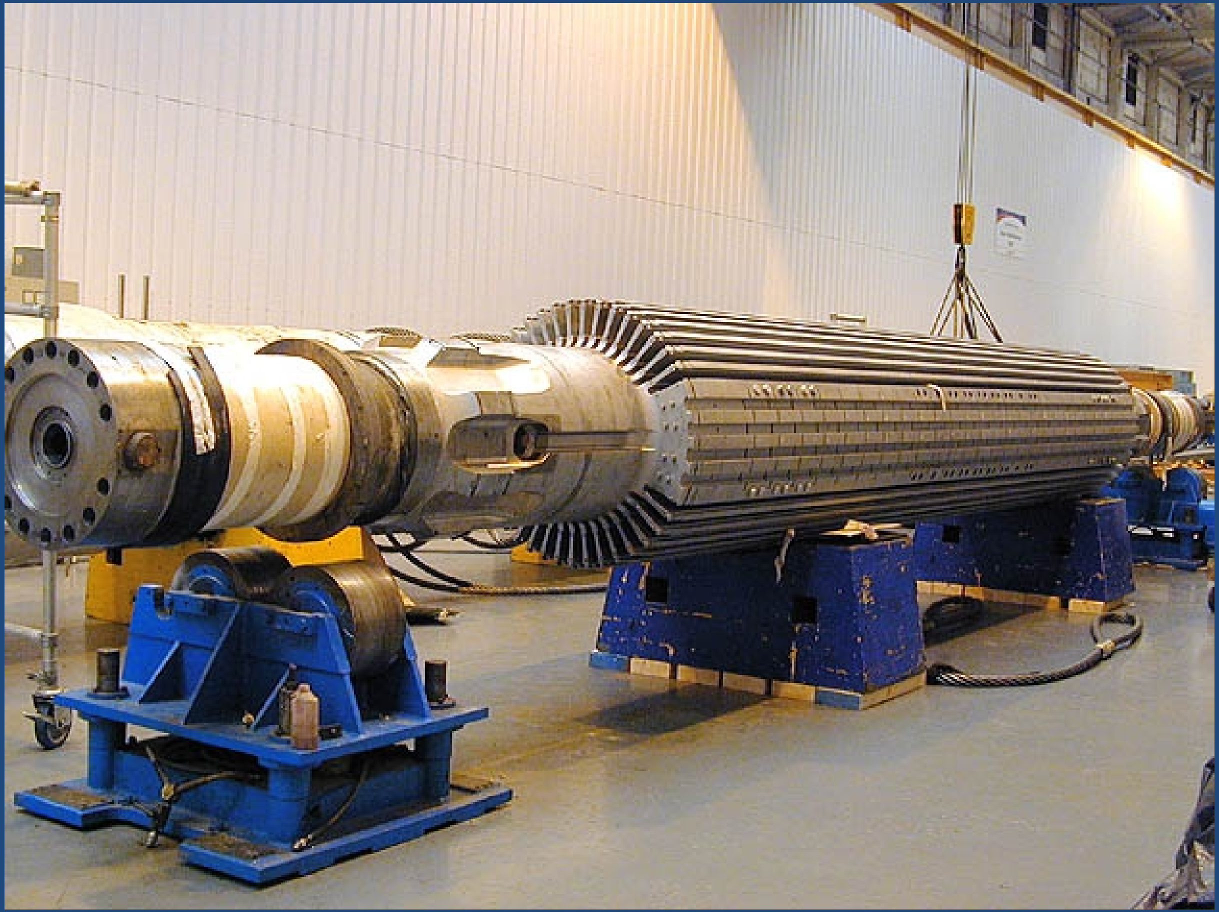


SALIENT POLE AND CYLINDRICAL ROTORS



VERY LARGE 2-POLE ROTOR

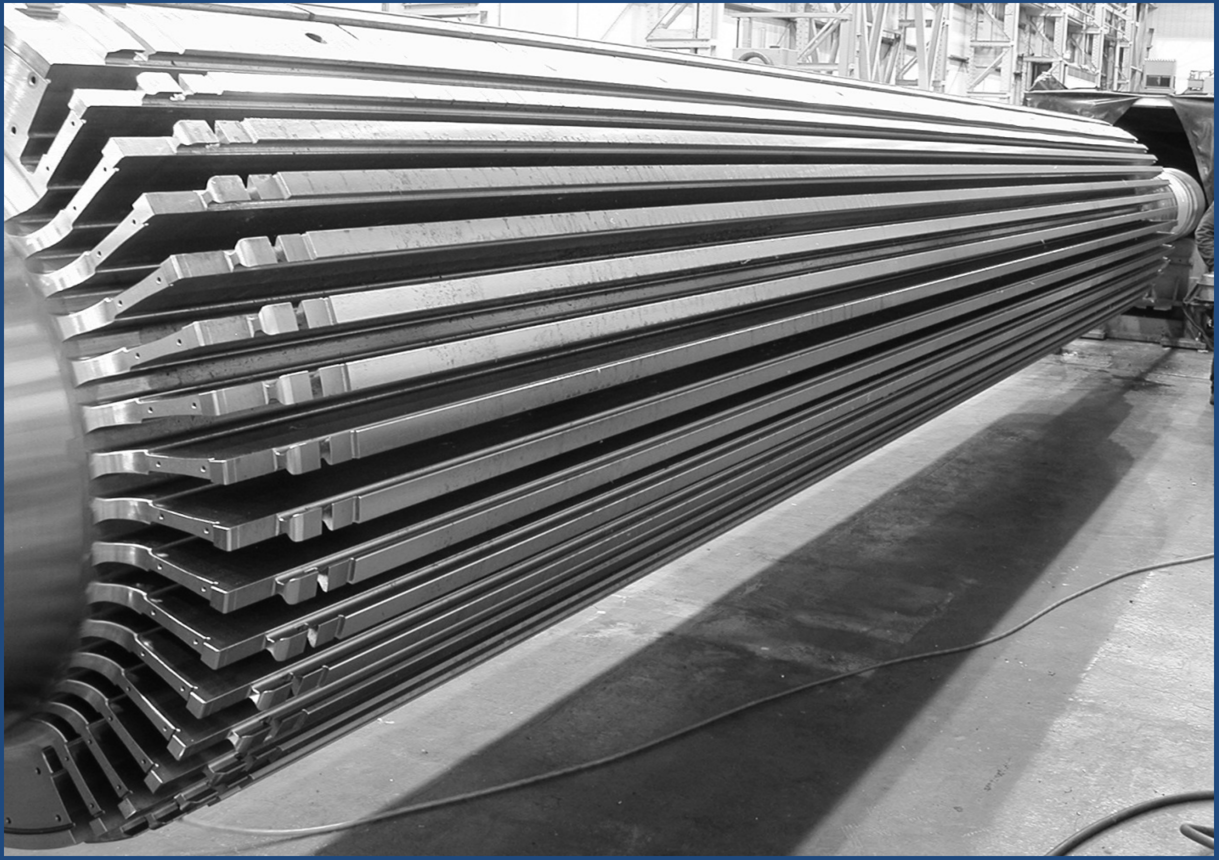
Alstom



A THING OF BEAUTY

ALL MACHINED FROM THE SOLID.

Alstom

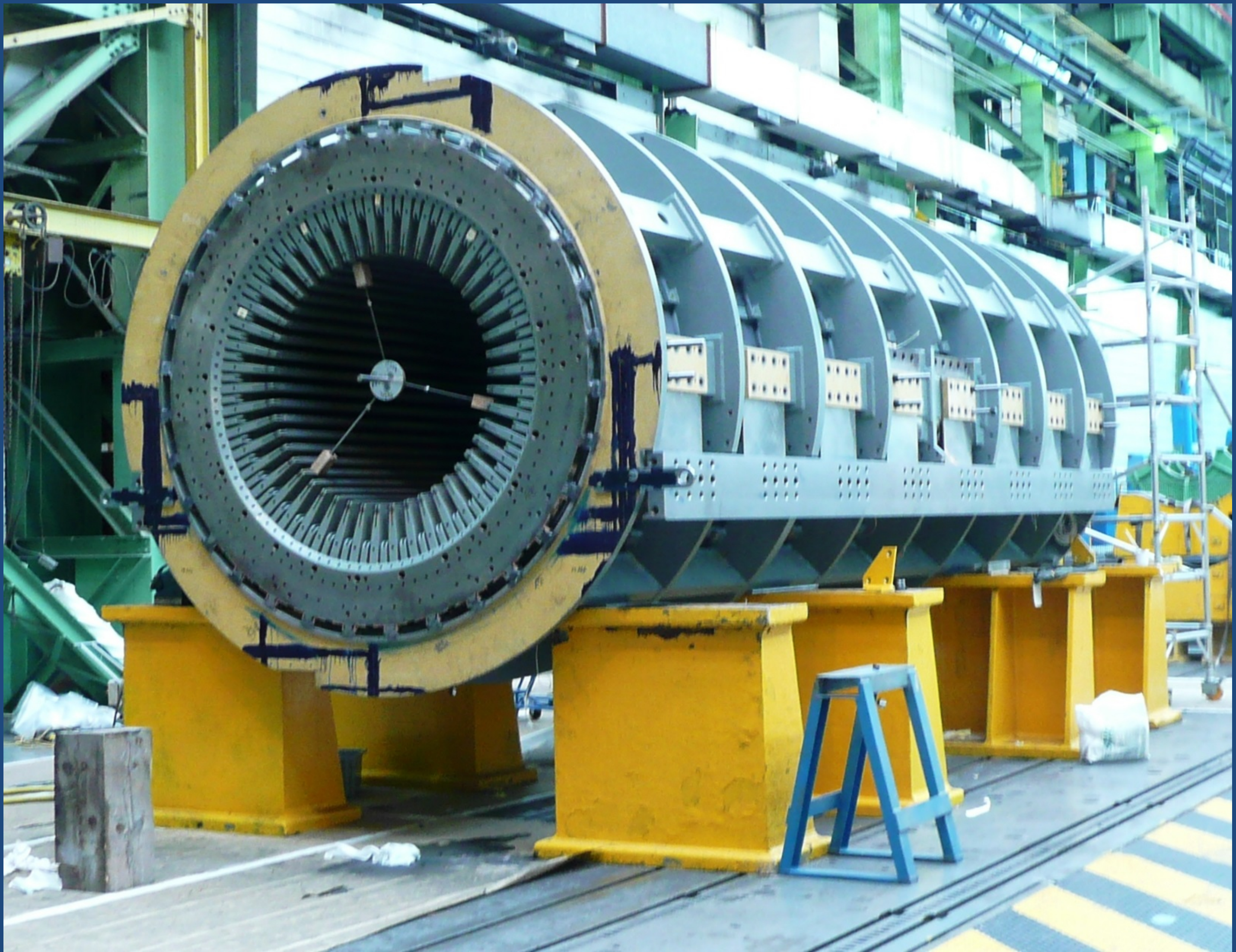


COMPLETED

Alstom

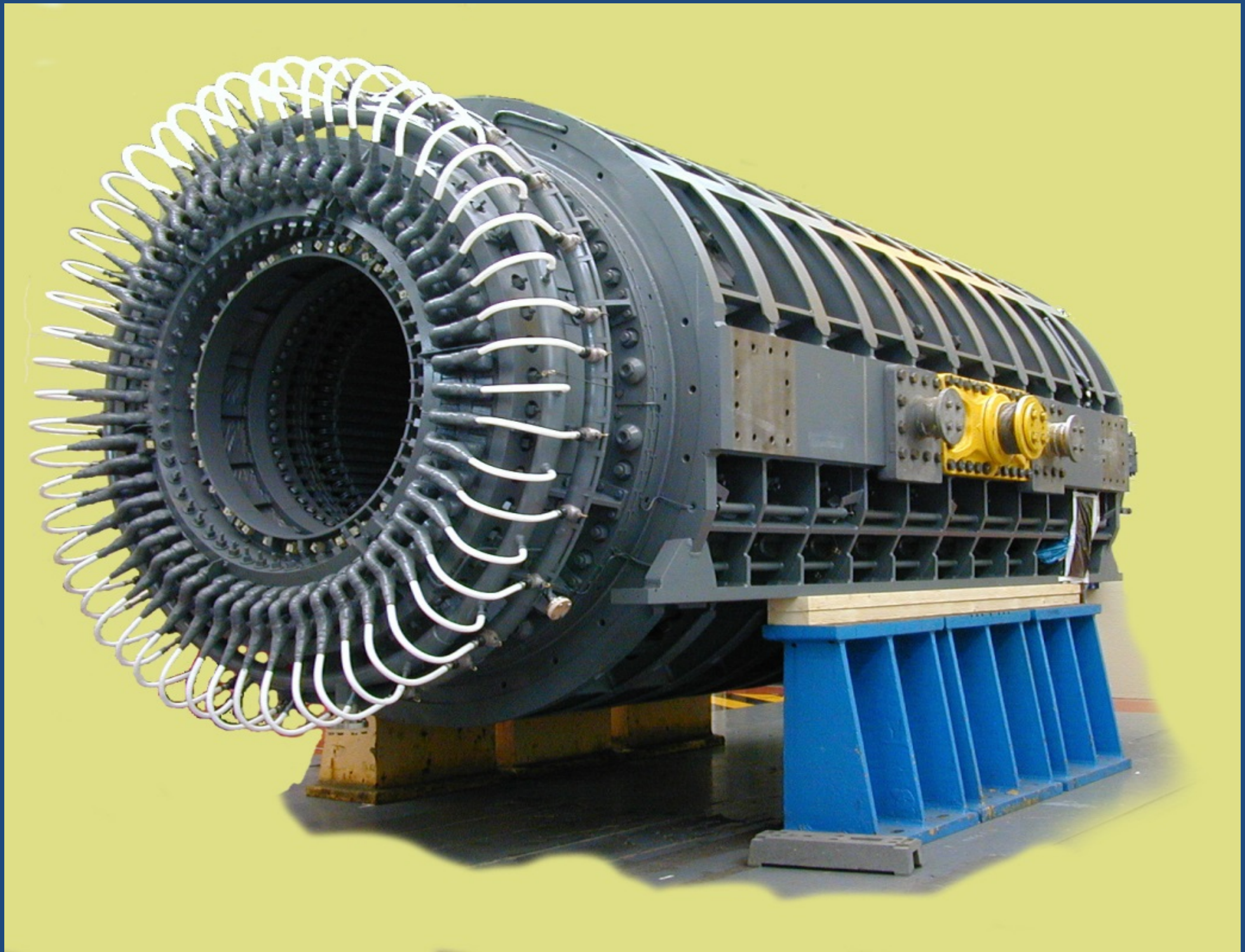
STATOR

Alstom



INNER STATOR. AIR GAP HYDROGEN COOLED.
ROTOR & STATOR WINDINGS WATER COOLED.
COMPLEX? YES! EFFICIENT? 99%.

Alstom

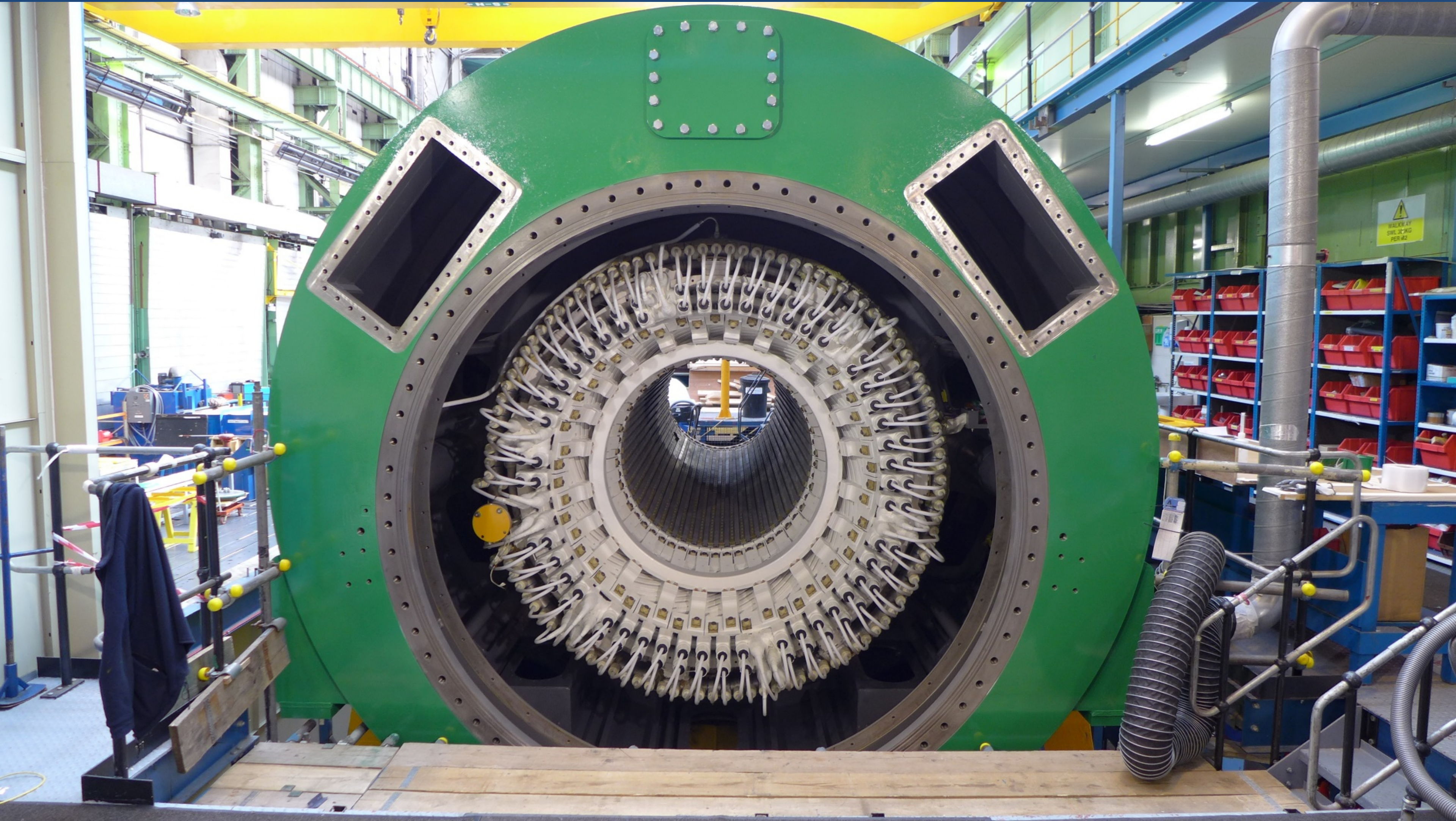


SUNDANCE 500 MW

ALSTOM

SUNDANCE 500 MW

ALSTOM

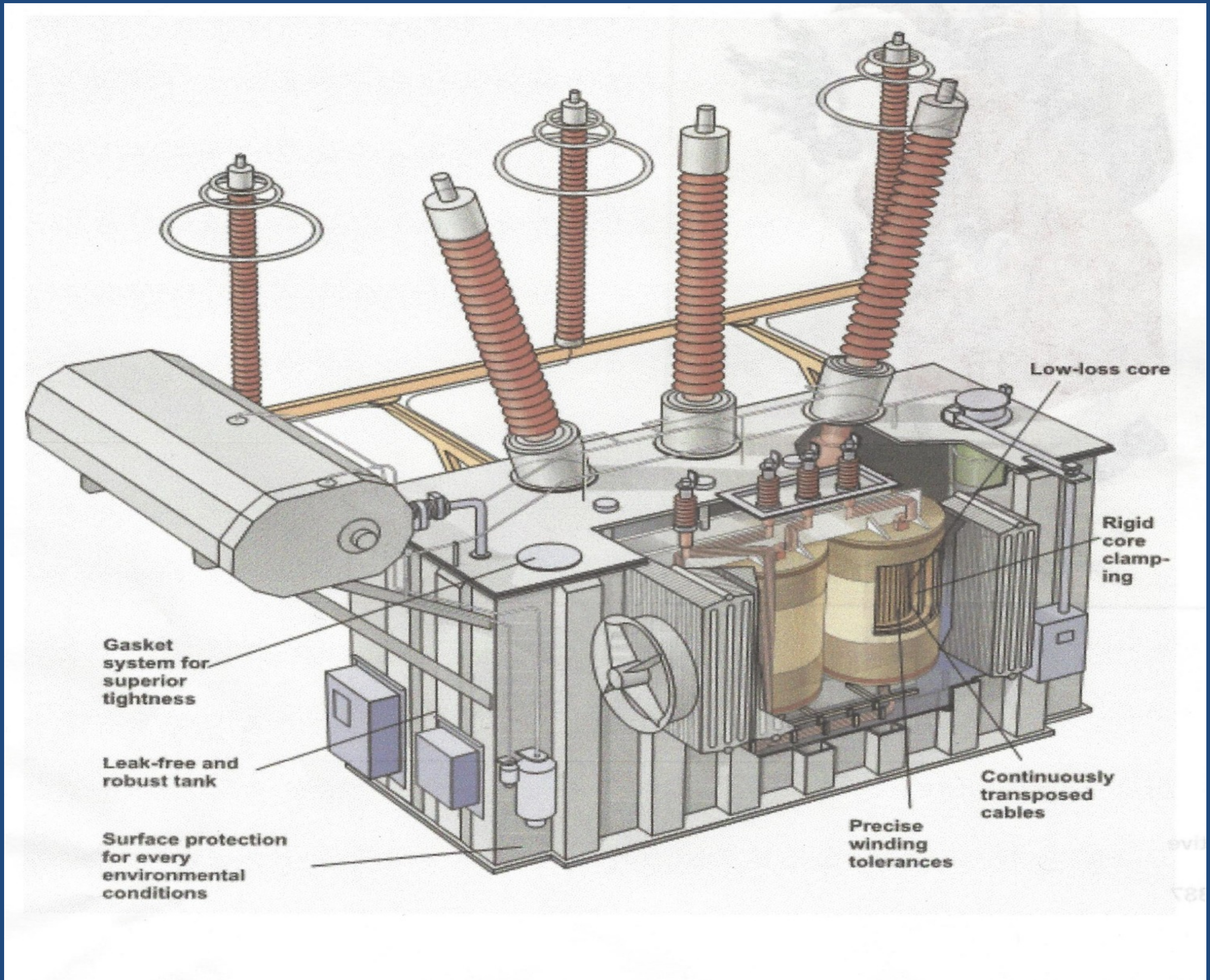


DOG'S BREAKFAST

Wikipedia

LARGE POWER TRANSFORMER.
MAYBE 500 MVA, 3 PHASE, 500/33 kV
I WILL EXPLAIN,

Wikipedia



LARGE TRANSFORMER WITH COOLING

Wikipedia

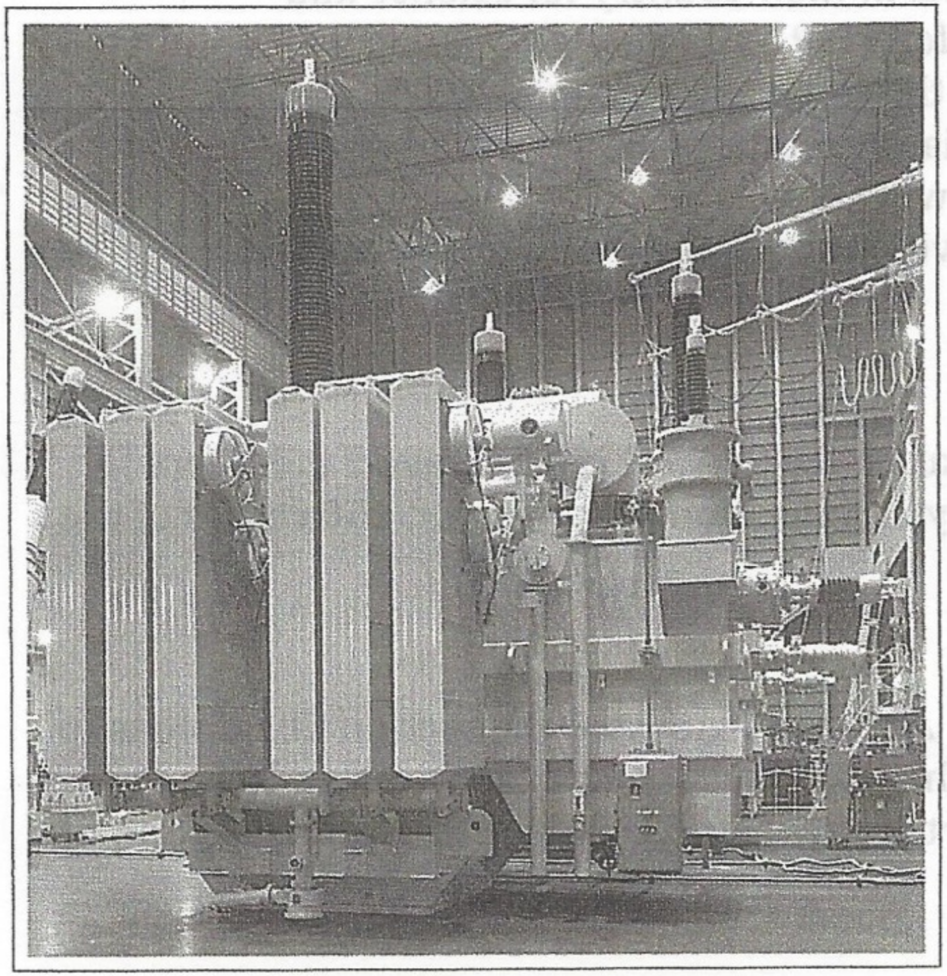


Fig. 26 450-600-750/3MVA, 500kV, single-phase, ONAN-ONAF-OFAF autotransformer

300 MVA 3-PHASE TRANSFORMER

Wikipedia

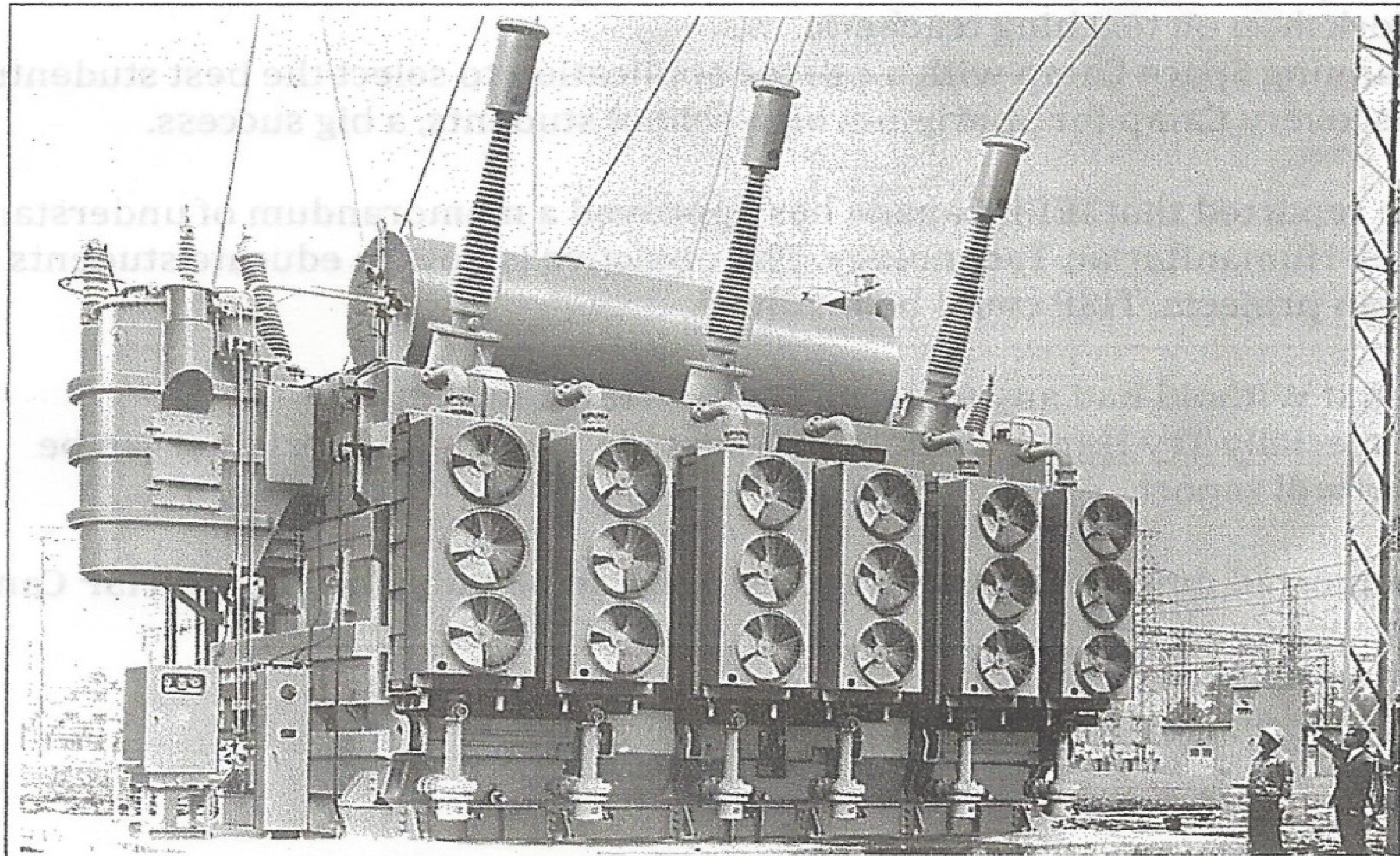


Fig. 37 275/147/63kV, 300/300/90MVA special three-phase transformer

SOME USEFUL NUMBERS - 1

- **EFFICIENCIES**

- **LARGE TRANSFORMER 99.95%**
- **DISTRIBUTION TRANSFORMER 97.5%**
- **HYDRO TURBINE & GENERATOR 93%**
- **COMBINED CYCLE TURBINE & GENERATOR 55-60%**
- **GAS FIRED STEAM 40%**
- **COAL FIRED STEAM GENERATION 35%**
- **SIMPLE CYCLE COMBUSTION 25 – 30%**
- **THE EXHAUST TEPMPERATURE OF A GAS TURBINE IS 600 C !**
- **EHV TRANSMISSION SYSTEM LOSS 2%**
- **MV TRANSMISSION SYSTEM LOSS 2%**
- **DISTRIBUTION SYSTEM LOSS 3%**
- **TOTAL LOSS ABOUT 7%**
- **TRANSFORMERS & LINES 100 YEARS. THE REST 40 YEARS**

USEFUL NUMBERS - 2

- POWER GENERATED BY HYDRO

- $P = Q.H.g.E$

- **WHERE:-**

- **P = POWER IN kW.**
- **Q = WATER FLOW IN CUBIC METERS PER SECOND**
- **G = ACCELLERATION DUE TO GRAVITY**
- **E = OVERALL EFFICIENCY OF TURBINE & GENERATOR. (92-93%)**

- **KEEP IN MIND THAT ONE CUBIC METER OF WATER WEIGHS ONE METRIC TONNE**

USEFUL NUMBERS – 3

THE PER UNIT SYSTEM. USED IN ALL SYSTEM CALCULATIONS.

- **VERY USEFUL BECAUSE EVEN WHEN NUMBERS ARE SQUARED, THE ACTUAL FIGURE IS STILL EASY TO HANDLE WITHOUT TOO MANY ZEROS.**
- **SELECT A "BASE MVA", USUALLY 100 MVA, AND A RANGE OF "BASE kV's", LIKE 132 kV, 230 kV and 500 kV ETC., DEPENDING ON THE SYSTEM.**
- **FROM THESE TWO FIGURES, BASE OHMS, BASE AMPS, BASE REACTANCE ARE EASY TO CALCULATE.**
- **DON'T FORGET THAT THESE ARE ALL 3-PHASE SYSTEMS, SO YOU MUST TAKE THE ROOT OF 3 INTO ACCOUNT WHEN CALCULATING BASE AMPS.**
- **Eg, WITH A BASE VOLTAGE OF 230 kV, A CALCULATED FIGURE OF 1.03 P.U. VOLTS REPRESENTS 236.9 kV. BUT $(1.03)^2$ IS STILL EASY TO ENVISAGE.**
- **FURTHERMORE WITH A P.U. SYSTEM, A SINGLE PHASE REPRESENTATION IS SUFFICIENT**

USEFUL NUMBERS - 4

- **POWER FLOW AND STABILITY**

- POWER TRANSMITTED DOWN A LINE IS PROPORTIONAL TO
  - V1 x V2 x Sin θ.
- AND SINCE (Sin 91) IS LESS THAN (Sin 90), THE POWER WHICH CAN BE TRANSMITTED WILL START AN IRREVERSIBLE DECLINE, UNLESS SOMETHING IS DONE ABOUT IT – QUICKLY. USUALLY A CIRCUIT BREAKER TRIPS AND REMOVES THE FAULT. THIS IS EXACTLY WHAT HAPPENS WHEN A SYSTEM BEGINS TO GO “UNSTABLE” AND THE LIGHTS START TO FLICKER UP AND DOWN QUITE SLOWLY.
- AND FURTHERMORE, IF THE “POWER ANGLE” GETS TO (181 DEGREES), THE POWER WILL START TO FLOW IN THE REVERSE DIRECTION, WHICH EXPLAINS WHY THE LIGHTS SOMETIMES FLARE UP EXTRA BRIGHT.

STABILITY - 1

- SURPRISINGLY, THE SPEED OF EVEN VERY LARGE HYDRO MACHINES ARE MORE EASY TO CONTROL THAN THAT OF STEAM TURBINES. THE NEED TO ACCELERATE A LARGE COLUMN OF WATER IS ADMITTEDLY A FACTOR. BUT TO MAKE STEAM TAKES LONGER.
- BUT:-
- THE “LOADING RATE” OF A HYDRO UNIT IS BETWEEN 60 AND 100 MW/MINUTE.
- THE “LOADING RATE” OF A STEAM TURBINE IS MUCH LESS, MAYBE BETWEEN 5 AND 15 MW PER MINUTE. WHY?
- TWO REASONS:-
- THE “LOADING RATE” IS VERY SLOW BECAUSE OF THE NEED TO, LITERALLY, “BOIL UP A LOT MORE WATER”.
- AND:-

STABILITY - 2

- THE SECOND REASON IS BECAUSE OF WHAT IS KNOWN AS THE INERTIA CONSTANT , SYMBOL “H “.
- INERTIA IS OF COURSE:- WR^2. AND THE WEIGHT AND RADIUS OF GYRATION OF A HYDRO UNIT ARE BOTH LARGE.
- BUT THE INERTIA CONSTANT “H” EXPRESSES THE INERTIA AS A PROPORTION OF THE MW RATING AND THE SQUARE OF THE SPEED.
- THUS:- $H = K.(WR^2).N^2$ (K = 0.231 FOR THOSEWHO ARE INTERESTED).
- THE UNITS ARE IN kW.SECONDS/MVA.
- THE SPEED OF A HYDRO UNIT IS LOW, SAY:- 300 RPM.
- THE SPEED OF A TURBO ROTOR IS VERY HIGH:- 3,600 RPM, AND WHEN SQUARED BECOMES **VERY** LARGE.
- $(300)^2$ = 90,000
- $(3,600)^2$ = 1,296,000
- BUT THIS HUGE DIFFERENCE IS TO SOME EXTENT OFF SET BY THE GREATER WEIGHT AND RADIUS OF A HYDRO MACHINE. NET RESULY IS THAT THE H CONSTANT OF A TURBO IS ABOUT 8 AND THAT FOR A HYDRO MACHINE IS ABOUT 5.
- IN OTHER WORDS A STEAM UNIT IS ABOUT 8/5 OR 1.6 TIMES MORE DIFFICULT TO ACCELERATE.
- COMBINE THIS WITH THE SLOW LOADING RATE MAKES FOR A MESS.

TRANSMISSION LINE CONDUCTORS - 1

Aluminum-conductor steel-reinforced (ACSR) cables are primarily used for medium- and high-voltage lines, and may also be used for overhead services to individual customers. Aluminum cable is used because it has about half the weight of a comparable resistance copper cable (though larger diameter due to lower fundamental conductivity), as well as being cheaper.[1] Some copper cables are still used, especially at lower voltages and for grounding.

Sample cross-section of ACSR power line

While larger conductors may lose less energy due to lower electrical resistance, they are more costly than smaller conductors. An optimization rule called *Kelvin's Law* states that the optimum size of conductor for a line is found when the cost of the energy wasted in the conductor is equal to the annual interest paid on that portion of the line construction cost due to the size of the conductors. The optimization problem is made more complex by additional factors such as varying annual load, varying cost of installation, and the discrete sizes of cable that are commonly made.[1]

Since a conductor is a flexible object with uniform weight per unit length, the geometric shape of a conductor strung on towers approximates that of a catenary. The sag of the conductor (vertical distance between the highest and lowest point of the curve) varies depending on the temperature and additional load such as ice cover. A minimum overhead clearance must be maintained for safety. Since the temperature of the conductor increases with increasing heat produced by the current through it, it is sometimes possible to increase the power handling capacity (uprate) by changing the conductors for a type with a lower coefficient of thermal expansion or a higher

http://www.ask.com/wiki/Overhead_power_line?o=2801&qsrc=999&ad=doubleDown&an=apn&ap=ask.com

TRANSMISSION LINE CONDUCTORS - 2

allowable operating temperature.

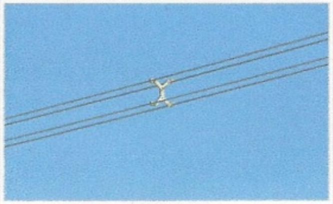
One such conductor that offers reduced thermal sag is known as aluminum conductor composite core (ACCC). In lieu of steel core strands that are often used to increase overall conductor strength, the ACCC conductor uses a carbon and glass fiber core that offers a coefficient of thermal expansion about 1/10 of that of steel. While the composite core is nonconductive, it is substantially lighter and stronger than steel, which allows the incorporation of 28% more aluminum (using compact trapezoidal shaped strands) without any diameter or weight penalty. The added aluminum content helps reduce line losses by 25 to 40% compared to other conductors of the same diameter and weight, depending upon electrical current. The ACCC conductor's reduced thermal sag allows it to carry up to twice the current ("ampacity") compared to all-aluminum conductor (AAC) or ACSR.

Conventional ACSR and modern ACCC conductors

Power lines sometimes have spherical markers to meet International Civil Aviation Organization recommendations.[5]

Bundled conductors

At very high voltages, *bundle conductors* are used to reduce corona losses. Bundle conductors consist of several parallel cables connected at intervals by spacers, often in a cylindrical configuration. For 220 kV lines, two-conductor bundles are usually used, and for 380 kV lines usually three or even four. American Electric Power[6] is building 765 kV lines using six conductors per phase in a bundle. Spacers must resist the forces due to wind, and magnetic forces during a short-circuit.



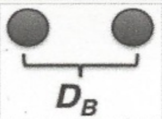
A bundle conductor

Advantages

At extra high voltage, the electric field gradient at the surface of a single conductor is high enough to ionize air, which loses power and generates both audible noise and interference with communication systems. The field surrounding a bundle of conductors is similar to the field that would surround a single, very large conductor—this produces lower gradients which mitigates issues associated with high field strength. When transmitting alternating current, bundle conductors also avoid the reduction in ampacity of a single large conductor due to the skin effect. A bundle conductor also has lower reactance, compared to a single conductor. Additionally, bundled conductors cool themselves more efficiently due to the increased surface area of the conductors, further reducing line losses.

Bundle conductor attachment

In addition to reducing Corona losses and improving the skin effect, conductor bundling also reduces line inductance. Low line inductance is highly desired because it reduces reactive current flow, line heating, and voltage drop across transmission lines. For a non-bundled transmission line, two parameters of transmission lines affect the inductance: the geometric mean radius, D, and the equivalent conductor radius, r_x. The geometric mean radius is the geometric mean of the distance between phases in a bundled or non-bundled transmission line. For example, a 3-phase system with equal line spacing d and conductors arranged in a straight line has a geometric mean radius of where 2d represents the distance between the two outermost phases. The conductor radius r_x is the effective radius of a single conductor. The equation for inductance is then:



Two-conductor

500 kV AT TARBELA
4-CONDUCTOR BUNDLE. 16” CRS.

CONDUCTOR PROBLEMS

- **ALUMINUM IS CHEAP, LIGHT AND A GOOD CONDUCTOR.**
- **BUT:-**
- **IT SUFFERS FROM "COLD FLOW", WHICH MAKES IT DIFFICULT TO SPLICE.**
- **COPPER OXIDE HAS COMPARATIVELY LOW RESISTANCE. ALUMINUM OXIDE HAS HIGH RESISTANCE . ALSO IT OXIDISES ASTONISHINGLY QUICKLY – LIKE 5 MINUTES. AGAIN DIFFICULT TO SPLICE.**
- **VOLTAGES > 800 KV REQUIRE EIGHT OR MORE CONDUCTORS IN THE BUNDLE. THIS PLUS THE GREAT HIGHT TO GET CLEARANCE TO GROUND MAKES THEM UNSIGHTLY. I THINK 800 KV IS A PLATEAU. RUSSIA BUILT AN 1,100 KV LINE. LOTS OF PROBLEMS. BUILT NO MORE.**

CIRCUIT BREAKERS - 1

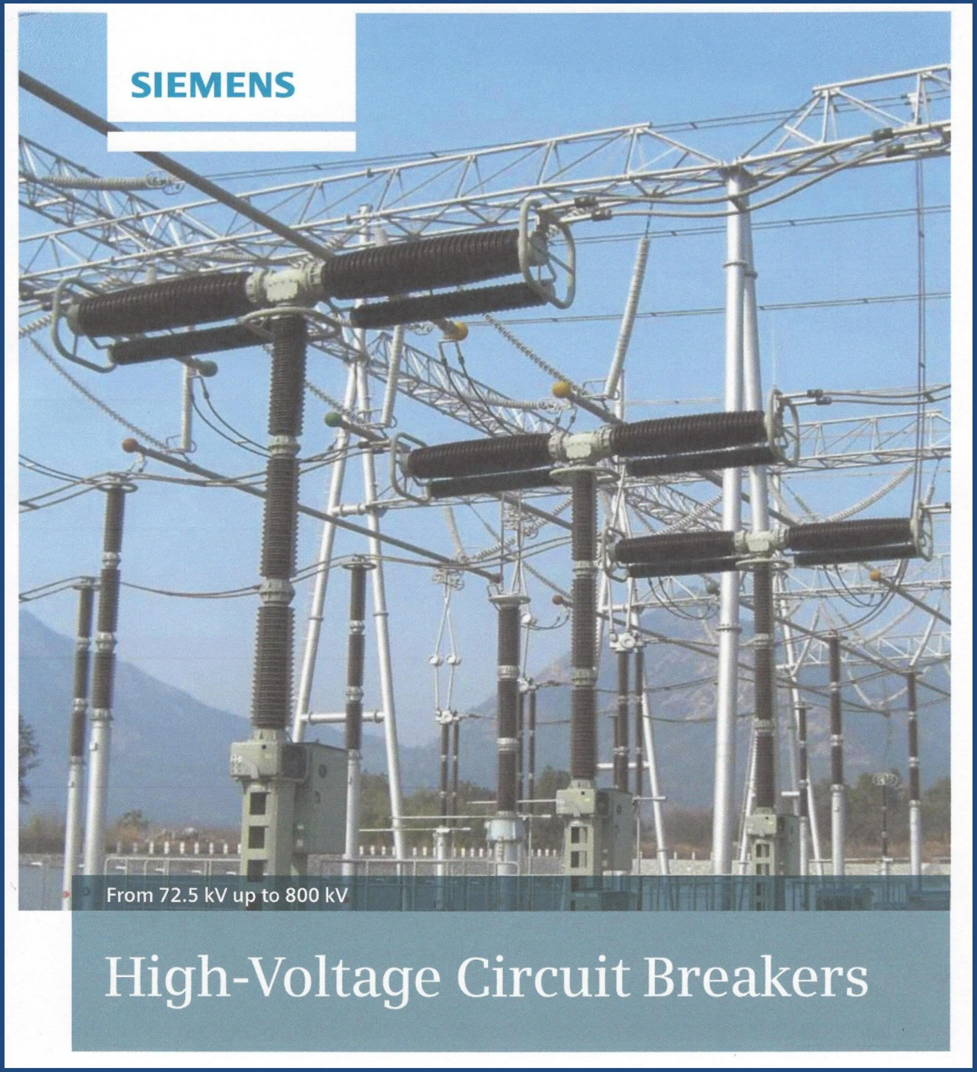
- **IT IS VERY DIFFICULT TO EXTINGUISH AN ELECTRIC ARC. JUST AS THE BREAKER CONTACTS PART, THE VOTAGE ACROSS THEM IONIOZES THE AIR IN THE GAP, AND OF COURSE, IONIZED AIR IS A CONDUCTING MEDIUM.**
- **FOR AC CURRENT YOU HAVE TO WAIT FOR THE NEXT CURRENT ZERO.**
- **DC ARCS ARE VIRTUALLY IMPOSSIBLE EXCEPT BY PULSING A CURRENT IN THE OPPOSITE POLIRITY.**
- **LOOK UP IEEE SPECTRUM, CIRCA FALL 2013, AND READ ABOUT THE TELURIDE PROJECT – IT'S HILLARIOUS**

CIRCUIT BREAKERS - 2

- **THE LIFE OF A CIRCUIT BREAKER IS VERY STRANGE. IT SITS OUTSIDE IN ALL WEATHERS FOR YEARS. AND THEN SUDDENLY IT IS REQUIRED TO INTERRUPT THOUSANDS OF AMPS IN 1-1/2 CYCLES (3 CURRENT ZEROS). AND IT DOES.**

- **EARLY BREAKERS USED OIL (SURPRISINGLY).**
- **FOR MANY YEARS, COMPRESSED AIR WAS USED.**
- **VACUUM BREAKERS WERE TRIED.**
- **CURRENT MEDIUM IS SULFURHEXAFLUORIDE, SF_6.**
- **CO_2 IS NOW BEING CONSIDERED.**
- **DC BREAKERS REALLY DON'T EXIST. EXCEPT BY PULSING A REVERSE CURRENT OF EXACTLY THE RIGHT AMPLITUDE. HENCE THE EXPENSE OF DC SYSTEMS.**

CIRCUIT BREAKER
MY GUESS IS 230 kV. WHY?



OTHER BREAKER TYPES

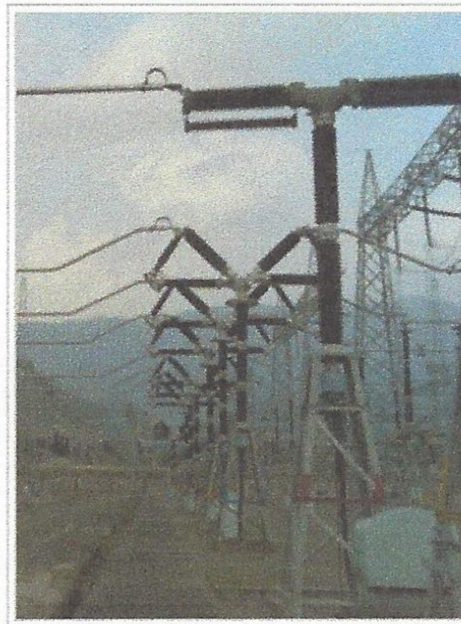
Three single phase Russian 110 kV oil circuit breakers

transformers. In substations the protective relay scheme can be complex, protecting equipment and buses from various types of overload or ground/earth fault.

High-voltage breakers are broadly classified by the medium used to extinguish the arc.

- Bulk oil
- Minimum oil
- Air blast
- Vacuum
- SF_6
- CO_2

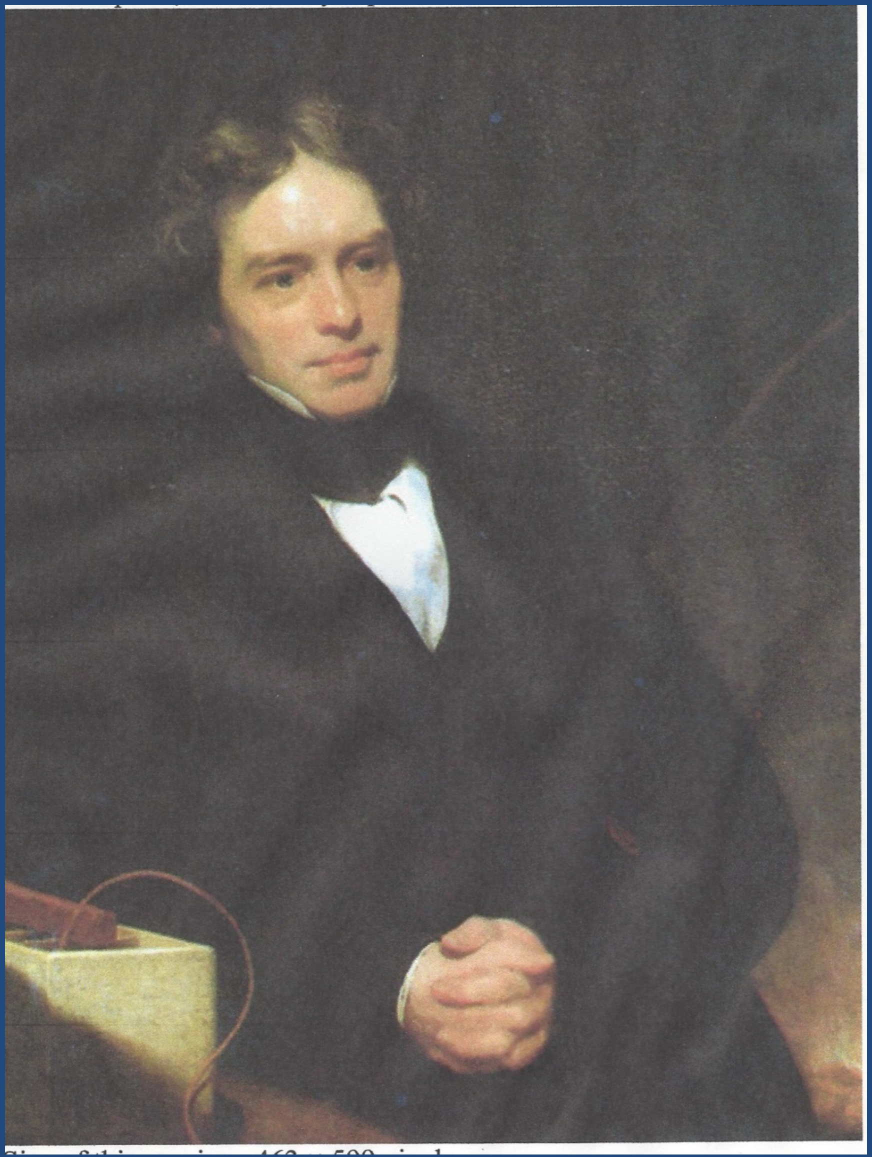
Some of the manufacturers are ABB, Alstom, General Electric, Hitachi, Hyundai Heavy Industry(HHI), Mitsubishi Electric, Pennsylvania Breaker, Siemens, Toshiba, Končar HVS, BHEL, CGL, and Becker/SMC (SMC Electrical Products).



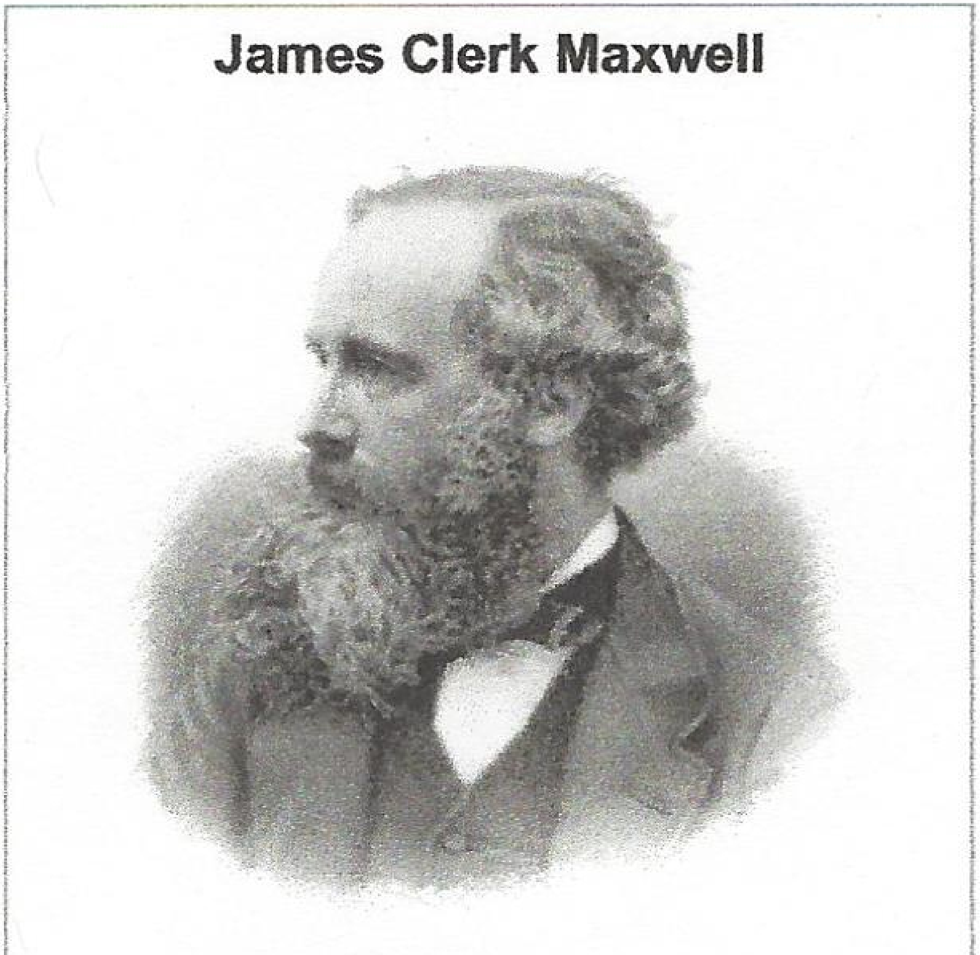
400 kV SF_6 live tank circuit breakers

- **QUESTIONS?**

MICHAEL FARADAY



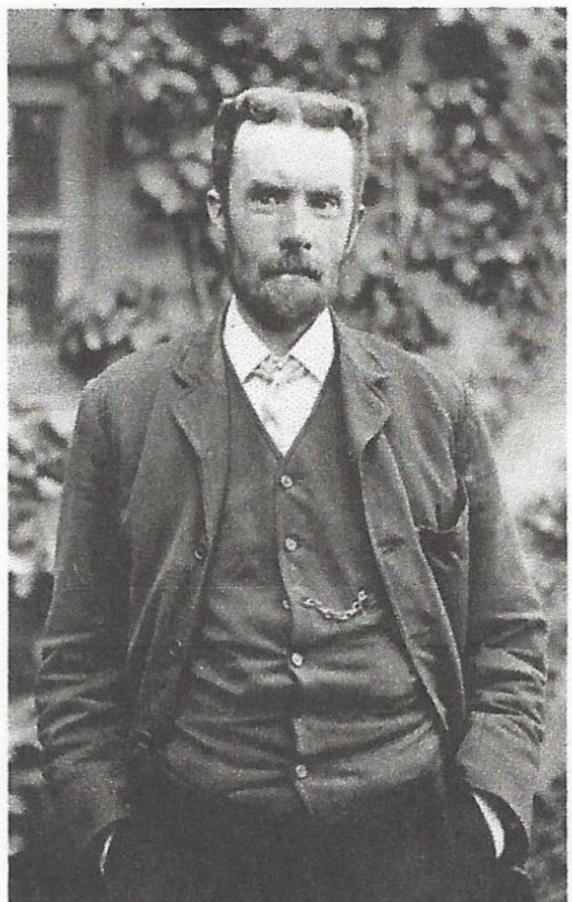
JAMWES CLARK MAXWELL



James Clerk Maxwell (1831–1879)

OLIVER HEAVISIDE

Oliver Heaviside

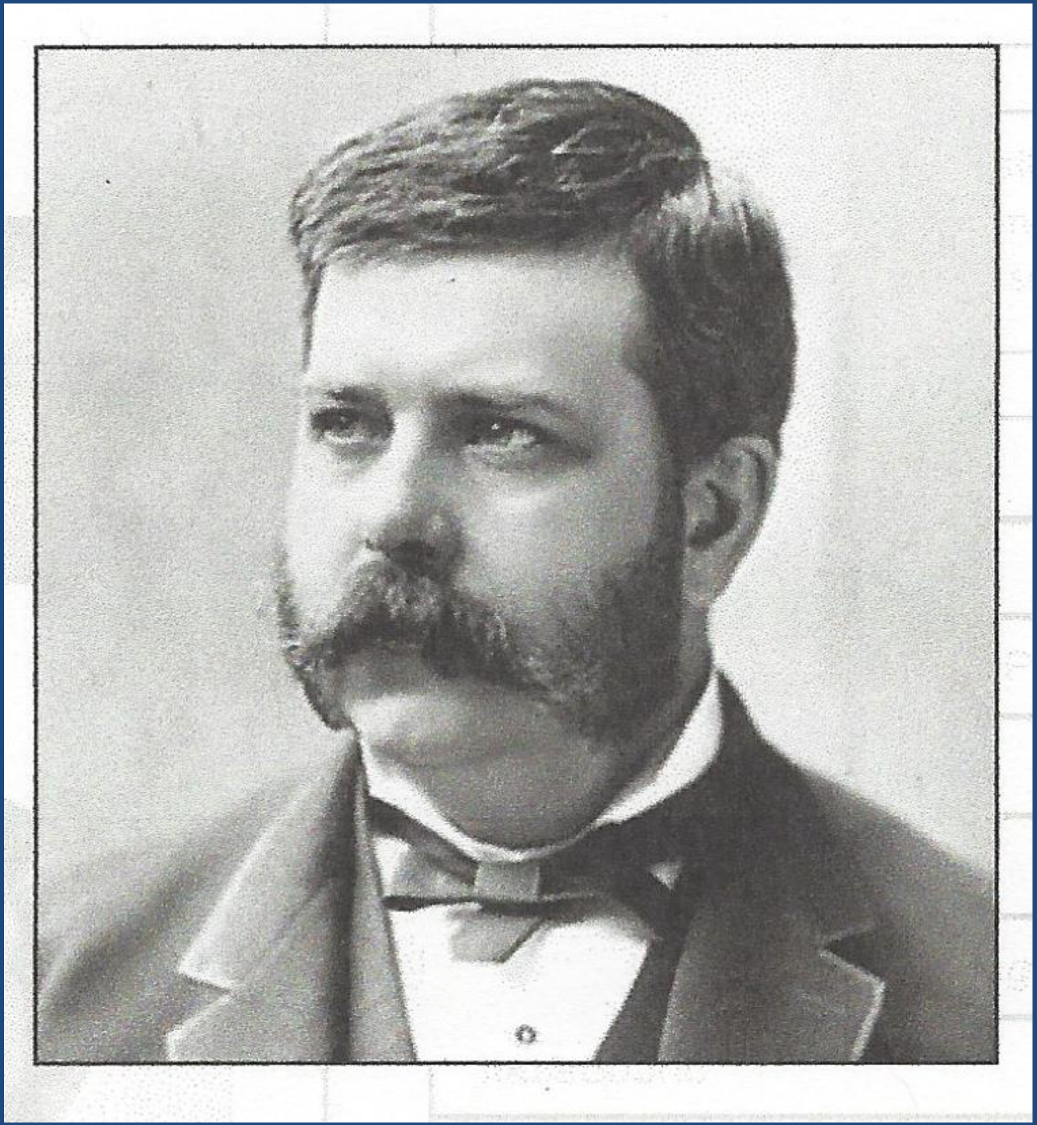


Born 18 May 1850
Camden Town, London, England

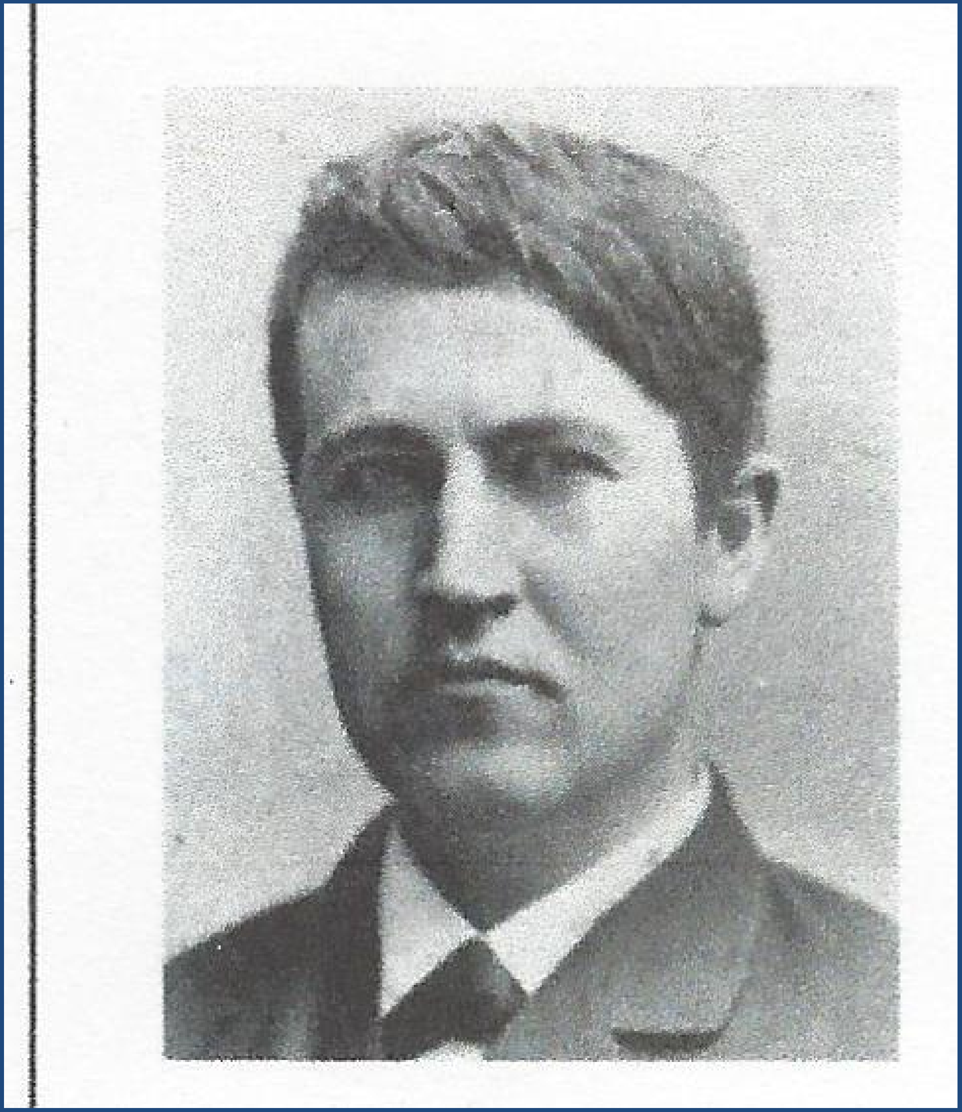
HEINRICH HERTZ

Heinrich Hertz

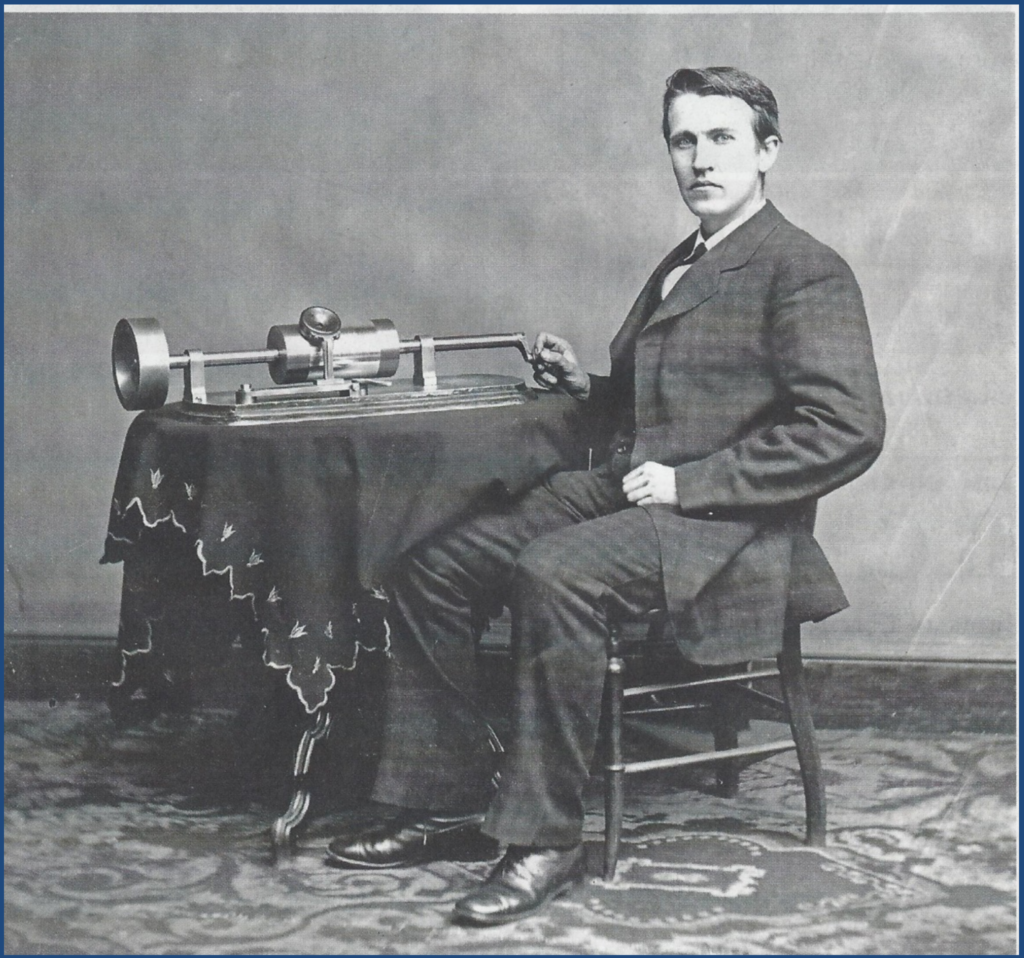
GEORGE WESTINGHOUSE



THOMAS EDISON

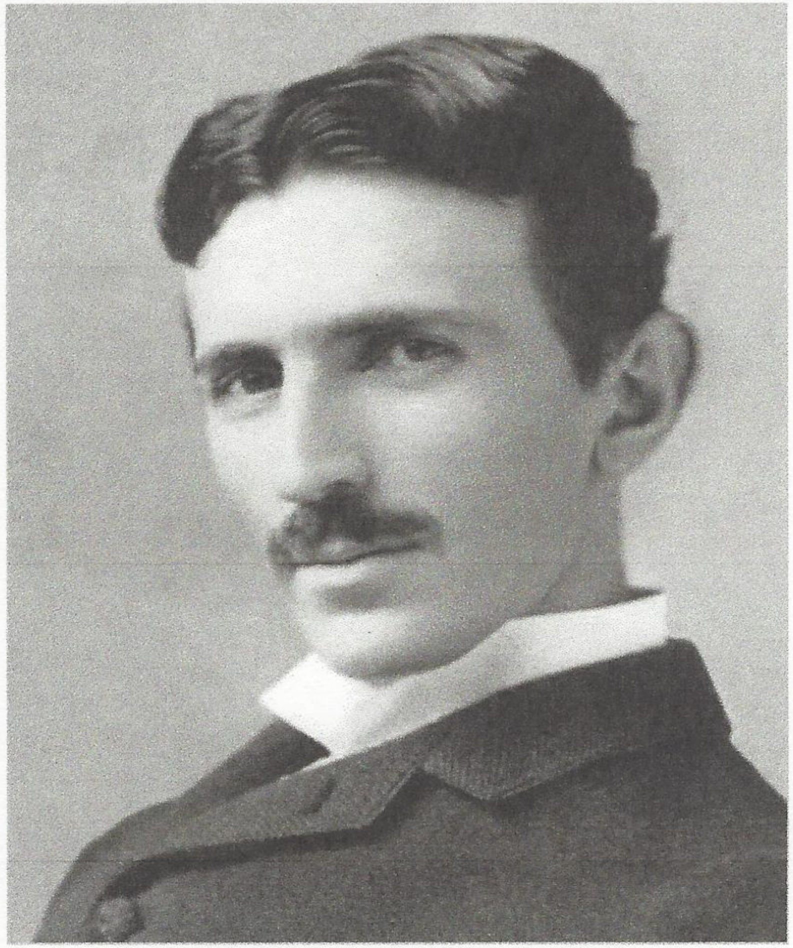


THOMAS EDISON & PHONOGRAPH
1878



NIKOLA TESLA

Nikola Tesla



Napoleon Sarony via Wikimedia Commons

TESLA X-RAY 1896

BUT HE LOST INTEREST.
RONTGEN GOT THE CREDIT.

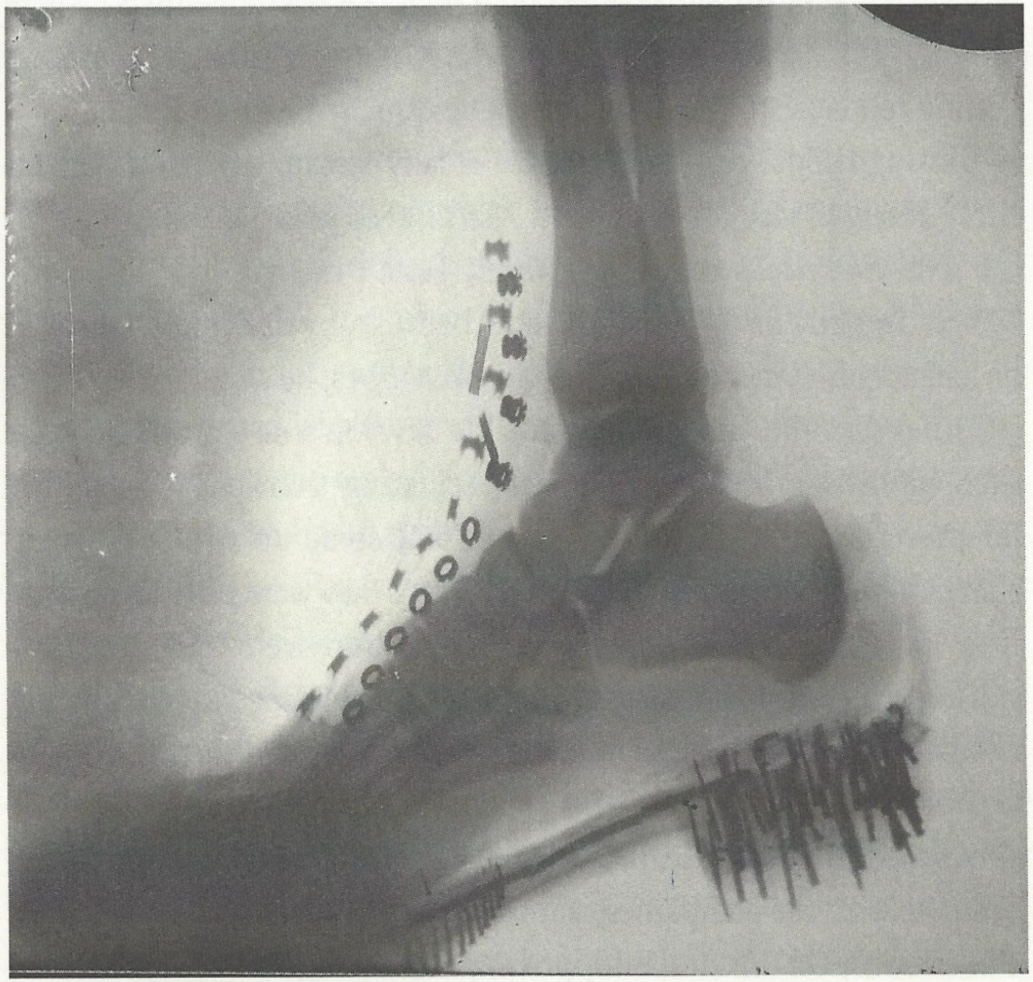


FIGURE 12.3. Shadowgraph made by Tesla of a human foot in a shoe in 1896. From NTM.