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The History And Technical Evolution Of High Frequency Fluorescent Lighting

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December 1977

Lawrence Berkeley Laboratory University of California/Berkeley

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for the

Energy Efficient Lighting Program

Lawrence Berkeley Laboratory

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NOTICE

THE HISTORY AND TECHNICAL EVOLUTION

OF

HIGH FREQUENCY FLUORESCENT LIGHTING

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I N D E X

THE HISTORY AND TECHNICAL EVOLUTION OF HIGH FREQUENCY LIGHTING

BY JOHN H. CAMPBELL

PREPARED FOR THE LAWRENCE BERKELEY LABORATORIES
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INTRODUCTION OF THE FLUORESCENT LAMP

BEFORE PURSUING THE HISTORY OF HIGH FREQUENCY LIGHTING IT SEEMS APPROPRIATE TO BRIEFLY REVIEW THE INTRODUCTION OF THE FLUORESCENT LAMP AND THE IMPACT THIS NEW LIGHT SOUCRCE HAS HAD ON THE LIGHTING INDUSTRY.

PRIOR TO THE INTRODUCTION OF THIS LAMP AS A PRODUCT, MANY TESTS WERE MADE IN THE LABORATORY, ENGINEERING SECTION AND PILOT MANUFACTURING FACILITIES. THE FIRST APPLICATION OF THE FLUORESCENT LAMP WAS A TEST INSTALLATION IN THE NEW YORK CENTRAL 20TH CENTURY LIMITED SIGN LOCATED ON THE REAR END OBSERVATION CAR. THE EIGHT 18" 15 WATT, 1" DIAMETER LAMPS WERE LOCATED BEHIND AN OPAL GLASS COVER PLATE AND COULD NOT BE SEEN. THIS TEST WAS CARRIED ON SECRETLY FOR SEVERAL MONTHS WITH THE WRITER GOING TO THE COLLINWOOD TRAIN YARD TO INSPECT THE LAMPS AND MEASURE THE BRIGHTNESS OF THE SIGN 2 OR 3 TIMES PER WEEK AS THE TRAIN STOPPED IN CLEVELAND TO CHANGE ENGINE CREWS.

THIS APPLICATION WAS THOUGHT TO BE THE MOST SEVERE FROM THE STANDPOINT OF VIBRATION, SHOCK AND TEMPERATURE VARIATION. HOWEVER, THE LAMPS, BALLASTS AND 60 CYCLE M.G. SET STOOD UP WELL AND THE SIGN OPERATED FOR MANY YEARS ON THE CHICAGO TO NEW YORK RUN.

THE FIRST PUBLIC APPLICATION WAS MADE AT THE 1939 NEW YORK WORLD'S FAIR FOLLOWING THE ANNOUNCEMENT OF THE FLUORESCENT LAMP EARLIER THAT YEAR.

IT WILL BE SURPRISING TO MANY PEOPLE TO LEARN THAT THIS LIGHT SOURCE WAS FIRST DESIGNED FOR USE IN ARCHITECTURAL LIGHTING AS THE MOST EFFICIENT WAY TO PRODUCE COLORS OF LIGHT. THE LAMPS FIRST ANNOUNCED WERE AVAILABLE IN BLUE, GREEN, PINK, RED, GOLD AND WHITE. INCANDESCENT LAMPS OF VARIOUS COLORS REQUIRED A FILTER IN THE FORM OF A COLOR COATING OVER THE BULB, PERMITTING ONLY THAT NARROW BAND OF THE FILAMENT SPECTRUM TO BE TRANSMITTED AND ABSORBING A LARGE PERCENTAGE OF ALL OTHER PARTS OF THE SPECTRUM AS HEAT. FLUORESCENT LAMPS PRODUCE COLOR IN A POSITIVE MANNER BY SELECTION OF THE APPROPRIATE PHOSPHOR. THE GOLD AND RED COLORS USE SUPERFICIAL COATINGS, BUT STILL PRODUCE THE COLOR AT MANY TIMES THE EFFICIENCY OF INCANDESCENT LAMPS. APPLICATIONS FOR THE FLUORESCENT COLORS WERE THOUGHT TO BE PREDOMINATELY IN THE DECORATIVE LIGHTING FIELD AS WELL AS THEATER MARQUEES, DEPARTMENT STORES, LIGHTED DISPLAYS ETC.

THE WHITE LAMP WAS MADE BY MIXING THREE COMPONENTS OF PHOSPHOR. THIS LAMP WAS INITIALLY EARMARKED FOR USE IN RAILWAY PASSENGER CARS. A LARGE NUMBER OF COACHES AND PULLMAN CARS WERE CONVERTED TO FLUORESCENT LIGHTING USING A 15", 14 WATT 1½" DIAMETER LAMP DESIGNED TO MATCH THE REQUIREMENTS OF THEIR 64 AND 32 VOLT D.C. POWER SYSTEM. IT IS INTERESTING TO NOTE THAT THE TRAIN LIGHTING SYSTEM USED A SMALL FILAMENT LAMP AS A BALLAST AND REGULATOR AND STARTING WAS ACCOMPLISHED BY MEANS OF A PREHEAT MAGNETIC STARTER WHICH PROVIDED HIGH FREQUENCY COMPONENTS TO INITIATE THE IONIZATION IN THE LAMP.

DURING THE FIRST FEW MONTHS AFTER THE PRODUCT ANNOUNCEMENT THE VARIOUS COLORED LAMPS WERE IN GREATEST DEMAND. HOWEVER, AT THE END OF THE FIRST YEAR, WHITE LAMPS HAD TAKEN OVER THE LEAD AND BY 1957, THE PRODUCTION OF ALL COLORED LAMPS REPRESENTED ONLY 1% OF THE FLUORESCENT PRODUCTION.

THE IMPACT OF THE FLUORESCENT LAMP AS A LIGHT SOURCE FOR GENERAL ILLUMINATION WAS QUITE DRAMATIC. THE HIGHER EFFICIENCY, LONGER LIFE LAMP PROVIDED THE INCENTIVE FOR INCREASED ILLUMINATION LEVELS, WITH LOWER GLARE RATIOS, BETTER DISTRIBUTION AND LESS HEAT.

INITIALLY THE LAMP WAS A LITTLE OVER TWO TIMES THE EFFICIENCY AND ABOUT DOUBLE THE LIFE OF FILAMENT LAMPS OF EQUAL LUMEN OUTPUT. OVER THE YEARS IMPROVEMENTS IN LAMP DESIGN HAVE INCREASED THESE RATIOS TO 4 TIMES THE EFFICIENCY ON AN EQUAL LIGHT OUTPUT BASIS AND 7 TIMES ON AN EQUAL WATTAGE BASIS. THE LIFE RATIO HAS BEEN EXTENDED TO FROM 8 TO 26 TIMES, DEPENDING ON THE DESIGN LIFE OF THE INCANDESCENT LAMPS.

THE GENERAL REACTION TO THE ANNOUNCEMENT OF THE FLUORESCENT LAMP WAS POSITIVE AND ENTHUSIASTIC PARTICULARLY IN COMMERCIAL AND INDUSTRIAL LIGHTING WHERE INCREASES IN LIGHTING LEVELS WERE BADLY NEEDED. ANY NEGATIVE REACTIONS BASED ON THE APPREHENSION THAT THE NEW LAMP WOULD REPLACE FILAMENT LAMPS ON A LAMP FOR LAMP BASIS WAS SHORT LIVED DUE TO THE DEMAND FOR MUCH HIGHER ILLUMINATING LEVELS THAN COULD BE OBTAINED COMFORTABLY WITH INCANDESCENT LAMPS AND THE SUBSEQUENT INCREASE IN LOAD LEVELS TO MEET THE SPECIFICATIONS. TODAY IT IS ESTIMATED THAT 2/3 OF ALL LIGHTING IN THE UNITED STATES IS FURNISHED BY FLUORESCENT LAMPS.

CIRCUITS AND BALLASTS FOR FLUORESCENT LAMPS

SINCE THE FLUORESCENT LAMP IS ESSENTIALLY A MERCURY VAPOR DISCHARGE DEVICE, IT DEVELOPES A NEGATIVE RESISTANCE CHARACTERISTIC AND MUST HAVE A BALLAST IN THE FORM OF A CURRENT CONTROL. THE EARLY BALLASTS PROVIDED INSTANT STARTING BY APPLYING A SUFFICIENTLY HIGH VOLTAGE TO IONIZE THE ARGON FILLING GAS IN THE LAMP AND EVENTUALLY PRODUCING A 'HOT SPOT' BY BOMBARDMENT OF THE EMISSION MATERIAL OF THE CATHODES. ELECTRON EMISSION DEVELOPED BY THE 'HOT SPOT' THEN SUPPORTED THE STEADY STATE ARC. IT WAS SOON DISCOVERED THAT THIS 'BRUTE FORCE' METHOD OF STARTING RESULTED IN A SHORTER LAMP LIFE THAN THE SAME CATHODE WHICH COULD BE PREHEATED TO PROVIDE THERMAL EMISSION AND COINCIDENTALLY REDUCE VOLTAGE REQUIRED TO START THE LAMP. AN INSTANT START LAMP WAS DESIGNED BY APPLYING A FINE WIRE, 'OVERWIND' TO THE CATHODE TO FACILITATE FORMATION OF THE 'HOT SPOT' WITHOUT EXCESSIVE BOMBARDMENT. THESE LAMPS ARE STILL AVAILABLE TODAY, BUT DO NOT HAVE MANY APPLICATIONS DUE TO THE LOW EFFICIENCY AND HIGH COST OF THE

INSTANT START BALLAST.

THE FIRST PREHEAT TYPE BALLASTS CONSISTED OF A U-SHAPED CHOKE COIL IN SERIES WITH ONE SIDE OF THE LINE AND THE LAMP. A MAGNETIC STARTING SWITCH WITH NORMALLY CLOSED CONTACTS CONNECTED IN SERIES WITH THE LAMP CATHODES WAS ACTUATED BY ONE LEG OF THE U-SHAPED CORE. WHEN THE LINE SWITCH WAS TURNED ON, THE LAMP CATHODES RECEIVED PREHEAT CURRENT AND THE MAGNETIZED CORE PULLED THE ARM TO OPEN THE STARTING SWITCH CONTACTS, THE LAMP THEN RECEIVED LINE VOLTAGE PLUS AN INDUCTIVE 'KICK' FROM THE CHOKE COIL AND A HIGH FREQUENCY COMPONENT FROM THE VIBRATING CONTACTS WHICH DID NOT STAY OPEN UNTIL THE LAMP WAS OPERATING. THIS METHOD WAS SOON REPLACED BY A SEPARATE MAGNETIC SWITCH HAVING ITS OWN COIL. THEN A FEW MONTHS LATER BY A NORMALLY CLOSED THERMAL SWITCH AND THEN BY THE NORMALLY OPEN GLOW SWITCH STARTER WHICH IS STILL USED TODAY TO START FLUORESCENT LAMPS OF THE 20 WATT SIZE AND SMALLER. THE RAPID START SYSTEM WHICH PROVIDES PREHEAT CURRENT BY MEANS OF CATHODE WINDINGS ON THE BALLAST TRANSFORMER WAS INTRODUCED IN 1948 AND IS NOW THE PREDOMINENT SYSTEM FOR 40 WATT AND HIGH OUTPUT LAMPS.

THE EVOLUTION OF THE BALLAST TOOK PLACE AS FOLLOWS:

1. SINGLE LAMP INSTANT START LOW POWER FACTOR.
2. SINGLE LAMP SWITCH START LOW POWER FACTOR.
3. SINGLE LAMP SWITCH START HIGH POWER FACTOR (SEPARATE CAPACITOR ACROSS LINE)
4. TWO LAMP SWITCH START LEAD LAG SPLIT PHASE HIGH POWER FACTOR.
5. FOUR LAMP SWITCH START SERIES SEQUENCE SPLIT-PHASE HIGH POWER FACTOR.
6. TWO LAMP SWITCH START SERIES SEQUENCE HIGH POWER FACTOR.
7. TWO LAMP RAPID START SERIES SEQUENCE HIGH POWER FACTOR.

THERE ARE MANY ADDITIONAL CIRCUITS AND BALLASTS TO SATISFY[52] SPECIAL APPLICATIONS OF FLUORESCENT LAMPS SUCH AS TRANSPORTATION,

OUTDOOR AND SIGN LIGHTING.[53] DIMMING AND[54] FLASHING OF FLUORESCENT LAMPS ALSO GENERATED NEW CIRCUITS AND BALLASTS TO ADD FLEXIBILITY TO THE FAMILY OF FLUORESCENT LAMPS.

SINCE INCANDESCENT LAMPS HAD NEVER REQUIRED BALLASTS FOR THEIR OPERATION, THE MANUFACTURERS OF LIGHTING FIXTURES AT FIRST CONSIDERED THE BALLAST AS AN UNDESIRABLE APPENDAGE AND A DEVICE TO BE ELIMINATED. IN FACT ONE OF THE STANDARD JOKES CIRCULATED IN THE TRADE WAS THAT IF EDISON HAD INVENTED THE FLUORESCENT LAMP FIRST, THE FILAMENT LAMP WOULD COME ALONG AS A GREAT IMPROVEMENT. SOME ATTEMPTS WERE MADE TO REMOVE THE BALLASTS FROM THE LUMINAIRES OR FIXTURES TO A CABINET, BUT THE ADDITIONAL WIRING MADE THIS SYSTEM TOO COSTLY EXCEPT FOR CRITICAL APPLICATIONS WHERE BALLAST HUM OR HIGH TEMPERATURE AMBIENTS WERE FIRST ORDER PROBLEMS.

FLUORESCENT LAMP MANUFACTURERS CONSIDERED THE BALLAST AS A NECESSARY EVIL BROUGHT ON BY THE BASIC REQUIREMENTS OF THE LAMP. THERE WERE ATTEMPTS BY AT LEAST ONE LAMP MANUFACTURER TO PROVIDE A SELF BALLASTING FLUORESCENT LAMP.[55] A SUCCESSFUL LAMP WAS MADE IN THE 15 WATT SIZE, BUT WAS NOT MARKETED BECAUSE OF COST COMPARED WITH THE CONVENTIONAL LAMP AND THE SOMEWHAT LOWER EFFICIENCY COMPARED TO A SEPARATELY BALLASTED LAMP.

WHEN THE FIRST FLUORESCENT LAMPS WERE MARKETED, THE LAMP DIVISION OF THE GENERAL ELECTRIC CO. ALSO MADE THE BALLASTS. HOWEVER AS PRODUCTION INCREASED TO MEET THE GROWING DEMAND, THE MANUFACTURE OF BALLASTS WERE TURNED OVER TO THE SPECIALTY TRANSFORMER DEPARTMENT AT FT. WAYNE, INDIANA. THE LAMP DIVISION RETAINED A CIRCUIT AND BALLAST LABORATORY TO CONTINUE RESEARCH AND DEVELOPMENT OF THIS PRODUCT TO INSURE IMPROVEMENTS IN BALLASTS AND TO DEVISE NEW METHODS OF OPERATION FOR THE INCREASING NUMBER OF APPLICATIONS OF FLUORESCENT LIGHTING.

A NUMBER OF IMPROVEMENTS WERE MADE AS THE FOREGOING LIST INDICATES. THERE WERE TWO BASIC CIRCUIT CHANGES. THE FIRST CHANGE PROVIDED HIGH POWER FACTOR AND GREATLY REDUCED STROBOSCOPIC EFFECT BY OPERATING ONE LAMP ON A LEAD CIRCUIT USING BOTH INDUCTIVE AND

CAPACITIVE REACTANCE IN SERIES. THE SECOND LAMP OPERATED ON AN INDUCTIVE REACTANCE, THE COMBINATION PRODUCING A SUFFICIENT PHASE DISPLACEMENT TO MAINTAIN A RELATIVELY EVEN ILLUMINATION FROM THE TWO LAMPS.

THE MOST SIGNIFICANT AND THE LAST BASIC CHANGE IN 60HZ MAGNETIC BALLASTS RESULTED FROM THE DESIGN OF THE SEQUENCE STARTING SERIES OPERATING CIRCUIT IN WHICH THE STARTING VOLTAGE WAS APPLIED FIRST TO ONE LAMP AND THEN THE OTHER BY MEANS OF A SHUNT CIRCUIT CONNECTED ACROSS ONE OF THE LAMPS WHICH WERE CONNECTED IN SERIES. WITH THE LAMPS OPERATING IN SERIES THE VOLTAGE DIFFERENCE BETWEEN THE LAMPS AND THE OPEN CIRCUIT VOLTAGE OF THE BALLAST IS GREATLY REDUCED, THUS PERMITTING AN OPTIMUM BALLAST DESIGN FROM THE STANDPOINT OF SIZE, COST AND EFFICIENCY.

THE [56] FIRST SERIES SEQUENCE BALLAST WAS DEVELOPED TO SIMPLIFY BALLASTING FOR SMALL LAMPS SUCH AS THE 14 WATT 15" TYPE. IN THIS DESIGN A SMALL INCANDESCENT LAMP WAS USED AS A BALLAST FOR TWO LAMPS, THE SEQUENCE STARTING ACTION WAS OBTAINED BY MEANS OF A SPECIALLY DESIGNED MANUAL STARTING SWITCH. THIS SYSTEM WAS USED PRIOR TO AND DURING WORLD WAR II WITH APPLICATION IN DESK LAMPS, MIRROR LIGHTING AND PORTABLE FIXTURES.

[57] IN 1941 A MODIFIED VERSION OF THE FIRST SERIES SEQUENCE CIRCUIT WAS DEVELOPED IN WHICH FOUR 100 WATT 60", 2½" DIAMETER FLUORESCENT LAMPS WERE OPERATED WITH 2 LAMPS IN SERIES SEQUENCE ON EACH PHASE OF A LEAD-LAG CIRCUIT. THIS BALLAST SAVED HALF OF THE COPPER AND IRON WHILE REDUCING BALLAST LOSSES BY ABOUT 50%. SIZE AND WEIGHT WERE ALSO CUT IN HALF. DUE TO THE DRAMATIC SAVINGS IN CRITICAL MATERIALS THIS BALLASTING SYSTEM WAS USED IN ALMOST ALL LARGE INDUSTRIAL PLANTS DURING THE WAR AND FOR A NUMBER OF YEARS AFTER THE WAR IN NEW INSTALLATIONS.

AFTER THE WAR THE SERIES SEQUENCE CIRCUIT WAS APPLIED TO THE SLIMLINE LAMP BALLASTS AND SUBSEQUENTLY MOST ALL RAPID START BALLASTS. THE SYSTEM IS NOW STANDARD FOR TWO LAMP MAGNETIC BALLASTS AND IS PRESENTLY BEING APPLIED TO EXPERIMENTAL SOLID STATE HIGH FREQUENCY BALLASTS.

HIGH FREQUENCY SYSTEMS

EARLY DESIGNS

THE DRIVE TO REDUCE CRITICAL MATERIALS LED TO THE INVESTIGATION OF BALLAST AND LAMP BEHAVIOR AT A FREQUENCY OF 400HZ. IN 1941 THE WRITER OBTAINED AN M.G. SET AND MADE SOME TESTS ON MAGNETIC BALLAST DESIGNS TO DETERMINE THE EFFECT ON THE REACTIVE COMPONENTS FOR REDUCTION OF SIZE AND WEIGHT. MEANWHILE THE SMALL LAMPS SUCH AS THE 6 WATT 9", 5/8" DIAMETER LAMPS WERE BEING APPLIED TO THE INSTRUMENT PANELS OF MILITARY AIRCRAFT WHERE 400HZ GENERATORS WERE THE MAIN SOURCE OF POWER. LABORATORY WORK WAS STOPPED DUE TO HIGHER PRIORITY PROJECTS. [1,2] HOWEVER, R. F. HAYES IN A WESTINGHOUSE LABORATORY DOING SIMILAR WORK REPORTED HIS RESULTS IN TWO ILLUMINATING ENGINEERING PAPERS.

HIGH FREQUENCY CHARACTERISTIC STUDY

AFTER THE WAR I RETURNED TO THE LAMP DIVISION AT NELA PARK AND WAS ENCOURAGED BY THE ADMINISTRATION TO CONTINUE WORK ON LAMP SYSTEMS. I CHOSE HIGH FREQUENCY LIGHTING AS A MAJOR PROJECT AND PROCEEDED TO LAUNCH INTO A COMPREHENSIVE STUDY OF LAMP AND BALLAST CHARACTERISTICS OVER A RANGE OF 60 TO 600HZ. [3] RESULTS OF THIS STUDY WERE REPORTED IN A PAPER PRESENTED AT THE NATIONAL TECHNICAL CONFERENCE OF THE ILLUMINATING ENGINEERING SOCIETY IN NEW ORLEANS, LA. IN SEPTEMBER OF 1947.

ALTHOUGH THE TESTS WERE LIMITED TO 2500 HZ IT BECAME EVIDENT THAT THE FLUORESCENT LMAP CHARACTERISTICS WERE ENTIRELY DIFFERENT AT HIGHER FREQUENCIES THAN THE CONVENTIONAL 60HZ. LAMPS WERE HELD AT THEIR 40 WATT RATING OVER THE FREQUENCY RANGE AND ALL OTHER CHARACTERISTICS WERE ALLOWED TO VARY. SOME OF THE BASIC INFORMATION WORTH NOTING AT THIS POINT IS THE INCREASE IN LAMP EFFICIENCY IN LUMENS PER WATT AS FREQUENCY RISES. COINCIDENT WITH THE RISE IN LUMINOUS EFFICIENCY WERE THE CHANGES IN ELECTRICAL CHARACTERISTICS. AS FREQUENCY INCREASED FROM THE 60HZ BASE, LAMP OPERATING VOLTAGE DROPS AT A GREATER RATE THAN THE LAMP CURRENT RISES. WITH A SINE WAVE OF POWER APPLIED, THE APPARENT LAMP POWER FACTOR CHANGES

FROM ABOUT 90% AT 60HZ TO UNITY AT 400HZ AND ALL HIGHER FREQUENCIES. THE SIGNIFICANCE OF THIS CHANGE AS IT AFFECTS LAMP EFFICIENCY WAS SUBSEQUENTLY DISCUSSED IN A LATER PAPER. THE THREE BASIC MEANS OF BALLASTING FLUORESCENT LAMPS AND THE CHARACTERISTICS OF EACH AT VARIOUS FREQUENCIES WERE REPORTED IN THE 1947 PAPER ALONG WITH THEIR CORRESPONDING STARTING AND OPERATING CIRCUITS.

FREQUENCY CONVERSION

DURING THE PRECEDING STUDY, THE WRITER VISITED THE GENERAL ENGINEERING LABORATORY IN SCHENECTADY IN SEARCH OF A NEW AND EFFICIENT FREQUENCY CONVERTER TO PROVIDE POWER FOR TRIAL APPLICATIONS. B.D. BEDFORD OF THAT DEPARTMENT WAS EXPERIMENTING WITH A MAGNETIC FREQUENCY CONVERTER, ORIGINALLY DEVELOPED BY DR. E.F.W. ALEXANDERSON AND A.H. MITTAG. THE CIRCUIT PRODUCED 540HZ BY MEANS OF A RESONSANT CIRCUIT TUNED TO THE 9TH HARMONIC OF THE 60HZ THREE PHASE INPUT. THIS CONVERTER WAS IDEAL FOR FLUORESCENT LIGHTING BECAUSE IT HAD NO MOVING PARTS AND COULD BE TREATED AS A TRANSFORMER.

A PROTOTYPE SAMPLE OF THIS CONVERTER WAS QUICKLY BUILT AND TESTED. [4] A PAPER WAS PRESENTED TO THE NATIONAL ELECTRONICS CONFERENCE IN CHICAGO IN 1947 SHORTLY AFTER THE ILLUMINATING ENGINEERING CONFERENCE. A DEMONSTRATION OF THE MAGNETIC FREQUENCY CONVERTER OPERATING A BANK OF 10 FLUORESCENT LAMPS WAS MADE AT THE N.E.C. DURING THE PRESENTATION OF THE PAPER.

CONSIDERABLE INTEREST WAS SHOWN BY CONSULTING, SYSTEMS AND APPLICATION ENGINEERS IN THIS FORM OF HIGH FREQUENCY LIGHTING AND A CHALLENGE WAS EXTENDED TO ELECTRONICS ENGINEERS TO DEVELOP A SIMILAR NON-MAGNETIC CONVERTER AND IMPROVE THE POWER EFFICIENCY. COINCIDENTALLY, THE BELL LABORATORIES DEMONSTRATED THE FIRST TRANSISTOR AUDIO SYSTEM FOR TELEPHONE CIRCUITS AT THE SAME N.E.C. CONFERENCE.

MARKETING PHILOSOPHY

AFTER THE FIRST COMPREHENSIVE STUDY OF HIGH FREQUENCY OPERATION OF FLOURESCENT LAMPS IT BECAME QUITE OBVIOUS THAT WE WERE REACHING

THE POINT OF DIMINSHING RETURNS INSOFAR AS IMPROVEMENT OF THE CONVENTIONAL 60HZ BALLASTING SYSTEMS WERE CONCERNED. CONSEQUENTLY THE MAIN THRUST FOR IMPROVEMENT IN SYSTEM EFFICIENCY AND A SUBSEQUENT INCREASE IN ILLUMINATION LEVELS WAS THE ACCEPTANCE OF A NEW METHOD FOR OPERATION OF FLUORESCENT LAMPS SUCH AS HIGH FREQUENCY LIGHTING. IN ORDER TO ACHIEVE THE HIGHER LEVELS, OVERALL ECONOMICS BECAME A MOST IMPORTANT FACTOR. [58] IN MOST VISUAL TASKS THE ILLUMINATION LEVELS MUST BE DOUBLED TO PRODUCE SIGNIFICANT IMPROVEMENTS IN SEEING. CONSEQUENTLY ANY PROMOTION OF THE NEW METHOD FOR OPERATING FLUORESCENT LAMPS WAS TIED TO THE USE OF THE HIGH FREQUENCY SYSTEM AS A SALES TOOL FOR THE LIGHTING APPLICATION ENGINEER TO DOUBLE ILLUMINATION LEVELS WITHOUT DOUBLING THE NUMBER OF FIXTURES AND LAMPS. IT IS SIGNIFICANT TO NOTE THAT MOST COMMERCIAL OR INDUSTRIAL APPLICATIONS OF HIGH FREQUENCY LIGHTING DID INCREASE LEVELS TO 100 FOOTCANDLES COMPARED TO 50 TO 60 FOOTCANDLES WITH A COMPARABLE 60HZ FLUORESCENT SYSTEM.

EARLY APPLICATIONS

BY 1950 THE MAGNETIC FREQUENCY MULTIPLIER HAD BEEN DESIGNED AS A PRODUCT TO PROVIDE 5 K.W. OF POWER AT 360HZ. [5] THE FIRST APPLICATION WAS IN A PLANT GROWTH CHAMBER AT THE UNITED STATES DEPARTMENT OF AGRICULTURE IN BELTSVILLE, MD. THIS INSTALLATION PROVIDED AN IDEAL TEST FOR HIGH FREQUENCY LIGHTING AND A SIGNIFICANT COMPARISON WITH A PLANT GROWTH CHAMBER POWERED WITH A CONVENTIONAL 60HZ SYSTEM.

THE 60HZ EXPERIMENTAL PLANT GROWTH CHAMBER PROVIDED A MAXIMUM OF 1600 FOOTCANDLES WITH 120, 96" T-8 (1" DIA.) LAMPS SPACED 2" APART. BALLASTS WERE MOUNTED IN THE HALLWAY BECAUSE THE FIXTURE IN THE GROWTH ROOM WOULD NOT ACCOMMODATE THE SIZE OR WEIGHT OF THE 60HZ BALLASTS. DUE TO THE CLOSE GROUPING OF THE BALLASTS IT WAS NECESSARY TO APPLY A BLOWER TO KEEP BALLAST TEMPERATURES WITHIN SPECIFIED LIMITS. 121 WIRES WERE REQUIRED TO BRING POWER FROM THE BALLASTS TO THE LAMPS. [9] BY WAY OF COMPARISON, THE TWO 5 K.W. 360HZ MAGNETIC FREQUENCY MULTIPLIERS PROVIDED A RANGE OF 1600 TO 2400 FOOTCANDLES WITH A SINGLE CURRENT CONTROL KNOB. THE POWER

SUPPLIES WERE LOCATED IN THE TRANSFORMER VAULT AND ONLY 2 WIRES WERE REQUIRED TO BRING POWER TO THE 120 LAMPS IN THE GROWTH CHAMBER.

WHILE THE PLANT GROWTH INSTALLATION WAS A SPECIAL APPLICATION, AND THE COST OF THE CONVERTER WAS INITIALLY $490 PER K.W., IT WAS EXPECTED THAT THE COST PER K.W. WOULD BE MATERIALLY REDUCED WITH HIGHER PRODUCTION AND LARGER SIZES (25 TO 50 K.W.). HOWEVER, THIS DID NOT MATERIALIZE AND APPLICATIONS REMAINED IN THE PLANT GROWTH FIELD IN GOVERNMENT AND UNIVERSITY AGRICULTURE DEPARTMENTS.

THE CASE FOR HIGH FREQUENCY LIGHTING

IN REVIEWING THE HISTORY OF HIGH FREQUENCY LIGHTING IT MUST BE REMEMBERED THAT THE TECHNOLOGY WAS NOT YET AVAILABLE TO PRODUCE THE DESIRED FREQUENCY WITHIN INDIVIDUAL BALLASTS OR FIXTURES. CONSEQUENTLY MOST OF THE DESIGN EFFORTS WERE CONCENTRATED ON CENTRAL OR BRANCH CIRCUIT POWER SUPPLIES. ALSO FROM THE STANDPOINT OF THE COST OF LIGHTING, THE LARGER THE CONVERTER, THE LOWER THE COST PER K.W. AND THE HIGHER THE POWER EFFICIENCY.

[6]A PAPER GIVING NEW INFORMATION ON LAMP AND BALLAST CHARACTERISTICS WAS PRESENTED AT THE NATIONAL TECHNICAL CONFERENCE OF THE ILLUMINATING ENGINEERING SOCIETY IN CHICAGO IN SEPTEMBER OF 1952. RESEARCH AND DEVELOPMENT WORK TO DATE HAD REVEALED THE FOLLOWING GENERAL ADVANTAGES FOR HIGH FREQUENCY LIGHTING COMPARED TO CONVENTIONAL SYSTEMS:

1. INCREASED LAMP EFFICIENCY
2. INCREASED BALLAST EFFICIENCY (LOWER BALLAST LOSSES)
3. REDUCED BALLAST HUM
4. REDUCED BALLAST WEIGHT
5. REDUCED BALLAST SIZE
6. CAPACITOR BALLAST PRACTICAL TO USE
7. INCREASED LUMENS PER FOOT OF LAMP
8. HIGHER LIGHTING LEVELS OR FEWER FIXTURES FOR EQUAL MAINTAINED FOOTCANDLES
9. STROBOSCOPIC EFFECT REDUCED OR ELIMINATED DEPENDING UPON FREQUENCY
10. HIGHER VOLTAGE, LOWER COST DISTRIBUTION SYSTEMS.

11. RADIO INTERFERENCE GENERATED BY LAMP GREATLY REDUCED

DURING THE DISCUSSION OF THE 1952 PAPER, "CHARACTERISTICS AND APPLICATIONS OF HIGH FREQUENCY LIGHTING", *DOMINA EBERLE SPENCER HAD THE FOLLOWING TO SAY IN PART; "IF I HAD SUFFICIENT TIME, I WOULD LIKE TO GO MUCH FURTHER THAN CAMPBELL, SCHULTZ AND KERSHAW HAVE IN MAKING A STRONG CASE FOR USING HIGH FREQUENCY FLUORESCENT LIGHTING TODAY. IT IS TIME THE ILLUMINATING ENGINEER LEARNED TO DESIGN ELECTRIC CIRCUITS TAILORED FOR THE FLUORESCENT LAMP, JUST AS HE HAS LEARNED TO DESIGN FLUORESCENT LUMINAIRES BY NEW METHODS NOT REQUIRED IN THE DAYS WHEN INCANDESCENT LIGHTING WAS THE ONLY POSSIBILITY FOR MOST APPLICATIONS." "I THINK THERE IS A STRONG CASE FOR INTRODUCTION OF THE HIGH FREQUENCY FLUORESCENT ON A PURELY ECONOMIC BASIS IF THE PROBLEM IS THOROUGHLY ANALYZED."

**MR. G.C. HARVEY MADE THE FOLLOWING COMMENTS IN PART OF HIS DISCUSSION; "MANY PEOPLE HAVE ASKED HOW SOON BALLAST MANUFACTURERS WILL BE OUT OF BUSINESS." "BUT CERTAINLY, OUR CODE PROVIDES THAT WE WILL DO OUR BEST TO FURNISH BETTER LIGHT AT LOWER COST TO THE USER." "FOR THIS REASON, EFFORT IS BEING PLACED ON THIS SYSTEM AND NO DOUBT IMPROVEMENT IN COSTS WILL BE MADE. AT THE SAME TIME, THE DEVELOPMENT EFFORT BEING EXPENDED ON THE CONVENTIONAL SYSTEM WILL ALSO YIELD ADDITIONAL BENEFITS."

THE ONLY FREQUENCY CONVERTER DESIGNED SPECIFICALLY FOR USE WITH FLUORESCENT LAMPS AT THE TIME OF THE 1952 PAPER WAS THE MAGNETIC FREQUENCY MULTIPLIER. THIS DEVICE PRODUCED A TRIANGULAR VOLTAGE WAVE AT 360HZ. WHEN COMBINED WITH INDIVIDUAL CAPACITOR BALLASTS A NEARLY SQUARE LAMP CURRENT WAVE FORM WAS PRODUCED. SINCE THIS WAS IDEAL FROM THE STANDPOINT OF FLUORESCENT LAMP OPERATION, A CONSIDERABLE PART OF THE PAPER WAS DEVOTED TO LAMP AND BALLAST CHARACTERISTICS WITH LAMPS OPERATING ON A 360HZ SQUARE CURRENT WAVE FORM.

*UNIVERSITY OF CONNECTICUT, STORRS, CONN.

** GENERAL ELECTRIC CO. SPECIALTY TRANSFORMER AND BALLAST DEPT., FT. WAYNE, INDIANA

THE 5 K.W. MAGNETIC FREQUENCY MULTIPLIER WAS DEVELOPED BY GENERAL ENGINEERING IN SCHENECTADY, BUT WAS DESIGNED AND MANUFACTURED BY THE SPECIALTY TRANSFORMER AND BALLAST DEPT. AT FT. WAYNE, INDIANA. COST PER K.W. WAS SUBSEQUENTLY REDUCED BY MAKING THE CONVERTER IN 25 K.W. UNITS. HOWEVER, THE COST REDUCTION WAS NOT SUFFICIENT TO BE COMPETITIVE WITH CONVENTIONAL SYSTEMS ON THE BASIS OF INITIAL COSTS FOR GENERAL LIGHTING. THE MAIN ADVANTAGES IN THE USE OF THIS HIGH FREQUENCY SYSTEM WERE, THE REDUCTION IN THE NUMBER OF FIXTURES FOR EQUAL MAINTAINED FOOTCANDLES, REMOVAL OF THE BALLAST LOSSES AND BALLAST WEIGHT FROM THE FIXTURE, CAPACITOR LIGHT WEIGHT LOW LOSS BALLASTS, LOW AUDIBLE NOISE, HIGH VOLTAGE LOW COST DISTRIBUTION, AND NO STROBOSCOPIC EFFECT.

UNFORTUNATELY THE FIRST COST OF THE INSTALLATION WAS SLIGHTLY HIGHER THAN THE CONVENTIONAL SYSTEM AND THIS RELEGATED THE MAGNETIC FREQUENCY MULTIPLIER TO SPECIAL APPLICATIONS, MOST OF THEM PLANT GROWTH.

THE MOTOR-GENERATOR FREQUENCY CONVERTER

IN ORDER TO OBTAIN A LOW COST CONVERTER, THE OLD RELIABLE MOTOR GENERATOR SET WAS CONSIDERED. TESTS WERE MADE IN THE LABORATORY USING M.G. SETS WITH THREE PHASE 240 VOLT INPUTS AND AN OUTPUT OF 600 VOLTS (300 VOLTS TO GROUND). POWER FREQUENCIES TESTED WERE 420, 840, 1000 AND 10,000HZ.

WHILE IT WAS DESIRABLE TO USE THE HIGHEST FREQUENCY, IT WAS SOON DISCOVERED THAT THE LOWEST OVERALL COST OF LIGHT FAVORED THE 420HZ M.G. SET BECAUSE IT BECAME A STANDARD DEVICE DURING WORLD WAR II AND WAS IN FAIRLY HIGH PRODUCTION. THE COST PER K.W. OF A 420HZ, 100 K.W. FREQUENCY CONVERTER WAS UNDER $100/K.W.

AFTER CONSIDERABLE LABORATORY TESTING, A NEW FIELD HOUSE AT UNION COLLEGE IN SCHENECTADY BECAME THE NATION'S FIRST LARGE SCALE APPLICATION OF HIGH FREQUENCY LIGHTING OF A LARGE AREA. THIS INSTALLATION WAS NOT SUBSIDIZED, BUT WAS PURCHASED BY UNION COLLEGE ON ITS OWN MERITS AFTER CAREFUL CONSIDERATION BY THE ARCHITECTS. THE ORIGINAL SYSTEM FIRST CONSIDERED, USED A COMBINA-

TION INCANDESCENT AND MERCURY LAMP HIGH BAY LIGHTING WHICH WOULD HAVE PRODUCED 38 FOOTCANDLES. THE HIGH FREQUENCY SYSTEM PROVIDED 46 FOOTCANDLES AT AN INITIAL COST OF 10% LESS AND A SUBSTANTIAL SAVINGS IN ANNUAL OPERATING AND MAINTENANCE COSTS. DUE TO THE LIGHT WEIGHT CAPACITOR AND CHOKE BALLASTS, THE 35 FIXTURES IN THE INSTALLATION EACH CONTAINED 14, 96", 1½" DIAMETER FLUORESCENT LAMPS. THIS APPLICATION IS DESCRIBED IN DETAIL BY TWO PAPERS. [8]THE FIRST PRESENTED TO THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS IN CHICAGO ON OCTOBER 11, 1954 AND THE SECOND AN [10]ARTICLE BY BERLON C. COOPER PUBLISHED IN ELECTRICAL CONSTRUCTION AND MAINTENANCE FOR JUNE 1955 WITH THE TITLE "HI-CYCLE LIGHTING COMES OF AGE."

400HZ APPLICATIONS

AFTER THE INITIAL INSTALLATION AT THE UNION COLLEGE FIELD HOUSE, 400HZ LIGHTING WAS SPECIFIED AS A COMPLETE SYSTEM ALONG WITH THE 360HZ MAGNETIC FREQUENCY MULTIPLIER. THE SYSTEMS WERE DESCRIBED IN DETAIL INCLUDING COMPARATIVE COST DATA. IN ONE ANALYSIS OF A LARGE INDUSTRIAL PLANT THE 400HZ SYSTEMS SHOWED INITIAL, OPERATING AND TOTAL ANNUAL COSTS OF 68%, 90% AND 78% RESPECTIVELY WHEN COMPARED TO THE 60HZ BASE SYSTEM. THE SOURCE OF THIS INFORMATION WAS THE GENERAL ELECTRIC 20 PAGE BULLETIN GEA-6559 TITLED "GENERAL ELECTRIC HIGH FREQUENCY FLUORESCENT LIGHTING SYSTEMS." PUBLISHED IN OCTOBER 1958. ADDITIONAL FIELD HOUSE APPLICATIONS QUICKLY FOLLOWED. NOTABLE AMONG THEM ARE THE [23]UNIVERSITY OF NEW MEXICO FIELD HOUSE AND THE CAMDEN NEW JERSEY CONVENTION HALL. A CONSIDERABLE NUMBER OF INDUSTRIAL PLANTS WERE LIGHTED BY 400HZ SYSTEMS. IT WAS ESTIMATED THAT OVER 2000 K.W. OF HIGH FREQUENCY LIGHTING WAS INSTALLED IN THE FOUR YEARS AFTER THE UNION COLLEGE APPLICATIONS. [13-15]IN ADDITION THE WAKEFIELD BRASS COMPANY INTRODUCED AN 840HZ LIGHTING SYSTEM AND A NUMBER OF COMMERCIAL AND INDUSTRIAL INSTALLATIONS WERE MADE USING A COMPARATIVELY LOW COST "NO BRUSH" MOTOR GENERATOR FREQUENCY CONVERTER.

[11-12]THE SUCCESS OF THE 400HZ AND 840HZ SYSTEMS CAME FROM THE FAVORABLE OVERALL ECONOMICS AND THE FLEXIBILITY OF THE SYSTEM.

LAMPS COULD BE OPERATED AT A HIGHER LEVEL OF CURRENT, PRODUCING MORE LIGHT WITH THE SAME NUMBER OF FIXTURES AS A 60HZ SYSTEM OR THE SAME LIGHT OUTPUT WITH FEWER FIXTURES. CAPACITOR BALLASTS WEIGHING ONLY A FEW OUNCES COMBINED IN SOME INSTALLATIONS WITH SMALL LIGHT WEIGHT INDUCTANCE BALLASTS, PRODUCED A UNITY POWER FACTOR LOAD. THIS TOGETHER WITH A 600 VOLT OUTPUT (300 VOLTS TO GROUND) MADE A LOW COST DISTRIBUTION SYSTEM. IN PLANNING A NEW BUILDING WITH CONTINUOUS ROW FIXTURES, THE LIGHT WEIGHT BALLASTS PERMITTED A LESS RUGGED LOWER COST ROOF STRUCTURE. THE QUALITY OF ILLUMINATION WAS ALSO IMPROVED WITH THE HIGH FREQUENCY SYSTEM DUE TO THE GREATLY REDUCED STROBOSCOPIC EFFECT.

SEMI-CONDUCTOR DEVICES

AT THE TIME OF THE ANNOUNCEMENT OF THE SILICON CONTROLLED RECTIFIER AND THE POWER TRANSISTOR (1957-58) THERE WAS A BACKLOG OF REQUESTS FOR 400HZ LIGHTING SYSTEMS. MANY OF THESE PLANS AND CORRESPONDING INSTALLATIONS WERE DROPPED, PRESUMABLY TO WAIT FOR SOLID STATE FREQUENCY CONVERTERS WITH THEIR INHERENT HIGHER EFFICIENCY. THE SILICON CONTROLLED RECTIFIER WITH ITS LARGE CURRENT SWITCHING, CAPABILITY AND HIGH VOLTAGE RATING, MADE POSSIBLE THE DESIGN OF A FREQUENCY CONVERTER WITHOUT MOVING PARTS WHICH COULD DELIVER HIGH FREQUENCY POWER AT EFFICIENCIES IN THE RANGE OF 85 TO 92%.

THE POWER TRANSISTOR WHEN ANNOUNCED WAS ESSENTIALLY A LOW CURRENT, LOW VOLTAGE DEVICE. HOWEVER, CIRCUITS USING POWER TRANSISTORS FOR FREQUENCY CONVERTERS REQUIRED FEWER COMPONENTS THAN THE S.C.R. CIRCUITS AND WERE CAPABLE OF SWITCHING TO MUCH HIGHER FREQUENCIES.

POWER TRANSISTOR INVERTERS

THE WRITER AND HIS ASSOCIATES UNDER AUSPICES OF THE LAMP DIVISION OF GENERAL ELECTRIC, STARTED DEVELOPING INVERTER AND FREQUENCY CONVERTER CIRCUITS AS SOON AS POWER TRANSISTORS AND SILICON CONTROLLED RECTIFIERS WERE AVAILABLE. THESE TWO HIGH FREQUENCY SYSTEM DEVELOPMENTS WERE CARRIED ON CONCURRENTLY.

[28] A PAPER PRESENTED AT THE NATIONAL TECHNICAL CONFERENCE OF

THE ILLUMINATING ENGINEERING SOCIETY IN SEPTEMBER OF 1959 PROVIDES A PROGRESS REPORT FOR THE PLANNERS OF HIGH FREQUENCY FLUORESCENT LIGHTING SYSTEMS. INCLUDED IN THIS PAPER IS A DESCRIPTION OF A BASIC PARALLEL INVERTER CIRCUIT FOR S.C.R.'S AND 3 PROPOSED HIGH FREQUENCY POWER SYSTEMS TO COVER VARIOUS SIZES OF INSTALLATIONS FOR GENERAL LIGHTING.

THE INFORMATION ALSO INCLUDES A DESCRIPTION OF A 3000HZ POWER TRANSISTOR INVERTER DEVELOPED AND BUILT IN THE WRITER'S LABORATORY. THE SYSTEM WAS DESIGNED FOR BUS LIGHTING AND A PROTOTYPE INSTALLED IN A CLEVELAND RAILWAY BUS. THE LIGHTING SYSTEM PROVIDED 25 TO 35 FOOTCANDLES, OF EVENLY DISTRIBUTED ILLUMINATION, COMPARED TO 4 TO 12 FOOTCANDLES FOR THE INCANDESCENT SYSTEM IT REPLACE. THE LOCATION OF THE INVERTER IN A COMPARTMENT UNDER THE BUS PROVIDED A GOOD TEST TO DETERMINE TRANSISTOR AND COMPONENT RELIABILITY FOR POSSIBLE GENERAL LIGHTING SERVICE. THE INVERTER HAD A POWER EFFICIENCY OF 88% AT THE FULL LOAD OF 500 WATTS AND TODAY, WOULD BE ABOUT 92% WITH OUR PRESENT TRANSISTORS. A LARGE PERCENTAGE OF CITY TRANSIT BUSES ARE NOW EQUIPPED WITH HIGH FREQUENCY FLUORESCENT LIGHTING ON A SOMEWHAT LOWER LEVEL OF ILLUMINATION THAN PRODUCED BY OUR PROTOTYPE.

POWER TRANSISTORS AVAILABLE AT THAT TIME HAD MAXIMUM VOLTAGE RATINGS OF 40 VOLTS WHERE A MINIMUM RATING OF 400 VOLTS WOULD BE REQUIRED FOR AN INVERTER WITH A 120V, 60HZ INPUT.

[24-29] WESTINGHOUSE ATTEMPTED TO CIRCUMVENT THIS VOLTAGE DEFICIENCY AND DID BY OPERATING 10 POWER TRANSISTORS IN A SERIES PARALLEL CIRCUIT. THE RESULTING INVERTER OPERATED WITH CONVENTIONAL VOLTAGE AND FREQUENCY INPUT WITH AN OUTPUT OF 1500HZ. A MULTI-KILLOWATT PROTOTYPE INSTALLATION WAS MADE. ONE OF THE PROBLEMS WITH SERIES CONNECTED POWER TRANSISTORS IS THE CASCADE FAILURE OF TRANSISTORS WHERE AN UNUSUALLY HIGH VOLTAGE TRANSIENT APPEARS ACROSS THE ARRAY OF TRANSISTORS.

THE FIRST LIGHTING APPLICATION FOR THE LOW VOLTAGE POWER TRANSISTORS WAS THE OPERATION OF LOW WATTAGE FLUORESCENT LAMPS ON 12 VOLT INVERTERS.

A SINGLE TRANSISTOR INVERTER CIRCUIT DEVELOPED BY THE WRITER WAS THOROUGHLY TESTED IN THE LABORATORY. THE CIRCUIT WAS CHARACTERIZED BY ITS SIMPLICITY AND THE LOW COMPONENT COUNT COMPARED TO MORE COMPLEX INVERTER CIRCUITS. OUTPUT FREQUENCY IS LIMITED ONLY TO THE SWITCHING SPEED OF THE TRANSISTOR AND THE PRACTICAL LIMITS IMPOSED BY THE INTENDED APPLICATION. TRANSISTOR CHARACTERISTICS LIMITED THE PROTOTYPE DEVICES TO AROUND 15KHZ.

[39-59]THE CIRCUIT WAS PUBLISHED IN 1963 AND GENERAL ELECTRIC MADE THE DESIGN DATA AVAILABLE TO MANUFACTURERS OR OTHERS DESIRING IT.

APPLICATIONS AT FIRST CENTERED AROUND PORTABLE LAMPS, SUCH AS HAND LANTERNS OPERATING 4, 6 OR 8 WATT FLUORESCENT LAMPS. OTHER PROJECTED APPLICATIONS SUCH AS EMERGENCY, RAILWAY, TRAVEL TRAILERS, BUSES, BOATS, BUG TRAPS, ULTRAVIOLET EQUIPMENT AND MANY OTHERS SOON MATERIALIZED.

THIS BASIC CIRCUIT AND MODIFICATIONS OF IT IS IN GENERAL USE, WITH THE HIGH VOLUME PRODUCT, THE HAND LANTERN NOW NUMBERING IN THE MILLIONS.

[60]THE SAME INVERTER CIRCUIT WAS UTILIZED TO OPERATE SPECIAL HIGH OUTPUT FLUORESCENT LAMPS IN THE ORBITAL SKYLAB. THE INVERTER BALLAST CIRCUIT PROVIDES POWER AT 20KHZ TO EACH PAIR OF LAMPS CONNECTED IN A SEQUENCE STARTING SERIES OPERATING CIRCUIT. EACH LAMP IS 15" LONG WITH A DIAMETER OF 1" AND OPERATES AT 28 WATTS. [61]A SIMILAR INSTALLATION IS NOW BEING PLANNED FOR THE SPACE SHUTTLE ORBITER INTERIOR CABIN ILLUMINATION.

[46]A PAPER PRESENTED TO THE ILLUMINATING ENGINEERING SOCIETY IN 1966 PROVIDES COMPREHENSIVE DATA ON THE INVERTER CIRCUIT AND LAMP CHARACTERISTICS FOR A VARIETY OF APPLICATIONS.

SILICON CONTROLLED RECTIFIER FREQUENCY CONVERTER

THE NEED FOR AN EFFICIENT STATIC HIGH FREQUENCY POWER SUPPLY FOR FLUORESCENT LAMPS PROVIDED THE INCENTIVE FOR A MAJOR EFFORT TO UTILIZE THE NEWLY ANNOUNCED S.C.R. THE WRITER AND HIS ASSOCI-

DEVELOPED AN S.C.R. CIRCUIT CAPABLE OF DELIVERING LARGE BLOCKS OF POWER FOR POTENTIAL USE AS A CENTRAL SUPPLY FOR EACH FLOOR OF AN OFFICE BUILDING OR AS A LOAD CENTER SUPPLY IN AN INDUSTRIAL PLANT. THE FIRST PROVIDED 5 K.W. TO A BANK OF POWER GROOVE FLUORESCENT LAMPS. THE FIRST S.C.R.'S WERE LIMITED IN SWITCHING SPEED SO THE EARLY EXPERIMENTAL CONVERTER HAD AN OUTPUT OF 1500HZ. LATER DESIGNS WERE SUFFICIENTLY IMPROVED IN DV/DT TO JUSTIFY A CONVERTER DESIGN WITH AN OUTPUT OF 3000HZ. THE DEVELOPMENT WORK WAS COMPLETED IN 1963 AND THE DATA TURNED OVER TO THE SWITCHGEAR DEPARTMENT OF GENERAL ELECTRIC FOR DESIGN AND PRODUCTION.

THE PACKAGED CONVERTER WHICH EMERGED FROM THIS DEVELOPMENT, CONVERTED 60HZ, THREE PHASE 208 OR 230 VOLT POWER TO 20 K.W. OF 3000 CYCLE SINGLE PHASE POWER.

IT WAS DECIDED TO APPLY THE NEW HIGH FREQUENCY SYSTEM FIRST TO COMMERCIAL LIGHTING IN DIRECT COMPETITION WITH THE ESTABLISHED 40 WATT CONVENTIONAL 60HZ LIGHTING. THE PIONEER APPLICATIONS WERE MADE ON A SYSTEM INSTALLATION APPROACH IN WHICH ALL COMPONENTS WERE SPECIFIED AND INSTALLED IN ACCORDANCE WITH INSTRUCTIONS PROVIDED BY A SYSTEMS ENGINEER.

AT FIRST CONVERTERS WERE AVAILABLE IN 20 K.W. SIZES ONLY, BUT WERE LATER DESIGNED FOR A 40 K.W. CAPACITY. POWER EFFICIENCY IS OVER 90%, WITH A WEIGHT OF 25 LBS. PER K.W. COMPARED TO 72% AND 240 LBS. PER K.W. FOR ITS PREDECESSOR, THE MAGNETIC FREQUENCY MULTIPLIER. BALLASTS FOR THE SYSTEM WERE FOUR LAMP 40 WATT RAPID START USING SIMPLE CAPACITOR BALLASTS OPERATING EACH PAIR OF LAMPS IN A SERIES SEQUENCE CIRCUIT WITH A 3000HZ PREHEAT TRANSFORMER.

[42-43] A PAPER PRESENTED TO THE ILLUMINATING ENGINEERING SOCIETY IN 1964, DELINEATED THE ELECTRICAL CHARACTERISTICS AND ECONOMICS COMPARISONS IN A COMPREHENSIVE ACCOUNT DESCRIBING THE APPLICATION ADVANTAGES OF A FREQUENCY CONVERTER THAT COULD BE TREATED AS A TRANSFORMER. A FEW SALIENT POINTS COMPARED TO THE 60HZ SYSTEM ARE: AN 8% INCREASE IN LAMP LUMENS PER WATT, A 23% INCREASE IN LUMENS PER LUMINAIRE WATT AND 12% INCREASE IN SYSTEM LUMENS PER WATT. THE OVERALL TOTAL ANNUAL COST WAS 90% FOR A NON-AIRCONDI-

TIONED BUILDING AND 87% FOR AN AIR CONDITIONED BUILDING.

IN THE FOUR YEARS FROM 1964 TO 1968, A CONSIDERABLE NUMBER OF 3000HZ INSTALLATIONS WERE MADE TOTALING APPROXIMATELY A MEGAWATT OF 40 WATT RAPID START LAMPS. SOME DIFFICULTIES WERE EXPERIENCED AS WITH ANY NEW PRODUCT, BUT MOST ALL OF THE APPLICATIONS INSTALLED IN ACCORDANCE WITH SYSTEM SPECIFICATIONS AND INSTRUCTIONS GAVE A GOOD ACCOUNT OF PERFORMANCE.

ONE LARGE INSTALLATION EXPERIENCED AUDIBLE NOISE PROBLEMS WHEN THE ELECTRICAL CONTRACTOR PURCHASED AND INSTALLED THE WRONG CONDUIT AND WIRING.

THIS PRODUCT WAS FINALLY DISCONTINUED AFTER IT WAS APPARENT THAT IT WOULD NOT BE SUCCESSFUL UNLESS THE COMPANY BECAME SYSTEMS ORIENTED AND SOLD A COMPLETELY ENGINEERED PACKAGE.

GAS TURBINE GENERATORS

IN 1961, THE SOUTHERN GAS ASSOCIATION AND THE NORTHERN ILLINOIS GAS COMPANY PROPOSED THAT LAND GAS TURBINES BE USED TO DRIVE HIGH FREQUENCY GENERATORS TO SUPPLY FLUORESCENT LIGHTING AND CERTAIN MOTOR LOADS. THE TURBINES WOULD ALSO SUPPLY THE HEATING AND AIR CONDITIONING.

CIRCUITS AND BALLASTS WERE DEVELOPED TO OPERATE 40 WATT AND 96", 1½" DIA. LAMPS FOR 420 AND 840HZ. ALTHOUGH THE TURBINES OPERATE AT SPEEDS OF 20,000 R.P.M. AND GREATER, THE RELATIVELY LOW FREQUENCY WAS CHOSEN BECAUSE THE GENERATORS WERE AVAILABLE IN REASONABLE PRODUCTION QUANTITIES AND AT LOWER COST THAN GENERATORS AT THE PREFERRED FREQUENCY OF 10 KHZ OR HIGHER.

THE FIRST LARGE COMMERCIAL INSTALLATION OF THIS SYSTEM WAS INSTALLED IN TWO NEW NORTHERN ILLINOIS GAS COMPANY BUILDINGS IN AURORA, ILLINOIS. IN ADDITION TO THE HIGH FREQUENCY GENERATORS, THE SHAFT WAS GEARED DOWN FURTHER TO ACCEPT A 60 CYCLE GENERATOR FOR THE SERVICE OUTLETS, BUSINESS MACHINES, ETC. THIS INSTALLATION WAS COMPLETELY INDEPENDENT OF UTILITY CONNECTED LOAD. ALL OF THE GENERAL LIGHTING IN THE TWO BUILDINGS EXCEPT FOR A CONTROL BASE TEST

ON 60HZ, WERE OPERATED ON 420 OR 840HZ.

AFTER 2 YEARS OF SERVICE, THE NORTHERN ILLINOIS GAS CO. REPORTED THAT LAMP PERFORMANCE WAS EXCEPTIONALLY GOOD AND THE SYSTEM RELATIVELY FREE OF MAINTENANCE PROBLEMS. SINCE CAPACITOR BALLASTS WERE USED, THERE WERE NO NOISE PROBLEMS REPORTED. THE PROJECTED COST PER K.W.H. USING THE GAS TURBINE WAS GIVEN AS 0.3¢. IF THIS IS COMPARED WITH A CONVENTIONAL 40 WATT SYSTEM AT RATES OF 1,2 AND 3¢ PER K.W.H., THE SAME LAMP AT 420 AND 840HZ WOULD HAVE OVERALL COSTS OF 75%, 55% AND 44% RESPECTIVELY WITH THE CONVENTIONAL SYSTEM AT 100%.

[34] A NUMBER OF INSTALLATIONS USING THE GAS TURBINE WERE MADE IN THE 60'S. APPLICATIONS WERE SHOPPING CENTERS, MANUFACTURING PLANTS AND ONE HIGH SCHOOL.

WE WERE ADVISED THAT THE NORTHERN ILLINOIS GAS CO. HAD TO SHELVE THEIR PLANS TO EXTEND THE GAS TURBINE HIGH FREQUENCY SYSTEM TO THEIR CUSTOMERS' PLANTS DUE TO THE REDUCTION IN GAS SUPPLIES.

FOREIGN PARTICIPATION

THE JAPANESE, BRITISH, DUTCH AND GERMAN LAMP AND ELECTRICAL COMPANIES ALL HAVE HIGH FREQUENCY FLUORESCENT APPLICATIONS, BUT MOST OF THEM ARE FOR CENTRAL OR INDIVIDUAL TRANSISTOR, SOLID STATE INVERTERS FOR TRANSPORTATION LIGHTING. A NUMBER OF PAPERS HAVE BEEN WRITTEN COVERING THESE APPLICATIONS AND ARE LISTED IN THE ATTACHED BIBLIOGRAPHY.

THE RESEARCH AND DEVELOPMENT BY RUSSIAN SCIENTISTS AND ENGINEERS IN THE FIELD OF HIGH FREQUENCY LIGHTING WAS LATER THAN THE UNITED STATES WORK, BUT IN THE 1960'S WAS CARRIED ON IN A RATHER COMPREHENSIVE MANNER. [36-40] SEVERAL PAPERS HAVE BEEN WRITTEN ON THE SUBJECT WITH TESTS AND POWER SUPPLIES PARALLELING OUR EARLIER WORK. THE TWO REFERENCED PAPERS SEEM TO BE WELL PREPARED AND COGENT. THEIR FINDINGS SHOW VERY SIMILAR RESULTS AS TO EFFICIENCIES AND LAMP CHARACTERISTICS. [40] THE CONCLUSIONS OF ONE OF THEIR PAPERS INCLUDE THE FOLLOWING COMMENTS:

1. "PRACTICALLY ALL THE VARIANTS EXAMINED, WITH HIGH FREQUENCY LIGHTING, GIVE ECONOMY IN THE FULL YEARS EXPENSE AS COMPARED WITH PLANTS FED WITH INDUSTRIAL FREQUENCY CURRENT." (50HZ)

2. "THE HIGH-FREQUENCY FEEDING OF FLUORESCENT LAMPS IN PLANTS HAVING HIGH FREQUENCY DISTRIBUTION NETWORKS WITH RESERVE POWER IS INDISPUTABLY JUSTIFIED BY ECONOMY."

3. "AT THE PRESENT TIME (WITH PRESENT PRICE CONDITIONS) IT IS VERY REASONABLE, FROM AN ECONOMY STANDPOINT TO USE A SYSTEM OF FEEDING LIGHT PLANTS WITH FLUORESCENT LAMPS FROM ELECTROMECHANICAL TRANSFORMERS WITH HIGH FREQUENCIES ON THE ORDER OF 2500HZ. LIGHTING PLANTS WITH SAID SYSTEM OF FEEDING GIVE CAPITAL ECONOMIES OF 16 TO 22%."

THEY FAVOR OR AT LEAST DID AT THE TIME, THE USE OF S.C.R. FREQUENCY CONVERTERS IN A CENTRAL SYSTEM.

IN THE ACCELERATED TESTS MADE, THEY SHOW AN INCREASE IN LAMP LIFE OF 20% TO 35% DEPENDING ON FREQUENCY AND LOADING.

SUMMARY HIGH FREQUENCY LAMP CHARACTERISTICS

[6-28]THE FLUORESCENT LAMP ELECTRICAL AND LIGHT OUTPUT CHARACTERISTICS VARY CONSIDERABLY WHEN THE FREQUENCY OF THE POWER APPLIED IS INCREASED. THE REFERENCED PAPERS COVER THE DYNAMIC AND STEADY STATE CHARACTERISTICS TO 20 KHZ.

LAMP EFFICIENCY INCREASES AS FREQUENCY RISES DUE TO THE REDUCTION IN END LOSSES AND AN INCREASE IN POSITIVE COLUMN EFFICIENCY. THE LATTER EFFECT APPEARS TO BE THE RESULT OF AN EXPANSION OF THE ARC AS FREQUENCY INCREASES THUS PRODUCING THE 2537 RADIATION AT A POINT CLOSER TO THE PHOSPHOR. THE LATE DR. CARL KENTY MADE MEASUREMENTS WITH A D.C. PROBE NEAR THE CENTER AND AT THE WALL OF THE BULB WHICH BY IMPEDANCE CHANGE, INDICATE AN EXPANSION OF THE DISCHARGE AT HIGH FREQUENCIES. THE SAME IS AGAIN INDICATED BY VISUAL OBSERVATION. THE LARGER ION CURRENTS TO THE WALLS DUE TO THE SPREADING, RESULTS IN HIGHER ARC GRADIENTS, HIGHER ELECTRON TEMPERATURES, AND THEREFORE HIGHER EFFICIENCIES IN THE PRODUCTION OF 2537. THE PRODUCTION OF 2537 CLOSER TO THE BULB WALL PROVIDES BETTER UTILIZATION OF THIS RADIATION. ON BOTH COUNTS THE EFFICIENCIES SHOULD BE INCREASED.

[28]CURVES SHOWING FURTHER INCREASES IN EFFICIENCY WITH LAMPS

OF VARIOUS FILLING GAS PRESSURES AND MIXTURES INDICATE THAT AN OPTIMUM LAMP CAN BE DESIGNED FOR HIGH FREQUENCY APPLICATIONS. WHEN A SPECIFIC FREQUENCY RANGE IS ESTABLISHED FOR GENERAL LIGHTING, THE LAMP COMPANIES WILL NO DOUBT DESIGN AND MARKET A FLUORESCENT LAMP TO MATCH.

THE PRESENT STANDARD LAMPS EXHIBIT IMPROVED PERFORMANCE ON HIGH FREQUENCY SYSTEMS DUE IN PART TO THE FACT THAT THE LAMP DOESN'T DEIONIZE COMPLETELY. THIS RESULTS IN LESS SPUTTERING OF THE CATHODES DURING STARTING AND THE NEAR ELIMINATION OF RANDOM MOVEMENT OF THE 'HOT SPOT' DURING OPERATION. THIS IMPROVEMENT SHOULD BE REFLECTED IN AN INCREASE IN LAMP LIFE FOR EQUAL LOADING COMPARED TO 60HZ OPERATION AND SOME EARLY APPLICATION TESTS SEEM TO CONFIRM THIS.

ELECTRONIC BALLASTS

MANY ATTEMPTS HAVE BEEN MADE TO DEVISE A SIMPLE LOW COST ELECTRONIC BALLAST TO PROVIDE HIGH FREQUENCY POWER TO FLUORESCENT AND [49] HIGH INTENSITY DISCHARGE LAMPS. SOME OF THE EARLY CIRCUITS REQUIRED SERIES OPERATION OF THE POWER TRANSISTORS WITH ATTENDANT HIGH COST AND UNRELIABLE OPERATING CHARACTERISTICS. ALSO TO REALIZE ALL OF THE ADVANTAGES OF HIGH FREQUENCY FOR GENERAL LIGHTING, THE ELECTRONIC BALLAST MUST BE COMPETITIVE IN COST WITH CONVENTIONAL MAGNETIC BALLASTS OR HAVE A SUFFICIENT INCREASE IN EFFICIENCY TO PROVIDE AN OVERALL ECONOMIC GAIN.

IN RECENT YEARS HIGH VOLTAGE POWER TRANSISTORS HAVE BECOME AVAILABLE WITH SUFFICIENT SWITCHING SPEEDS TO PRODUCE FREQUENCIES IN THE RANGE OF 20 TO 35 KHZ.

SOME ELECTRONIC BALLAST DESIGNS WERE DEVELOPED AS SOON AS HIGH VOLTAGE POWER TRANSISTORS BECAME AVAILABLE IN ABOUT 1968. HOWEVER, COSTS WERE HIGHER THAN INDUSTRY WOULD SUPPORT SINCE ALL PRODUCTS OF THIS TYPE WERE JUDGED STRICTLY ON AN INITIAL COST BASIS.

THE ENERGY CRISIS AND THE ERDA, L.B.L. INCENTIVES FOR THE DEVELOPMENT OF AN EFFICIENT ELECTRONIC BALLAST HAVE SPURRED THE PROTOTYPE DESIGNS OF ELECTRONIC BALLASTS. IF SATISFACTORY OVERALL

ECONOMICS CAN BE ACHIEVED, THE FORTHCOMING TEST OF ELECTRONIC BALLASTS AT A PACIFIC GAS & ELECTRIC BUILDING IN SAN FRANCISCO MAY BE A HARBINGER FOR A HUGE SAVING IN ENERGY REQUIREMENTS FOR LIGHTING.

A TWO LAMP OR FOUR LAMP ELECTRONIC BALLAST IS THE MOST DESIRABLE DESIGN BECAUSE IT CAN BE DESIGNED TO RETROFIT THE LOWER EFFICIENCY MAGNETIC BALLASTS NOW IN USE BY THE MULTIMILLIONS.

CENTRAL SYSTEMS

IN RETROSPECT IT SHOULD BE REMEMBERED THAT THE TECHNOLOGY IS AVAILABLE TO PRODUCE LARGER BLOCKS OF HIGH FREQUENCY POWER FOR NEW INSTALLATIONS WITH THE ADVANTAGES OF A LOWER COST PER K.W. AND A HIGHER OVERALL EFFICIENCY. THE BALLAST AT THE FIXTURE CAN BE OF POSTAGE STAMP SIZE WITH NO MEASUREABLE WATTS LOSS.

[48]THE FEDERAL CONSTRUCTION COUNCIL PUBLISHED A REPORT IN 1968 CALLED "HIGH FREQUENCY LIGHTING". THIS IS A COMPREHENSIVE ANALYSIS OF HIGH FREQUENCY LIGHTING AS A POSSIBLE SYSTEM FOR UNITED STATES GOVERNMENT BUILDINGS. MUCH OF THIS REPORT WAS PREPARED BY DR. DONALD K. ROSS. THE SUMMARY OF THIS REPORT IN PART IS AS FOLLOWS; "ANALYSIS HAS INDICATED THAT JUSTIFICATION OF HIGH-FREQUENCY LIGHTING SYSTEMS, USING STATIC ELECTRONIC CONVERTERS, DEPENDS PRIMARILY ON THE ABILITY OF MANUFACTURERS TO SUPPLY HIGH FREQUENCY FIXTURES AND BALLASTS BELOW AT OR NEAR THE COST OF EQUIVALENT 60-CPS EQUIPMENT, AND TO SEE FREQUENCY CONVERTERS FOR A REASONABLE PRICE (E.G., LESS THAN $120 PER KW OUTPUT). IF BOTH OF THESE REQUIREMENTS COULD BE MET, HIGH FREQUENCY LIGHTING COULD BE JUSTIFIED FOR MANY GOVERNMENT APPLICATIONS."

ANY CENTRAL OR BRANCH CIRCUIT SYSTEM WOULD BE SUPPLEMENTARY TO THE INDIVIDUAL ELECTRONIC BALLAST, WHICH IS FAST COMING TO THE POSITION OF A VIABLE ENERGY SAVING PRODUCT.

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PREPARED BY JOHN H. CAMPBELL

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