The Lenkurt® Demodulator

NEWS FROM LENKURT ELECTRIC

VOL. 9 NO. 5 MAY, 1960

THE TUNNEL DIODE

In October, 1958, Dr. Leo Esaki, a Japanese physicist, published an account of a new phenomenon discovered in junction diodes which had been prepared in a special way. These diodes, now called "tunnel" diodes or Esaki diodes, exhibit remarkable properties which have unusual significance in the field of communications. Because the tunnel diode operates differently than transistors, and eliminates many of the transistor's inherent limitations, they are expected to have as great an effect on communications and electronics as did the discovery and development of the transistor itself. This article discusses some of the general characteristics of tunnel diodes and what may be expected from them.

It has been only about a year since the tunnel diode was announced in this country, and since then the tunnel diode has proved to be one of the most exciting advances in electronics since the announcement of the transistor. The reason is that the tunnel diode operates on new and different principles than the transistor, and is not subject to some of the limitations which restrict transistor performance at extremely high frequencies or in dfficult environments.

Tunnel diodes, unlike transistors and conventional diodes, have no inherent frequency limitations. These diodes operate at the speed of light, limited only by the inductance, capacitance, and resistance provided by their physical structure. For this reason, switching time of a diode used for computers or pulse communications, for instance, could readily be made as short as 10^{-12} second — that is, one-millionth of one-millionth of a second!

Transistors do not operate well while exposed to nuclear radiation — the radiation interferes with the lifetime of current carriers within the transistor. The tunnel diode uses a different type of current carrier and is not nearly as handicapped.

Temperature extremes do not interfere with the operation of the tunnel diode until the material becomes so hot

Figure 1. Tiny tunnel diode, shown here enlarged 2.5 times, actually takes up only about 1/100 the total volume of its glass "package." Physical dimensions are mostly determined by available mechanical techniques for sealing and making suitable connections to the device. Actual diode is thin wafer at upper end of S-shaped spring within glass. Since tunnel diodes require less than 1/100 the power of a typical transistor, and operate well in environments where transistors fail, unusually high numbers of such components may be crowded into tiny space for equipment of the future. An entire electronic telephone exchange might well fit into a coat closet or small vehicle.

as to lose its character. Tunnel diodes have operated quite successfully while immersed in liquid helium (-452°F.) and at temperatures above 750°F. By contrast, conventional transistors operate best at temperatures between the boiling point and freezing point of water.

Negative Resistance

How can any diode—which is a two-terminal device—amplify? The answer is provided by an examination of the E-I or voltage-current characteristics of the tunnel diode. Figure 2 compares the characteristics of a resistor, a conventional diode and a tunnel diode. Note that current through the resistor increases in direct proportion to the voltage applied across the resistor—just as defined in Ohm's law. The only time that this curve is not linear is when so much current is passed through a resistor as to change its resistance by heating.

The conventional junction diode will have an E-I curve similar to that shown in Figure 2-b. Note that current increases almost linearly with applied voltage in the forward direction. In the reverse direction, little or no current flows until the reverse potential is so great as to cause breakdown of the junction.

The tunnel diode exhibits entirely different characteristics. It is highly conductive for reverse voltage. Current increases almost linearly with the application of forward voltage until the curve suddenly reverses. At this point, increased forward voltage causes a *reduction* in current, while decreased voltage *increases* current. This negative resistance effect occurs over a relatively narrow voltage range in presently available experimental diodes. Decreasing temperature extends the voltage range over which the negative resistance effect occurs. If applied voltage is increased further, current again increases, as in other devices.

It is only the negative resistance portion of the curve that permits the diode to amplify. Negative resistance devices are not new, but have never been so simple, cheap, or convenient as the tunnel diode. For instance, negative resistance repeaters have been used for many years to amplify messages traveling in both directions on two-wire telephone lines. Figure 3 shows a simplified schematic diagram of such a repeater. The device requires two amplifiers (either tubes or transistors) plus many other components. A signal traveling in either direction is amplified and reapplied to the line in the proper phase required to reinforce the signal. A single, properly biased diode shunted across the line would have the same effect, as diagrammed in Figure 4. Practical tunnel diode amplifiers operating on this principle have been made. Figure 5 shows a suggested radio fre-

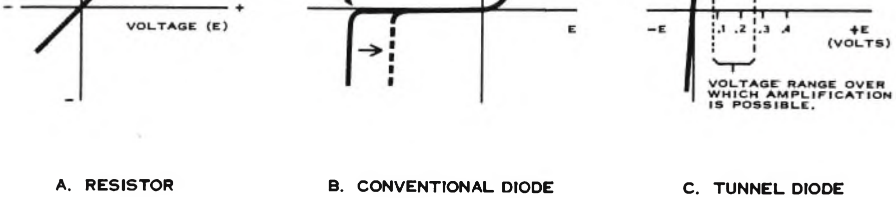

Figure 2. Comparison of the voltage-current relationships of an ordinary resistor, conventional junction diode, and a tunnel diode. As voltage across the resistor (A) is increased, current goes up proportionately. "Forward" voltage across junction diode (B) causes near-linear increase in current, high resistance to reverse voltage until breakdown voltage is reached. Increasing "doping" of junction results in lowered back resistance as indicated by dotted curve. Tunnel diode (C) is highly conducting for both reverse and forward voltages, but shows unique negative resistance over a narrow range of forward voltage.

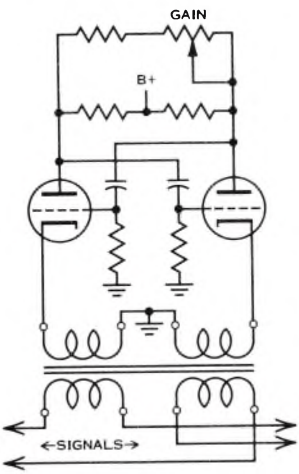

Figure 3. Typical negative impedance repeater such as long used for two-way amplification of telephone messages. Signal voltage in either direction is amplified and reinserted on line in correct phase to strengthen signal.

quency amplifier using a tunnel diode. Note the similarity to the telephone-type negative resistance repeater.

Negative resistance devices have been studied for at least thirty years, and many fascinating applications for the effect were proposed. The use of negative resistance to neutralize positive resistance in networks was described and sought, although researchers had difficulty in accomplishing it, due to instability of the resulting circuits.

As early as 1934, the use of negative resistance in voltage-controlled tuning was demonstrated, and circuits were devised to reduce or eliminate grid-plate capacitance in electron tubes, using negative resistance. Even the cumbersome negative resistance circuits then available were shown to provide significant advantages as heterodyne frequency meters and signal generators, and could readily be used as modulators, detectors, and oscillators.

How It Works

In order to explain the operation of tunnel diodes, let us first review briefly the operating principles of conventional junction diodes.

Tunnel diodes, transistors, and conventional junction diodes are composed of *semiconductor* material, that is, material having electrical properties midway between those of insulators and conductors. Whether a material is a conductor, semiconductor, or insulator is determined by its atomic structure.

All materials are composed of atoms consisting of a central nucleus having a positive charge, surrounded by negatively-charged electrons. In a complete atom, the number of electrons always matches the positive charge of the nucleus. Various materials will have different numbers of electrons. The electrons orbit around the nucleus in one or more "rings" or shells which repre-

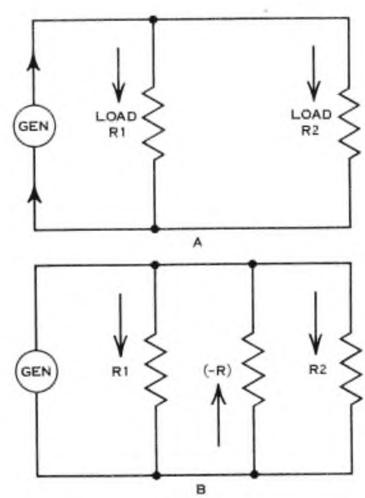

Figure 4. Generator in (A) causes flow of current through shunt loads as indicated by arrows. If negative resistance is inserted in circuit as shown in (B) negative conduction actually increases flow of current through R1 and R2.

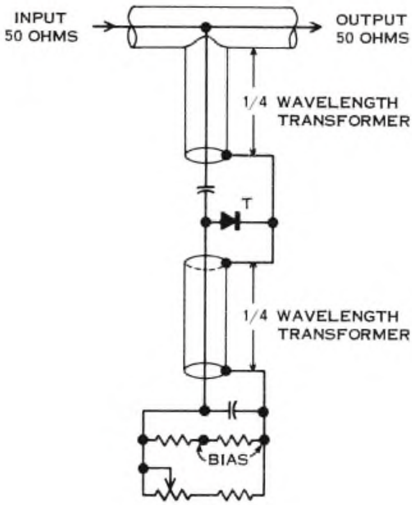

Figure 5. Tunnel diode equivalent of circuit shown in Figure 3. This amplifier is designed for UHF service, requires transmission-line transformers for impedance match between 50-ohm line and much lower impedance tunnel diode.

sent different energy levels of the electrons. Each ring has a definite quota of electrons that it can hold. For instance, there is room for only two electrons in the first ring, eight in the next, eight in the third ring, 18 in the fourth, and so forth.

Atoms always strive to complete their outer ring. Once the ring is completed, much greater amounts of energy are required to dislodge an electron than if the ring is incomplete. For this reason, atoms which have just enough electrons to completely fill one or more rings (such as helium, with two electrons, and neon with 10) are completely inert and will not react chemically with other elements. On the other hand, if the ring is incomplete, relatively little energy is required to attach or remove an electron from its incomplete ring. The actual energy required to free electrons depends on such factors as the number of electrons in the outer ring and how nearly complete it is.

Electrical current always requires the flow of electrons. These, and their positive counterparts ("holes") are often referred to as "current carriers" or just "carriers" in the language of solid-state electronics. Conductors have electrons so loosely bound to the outer ring that even a slight electrical potential will dislodge them, freeing them to conduct current. In the case of insulators, electrons are much more tightly bound, perhaps because the ring is very nearly complete. Much higher electrical potentials are required to loosen them. Higher temperatures may supply some of the energy necessary to dislodge electrons from the atoms of insulators. For instance, glass, which is an excellent insulator at normal temperatures, becomes a very good conductor at high temperatures.

Electrons must achieve a specific energy level before they can be freed

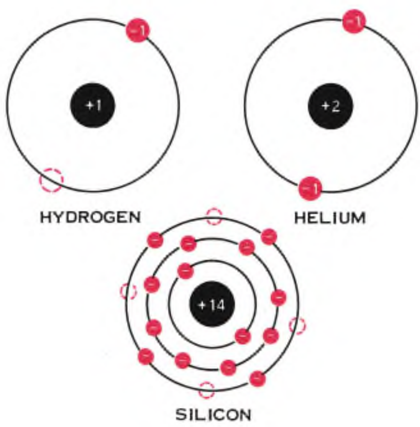

Figure 6. Hydrogen atom with one electron has incomplete outer ring. Helium atom has filled outer ring and is completely inert. Silicon atom has four of the eight possible electrons required to complete its outer ring. Relatively little energy is required to free electrons.

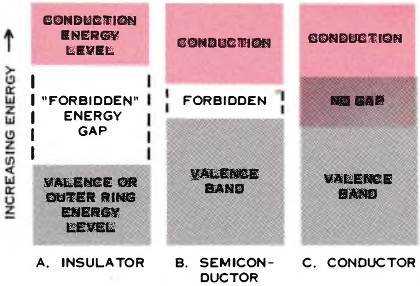

Figure 7. Electrons cannot occupy certain energy levels ("forbidden gap"), but must absorb enough energy to go "all the way" from valence band (energy level possessed by outer ring electrons) to conduction level, the level achieved by free electrons. Levels and forbidden gap vary from material to material, and according to applied voltage.

from their position in the outer shell of an atom. Sometimes there is a large gap between the normal energy of the outer-ring electrons and the energy required for freedom (conduction). In conductors, the gap is non-existent; that is, no extra energy is required for conduction. In semiconductors, the gap is very small; in insulators, it is quite large. Thus, only conductors have an abundance of electrons which are free to carry current.

In semiconductors, the application of external energy, such as heat, light, or electricity will free electrons for duty as current carriers. The number of electrons increases with the amount of energy applied. The number is never very large, however, compared to a conductor. Conventional semiconductor diodes make use of this characteristic to control the flow of current.

First, the pure semiconductor is modified to increase the number of easily-freed electrons. This is done by adding small amounts of selected impurities to the semiconductor; and the semiconductor material is crystallized. The impurities are selected for their ability to substitute for one of the semiconductor atoms in the crystal. In addition, after "locking arms" with the semiconductor atoms, the impurity atoms must have one electron left over, or be deficient by one electron. The presence of surplus electrons separate from the crystalline structure increases the number of carriers available. It also lowers the resistance of the material,

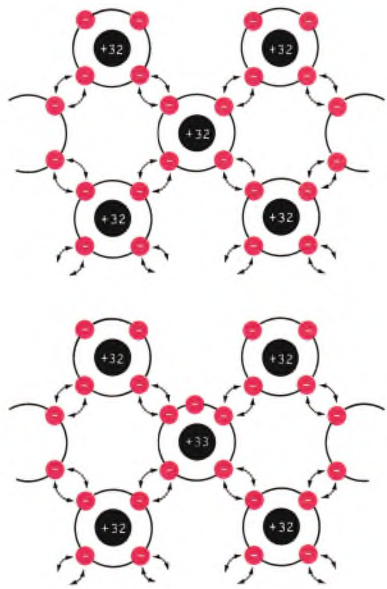

Figure 8. Crystalline structure of a semiconductor, showing how electrons are shared by atoms to complete their outer rings. If material is "doped" with impurity having the same valence, one outer electron is unused by crystal structure, thus increasing number of free electrons available for conduction. This type of doping produces n-type semiconductor. P-type semiconductor is produced by adding material which is one short of the number of electrons required by strong crystalline structure. Electron deficiency produces net positive charge ("hole") which may be transferred from atom to atom by shift of free electrons.

and makes it more sensitive to applied electrical potential. Just enough impurity is added to improve the sensitivity of the material, but not enough to create so many free electrons that they are impossible to control by applied voltage.

If the impurity provides a *surplus* electron, the semiconductor is called *n* type material because the current carriers are negative (electrons). If the impurity provides a *deficiency* of electrons, the material is called *p* type semiconductor because it behaves as though there were positive carriers for the current. Although no positive carriers physically exist, the *hole* caused by the absence of one electron exactly simulates a positively-charged particle.

PN Junctions

If samples of *p* and *n* semiconductor materials are intimately joined, a very efficient rectifier is produced. A situation similar to that diagrammed in Figure 10 exists. The *n* material consists of *donor* atoms (atoms which furnish an electron) and loosely-bound or free electrons. Donors have a positive charge because of the loss of the free electrons. The *p* material consists of acceptor atoms having a negative charge, and holes, which simulate mobile positive charges.

In the *n* material, the positively-charged donor atoms (ions) are locked in place by the crystalline structure. The free electrons, however, are able to migrate under the influence of electrical fields. A similar, but reverse, condition exists in the *p* material. At the junction, the positively-charged donor atoms create a field which extends across the junction and repulses the positively-charged holes. Similarly, the negative charges of the acceptor atoms in the *p* type semiconductor repulse the free electrons in the *n* material. This mutual repulsion creates a sort of "no man's land", called a *depletion zone* because it is depleted of current carriers.

The repulsive force is equivalent to a small voltage potential which must be overcome by the current-carrying holes and electrons before they can approach and cross the junction. Only carriers which have acquired enough energy to climb this electrical potential hill can cross the junction. Thus, the potential barrier may be symbolized as

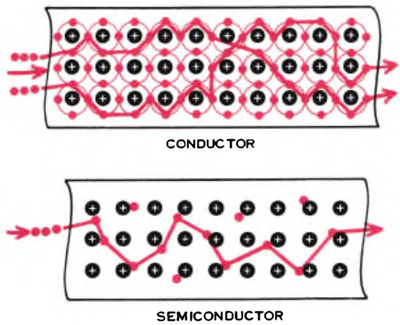

Figure 9. Flow of electricity through conductor results from entering electrons crowding free electrons out other end. In semiconductor, current carriers must hop from atom to atom in crystal lattice, requiring much more time than in conductor.

a small battery connected across the junction, or as a small voltage hill that must be "climbed" by carriers crossing the junction.

If an external battery is connected to the *pn* junction, as shown in Figure 11, the voltage or potential hill is reinforced, because the external voltage pulls the carriers even farther away from the depletion zone. This increases the electrical resistance of the junction by reducing the number of available carriers. If the polarity of the external battery is reversed, the applied voltage forces the carriers toward the junction, lowering the potential hill. This lowers the resistance of the junction to a low value.

If the impurity concentration of an ordinary *pn* junction is increased, the breakdown voltage is decreased, as shown in Figure 2-b. If the diode is heavily doped with impurities (roughly 10^{19} atoms per cc.), it becomes highly conductive when reverse-biased, and

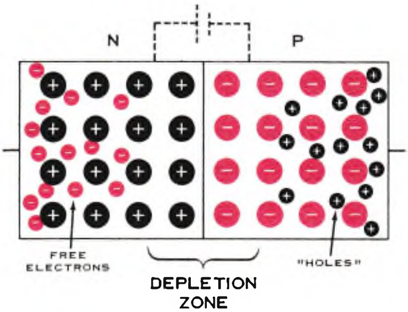

Figure 10. Field from donor atoms repulses similarly-charged carriers across junction. Simulated battery indicates potential that must be overcome to cause electron to diffuse from n *to* p *material.*

the negative conductance appears at certain values of forward bias. Apparently this occurs because the energy levels of the *p* and the *n* type materials shift with respect to each other so that the outer-ring electrons in the *p* material have the same energy level required for conduction in the *n* material. When this occurs, carriers "tunnel" through the depletion region at the speed of light. If the forward bias is further increased, the energy levels of the two materials are shifted so that the energy of outer-ring electrons of the *p* material no longer matches the conduction level of the *n* material. Therefore, tunneling is no longer possible and carriers can only cross the junction barrier by absorbing additional energy from the applied potential, as in ordinary diodes.

In conventional diodes and transistors, carriers must take a roundabout path, leaping from atom-to-atom in the crystal structure of the semiconductor. Because of this, carriers travel quite slowly through semiconductors, holes traveling only about 16 meters per second for each volt-per-centimeter of potential gradient. Electrons travel about 36 meters per second under the same conditions. It is this slow propagation rate that limits the frequency performance of transistors and diodes. The tunneling phenomenon, however, occurs at the speed of light, and frees the tunnel diode from such frequency limitations.

Unlike ordinary diodes and transistors, the tunnel diode is little affected by extremes of temperature. Since the shifting of the *relative* energy levels of

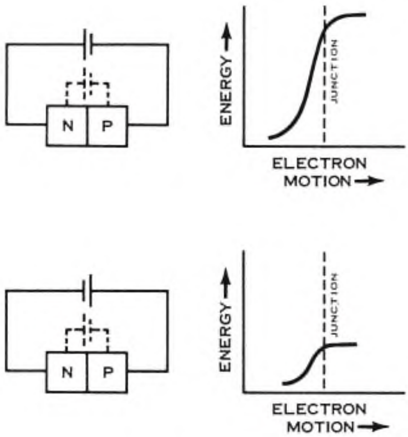

Figure 11. Potential "hill" to be overcome for conduction is increased by external battery connected as shown in (A), but is lowered when battery is connected as in (B). This accounts for high reverse-current resistance, low forward-current resistance of diodes.

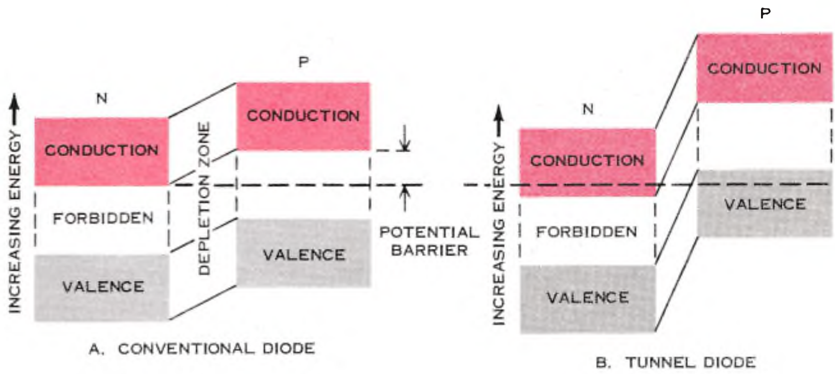

Figure 12. Very heavy doping of n *and* p *semiconductors shift their respective energy levels. Applied forward bias tends to reduce difference between two. When valence band of* p *material is directly opposite conduction level of* n *material, current carriers may "tunnel" through potential barrier at speed of light. Increased forward bias shifts* n *valence band opposite* p *forbidden zone, restoring normal diode behavior.*

the two types of material is primarily based on bias across the diode rather than temperature, tunneling is generally independent of temperature. In transistors and conventional diodes, temperature directly affects the number of carriers that are produced in both *p* and *n* materials, and this determines the current density and the performance of the device. Although various transistor and diode materials will have different sensitivities to temperature, they cannot avoid being influenced by temperature, so long as they continue to employ present operating principles.

Conclusions

The tunnel diode, for all its promise, presents many problems. It is a two-terminal device and will amplify equally well in either direction. This makes circuit design quite difficult. For instance, isolation between stages is difficult to obtain. Because of the negative resistance characteristics of the device, it tends to oscillate with almost any stray capacitance or inductance present—the value of the capacitance and inductance determining the frequency of oscillation. By using tunnel diodes with other components such as transistors and ordinary diodes, the disadvantages of both types may be overcome and the advantages of each reinforced. Just as the characteristics of transistors required new circuit designs, the tunnel diode presents similar design problems that will most certainly be overcome. ●

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Strong Response To Reader Survey

Questionnaires were sent to nearly 10,000 U. S. readers of the *Demodulator* with their February copy. The purpose of the survey was to sample reader opinion on the content, scope and format of the *Demodulator,* and to learn more about the people who read the *Demodulator.* Questionnaires were not sent to readers outside of the United States only because of postal technicalities and the excessive time required for response. Comments, suggestions, and inquiries from all readers, regardless of their location, are always welcomed.

On the facing page is a reproduction of the questionnaire, showing response in terms of percentage of readers checking each item. The figures do not add up to 100% because some readers omitted items, others checked several items.

Response was extraordinary. Normally, a questionnaire of this type will receive a response of from 2 to 5%. To date, 27.3% of the cards sent out have been returned, and they are still coming in. Responsibility or occupation level of the responding readers is much higher than was anticipated. For instance, more communications superintendents (or supervisors) than technicians returned cards, and more than 35% of all respondents were either company officers, communications superintendents or managers.

Most readers endorsed the present policies of the *Demodulator.* A notable exception was the overwhelming preference for references — many readers indicated that references would enhance the value of the *Demodulator.* So, starting last month, a bibliography is being included with feature articles, whenever appropriate.

A minority complaint was about the size of the *Demodulator* — some readers didn't know that binders are available or that the *Demodulator* may be stored in one of the standard-sized 3-ring notebooks. Durable leatherette binders imprinted with the name of the publication are available from the *Demodulator* for $0.50 each, postpaid. Other readers were evidently not aware that many of the more popular articles of past years have been compiled into book form. The book covers a wide range of communications subjects and is available for $2.50 postpaid.

To all who returned their questionnaires — many thanks!

The Editor.

CONTENT

(%)

1. Should technical subjects receive: very detailed and complete treatment, including mathematics 26; broad presentation and only the most fundamental mathematics 61; simplified explanations 14; other ________________?

(Choice)

2. Number the following subjects *in the order* of your interest or preference:

11 components
12 manufacturing techniques
2 system design
10 cable and wire techniques
1 microwave
6 general electronics
1 carrier techniques
4 data transmission
5 telephone principles
8 theoretical articles
9 maintenance techniques or tips
3 general communications
7 new developments
other ________________

3. List any *Demodulator* articles you remember as particularly useful or interesting ________________

4. Should references be listed after each article, where applicable?
yes 82; no 10.

5. Comments ________________

FORMAT

(%)

1. Do you think the *Demodulator* is: too long 2; too short 35; just right 61.

2. Would you like to see: longer articles 27; shorter articles 7; more articles 28; same as now 46?

3. A larger page size might permit more extensive coverage of some subjects—it would also clash with the present *Demodulator* as far as storing and preserving. Would you prefer: larger pages 17; same size 78?

4. What do you think of long articles presented in several parts? prefer 19; acceptable but not preferred 66; objectionable 13

5. Comments ________________

ABOUT YOU

(%)

Who You Are

7 Company Officer
18 Communication Supr.
11 Manager
54 Engineer
15 Technician
2 Teacher
1½ Student

What You Do

28 Telegraph
50 Telephone
31 Toll
21 Switching
16 Outside Plant
36 Microwave
44 Carrier
23 Design
30 Planning
32 Maintenance
17 Research & Develop.
Other 1

Where You Do It

28 Bell System
7 General Tel. System
9 Independent Tel. Co.
2 Western Union
11 Federal Government
6 Military
1 State Government
1 Local Government
2 School or College
8 Research Laboratory
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6 Other Utility
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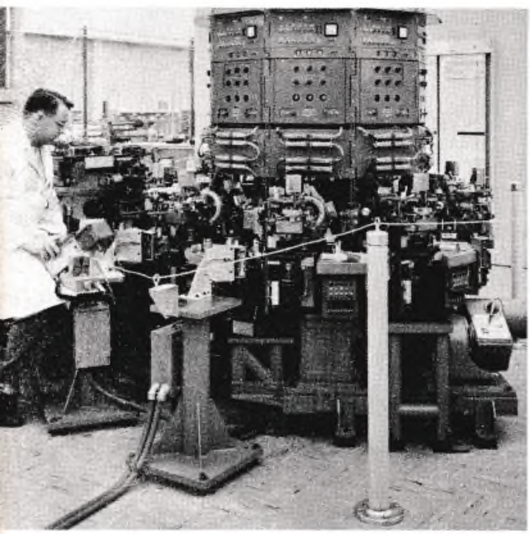

The heart of any frequency-division carrier system lies in its filters, and the success of the filters is highly dependent on the quality of their toroidal chokes and transformers.

Lenkurt's "Carousel" automatic toroid fabricating machine produces more than 2100 coils a day, performing every step in their fabrication, from molding and measuring core characteristics, to calculating and counting turns of wire, then automatically testing the performance of the finished units.

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