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SUMMARY REPORT ON CIVIL DEFENSE RADIOLOGICAL INSTRUMENT DEVELOPMENT, 1961 to 1966*

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ABSTRACT

ORNL provided technical assistance to the Office of Civil Defense on specialized instrumentation. Two instruments were developed and a number of tests were performed leading to the improvement of existing instrument designs. This report describes ORNL assistance to June 30, 1966.

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INTRODUCTION

In 1961, at the request of the AEC, the ORNL Instrumentation and Controls Division began to assist the Office of Civil Defense¹ (OCD) on problems concerning the design, development, and procurement of civil defense instrumentation. ORNL provided technical assistance to OCD in the preparation of specifications for instrumentation, in the evaluation of proposed modifications of equipment or specifications, and in the study of technical problems associated with long-term storage of OCD radiological measuring equipment. Two instruments were developed by ORNL for OCD, an aerial survey meter and a remote reading shelter monitor.

Three prototype models of the aerial survey meter were designed and constructed by ORNL and submitted to OCD for field evaluation. A derivative of this instrument, designated CDV-781, was approved and is part of the OCD instrument inventory. Production prototype aerial survey meters manufactured by RCA and production prototype aerial survey meters manufactured by Nuclear-Chicago Corporation were tested.

One prototype model of the remote-reading shelter monitor was designed and constructed by ORNL for OCD evaluation. Two models of the remote-reading shelter monitor manufactured by Nuclear-Chicago Corporation were tested by ORNL. This instrument, designated CDV-711, was also approved and is a part of the OCD instrument inventory.

ORNL provided other assistance to OCD. Field-effect transistors were studied for use in civil defense instruments. The cause of failure of a number of radiological dosimeters stored in OCD depots was studied. Tests were performed on a number of radiological monitoring instruments supplied by OCD. These instruments included CD-700, CDV-715, and CDV-717 survey meters of several manufacturers, and prototype radiation monitoring instruments from two manufacturers.

From 1961 until October 1963 the assistance given to OCD was given by ORNL on an informal basis. In October 1963 this agreement was made formal by interagency agreement between the OCD and the AEC, providing for more active ORNL participation. In 1964 the U. S. Naval Radiological Defense Laboratory (NRDL) was made responsible for administration of this contract.

In 1966 the character and level of ORNL support was revised, and two separate contracts were established. One contract with NRDL as the administrator provided for ORNL contribution in the research program. The other contract with OCD as the administrator provided for ORNL to assist the OCD staff, upon request, on problems relating to specification, procurement, and handling of OCD instrumentation. These agreements have been renewed periodically and are currently in force.

¹The organization with which ORNL has dealt concerning instruments for civil defense has changed its name and departmental affiliation from time to time since 1961. For clarity in this report the letters "OCD" refer to the formal title of the agency.

This report describes the assistance provided by ORNL to OCD under these contracts from 1961 through 1966.

AERIAL SURVEY METER (CDV-781)

The aerial survey meter, CDV-781, is designed for installation in an aircraft and, when flown at low altitude over a radioactive area, will indicate by a meter the approximate intensity of radiation at ground level. The need for such an instrument was recognized prior to 1960 when the OCD and the Radiological Services Division, Milwaukee Metropolitan Target Area Civil Defense Commission (MMTA), developed the criteria for this instrument. The proposed instrument would measure the radiation intensity at ground level while being flown at 100 mph over the area at altitudes of 500 to 1000 ft; have a flat response spectrum to gamma radiation in the energy range of 0.2 to 1.2 Mev; be compensated for air attenuation at altitudes of 300, 500, 700, and 900 ft; have a logarithmic-scale meter calibration of 0.1 to 500 r/hr in two overlapping ranges; and have a maximum response time of 1.5 sec. ORNL was asked to design an instrument for OCD meeting these requirements. A single-detector scintillation-photomultiplier assembly was considered for the instrument, but this type of detection system could not meet simultaneously all of the requirements of counting statistics, energy range, and response time of the original criteria.

A multichannel instrument was designed and constructed. With three G-M counter tubes (each of a different size and sensitivity), three linear rate meters, and three indicating meters, the instrument had three continuously indicating channels with full-scale ranges of 0.1, 1.0, and 10 r/hr. This instrument did not exhibit the flat response spectrum to gamma radiation originally desired. However, this requirement was relaxed by OCD. A model of this instrument, ORNL model Q-2192, with a battery supply was built into a single cabinet. The instrument was equipped with a loudspeaker which provided an audible tone whose frequency was proportional to radiation intensity. A change in the tone informed the pilot that the radiation level measured by the instrument had changed and that the meter should be read again.

Field tests were made by OCD, and some features of the instrument were unsatisfactory from an operational standpoint. In some aircraft a high noise level in the cabin masked the audible tone from the instrument. The single-cabinet construction was unsatisfactory because it was difficult for the pilot to place the instrument in a position where he could conveniently read the meters while flying the aircraft.

A second model was built using two cabinets. The detectors, count rate meters, and batteries were installed in one cabinet, and the indicating meters and audio output controls were installed in the other. The audio signal was delivered to the pilot through his earphones. The cabinet with indicating meters was designed to be mounted on the top of the pilot's instrument panel, and the other cabinet was designed to be fastened to the floor of the aircraft.

After the second model had been flight tested by OCD, a third prototype was built.² This prototype, although similar to the second one, could be operated on power either from self-contained batteries or from the aircraft 12-v dc supply, and was equipped for two persons to monitor the audio tone through earphones. The audio output circuit for the pilot allowed him to monitor the audio tone or the aircraft's radio, or both. The monitor was packaged in three boxes: the indicating meter unit; the detector, count rate meter, and power supply unit; and a detachable battery unit housing two 6-v lantern batteries. The indicating meter of the channel "in range" was illuminated, signifying which channel should be read. The instrument dials were compensated for dead time losses up to $\pm 3.5\%$. The stability of the system over the life of a set of batteries was $\pm 3\%$ (end point of 10 v). Drift due to temperature was $0.1\%/^{\circ}\text{F}$ positive. This instrument was delivered to OCD for testing and evaluation.

OCD contracted with the Radio Corporation of America to produce an instrument similar to the ORNL unit and amenable to mass production which would perform satisfactorily under adverse conditions after being stored for extended periods under uncontrolled conditions. During the execution of this contract, ORNL served as a technical consultant to OCD and evaluated changes in the design proposed by RCA.³

A prototype of the CDV-781BX aerial survey meter, designed by RCA, was tested. This instrument had a zener diode voltage regulator, improved capacitors in the dc-to-dc converter power supplies, and two lamps indicating which of the three channels was on scale and should be read. A manual bias control replaced the automatic blocking oscillator bias circuit used in previous models. Tests indicated that the meter indications changed as the supply voltage changed and that the frequency of the audible tone changed as the manual volume control was adjusted. Regulation of the self-contained battery supply was poor, because the heavy current drain on the power supply lowered the output voltage below the 15.5-v regulating point of the zener diode. Excessive anode voltage applied to the G-M tube caused the circuit to ring.

A production model of the Nuclear-Chicago CDV-781 aerial survey meter was received for testing in 1965. Results were transmitted to OCD at the completion of tests. Accuracy of the instrument⁴ was limited by severe width jitter in the waveform of the signal applied to the detector stages. The instrument would not maintain calibration. Replacement of the G-M tubes with tubes having different starting voltages was simulated and found to cause a change in the output meter indication by a factor of more than 3.

²F. M. Glass, E. E. Waugh, and C. C. Courtney, "Civil Defense Instruments," Instrumentation and Controls Div. Ann. Progr. Rept. Sept. 1, 1962, ORNL-3378, p. 29.

³Letters from F. M. Glass to R. B. Martin, Nov. 28, 1962, Jan. 18, 1964, and Feb. 21, 1963.

⁴Letter from F. M. Glass to C. R. Siebentritt, Dec. 22, 1965.

Since the circuit of the Nuclear-Chicago production model was essentially the same as the RCA and ORNL models previously tested, it was expected that the instrument would perform in a similar manner. Inspection showed that three diodes in the circuit had been reversed due to an error in the circuit diagram supplied by RCA, causing improper operation of the circuit. Accuracy of the instrument was impaired by crosstalk encountered between circuits on the etched circuit board and by inadequate decoupling provisions in the two reference power supplies.

ORNL proposed that the instruments be modified by replacing the circuit board in the instrument with a new board arranged to reduce intercircuit coupling. It was recommended that for future procurement a new circuit board be designed to accommodate a new line of epoxy encapsulated silicon transistors recently developed. An etched circuit board was constructed that minimized intercircuit coupling, provided additional decoupling in the power supply leads, and accommodated the higher G-M anode voltage supply. This circuit board was installed in the Nuclear-Chicago instrument and returned to OCD for evaluation.

Further work on this instrument has been continued on an as-needed basis in consultation with OCD and its contractors.

REMOTE-READING SHELTER MONITOR (CDV-711)

On May 4, 1961, ORNL submitted a proposal to OCD for a remote-reading shelter monitor. This high-level ion-chamber electrometer instrument would have four ranges of 1, 10, 100, and 1000 r/hr full scale. The circuit was designed such that the time constant of the system would not be adversely affected by connecting the ion chamber to the electrometer with 200 ft of cable. Linearity would be $\pm 3.5\%$ of full scale, zero drift would be less than 2%/hr of full scale, and calibration drift would be less than 6% of full scale within the useful portion of the life of the battery supply. The unit would be powered by a battery supply delivering 10 ma at 12 v to the transistorized electronic equipment, and to a transistorized power supply delivering 500 v to the ion chamber.

After OCD had reviewed the proposal, ORNL was instructed to proceed with the design of the instrument. An engineering prototype, ORNL model Q-2236-1, later known as CDV-711,² was constructed and delivered to OCD in July 1961. This prototype was to serve as a model for the design of an instrument which would be capable of being handled and stored under unsatisfactory conditions and which could be economically mass produced if the instrument were found satisfactory in OCD field tests.

In February 1964 a production prototype CDV-711 remote-reading shelter monitor, produced by Nuclear-Chicago, was received at ORNL for test and evaluation. A report of these tests was made to OCD in February 1963.⁵

⁵Letter from F. M. Glass to R. B. Martin, Feb. 21, 1963.

Briefly, these tests showed that the electrical battery connections tended to be unreliable because deformation of the plastic battery boxes resulted in low contact pressure on the battery terminals. The instrument was not equipped with a calibration circuit. ORNL recommended that the instrument be equipped with a test circuit for checking the condition of the instrument, including chamber and cable leakage. The instrument would be checked by setting the range selector switch on a "test" position, which would switch the instrument to its most sensitive range and apply a reference voltage to the input terminals. The radiation level indicated by the meter compared to the reference voltage would indicate the instrument error.

In October 1965, a CDV-711 Nuclear-Chicago, model 3 monitor was received for test and evaluation. Results of evaluation by ORNL were sent to OCD on October 18, 1965.⁶ The calibration of the instrument changed 20% when the ambient temperature was changed from 77 to -20° F, and the zero setting drifted 60% when the ambient temperature was changed from -20 to 125° F. Toward the end of the useful battery life, the zero setting could not be adjusted.

Filament voltage applied to the electrometer tube was regulated by a Ni-Cd cell. The Ni-Cd cell was connected in the circuit so that it would be completely discharged whenever the instrument was left turned on with an exhausted D cell in the circuit. The Ni-Cd cell was mounted in a location which made replacement difficult. ORNL suggested that, if the electrometer tube were used properly with the correct biasing technique, there would be no necessity for regulating the filament voltage.

Additional assistance during the period of October to November 1965 included recommendations⁷ for changes in the CDV-711 circuit which would improve calibration stability and permit zero adjustment throughout the life of the battery.

RADIOLOGICAL DOSIMETER (CDV-742)⁸

The Office of Civil Defense, after having purchased many quartz-fiber, self-reading 0- to 200-r radiological dosimeters (type CDV-742) from two manufacturers (A and B), found that approximately 20% of the meters developed excessive electrical leakage during storage and that the number of failures was continuing to increase. ORNL was requested to determine the causes of failure in order to eliminate them in the production of new dosimeters and to repair the unsatisfactory dosimeters on hand.

⁶Letter from C. J. Borkowski to C. R. Siebentritt, Oct. 18, 1965.

⁷Letter from F. M. Glass to C. R. Siebentritt, Nov. 10, 1965.

⁸This report by R. E. Zedler is a verbatim copy from p. 65 in Instrumentation and Controls Div. Ann. Progr. Rept. Sept. 1, 1965, ORNL-3875.

To meet the electrical-leakage-rate specification, the quartz-fiber electrometer and capacitor assembly must have a minimum insulation resistance of 6.5×10^{16} ohms. Work to date indicates that excessive electrical leakage results from large amounts of water vapor retained by plastic parts in the meter and from physical imperfections in the capacitor dielectric film, that is, foreign materials embedded in and retained on the film, cracks, thin spots, holes, and scratches.

Large and permanent reductions of the leakage rate of the meters from both manufacturers were obtained by continuous evacuation of the dosimeters at 78°C for a minimum period of ten days. Three months later, 75% of these dosimeters still met the leakage-rate specification. Mass spectrometer analysis of the vapors evolved during evacuation showed that water vapor was the main constituent with traces of O₂, N₂, CO₂, and Ar. Meters from manufacturer A also contained traces of toluene and possibly an amine compound. The total water content of the plastic components was as high as 100 mg in the meters from manufacturer A and 50 mg in the meters from manufacturer B. Most of the water was contained in the phenolic-type conducting plastic parts; the remainder of the water was contained by other plastic materials.

The resistance (or leakage rate) as a function of relative humidity was determined for dosimeters from manufacturer A. These meters initially had widely varying leakage rates. The test results showed that (1) even at the same relative humidity, there was a wide variation in resistance, which indicates some inherent variation in the condition of the dielectric films; and (2) a low relative humidity within the meter is necessary if a low electrical-leakage rate is to be maintained. The leakage resistance of the meters decreased by as much as a factor of 10 when the relative humidity was increased an increment of 10% over a range of 0 to 75% relative humidity. Several meters that initially were satisfactory could be made to exceed the specified leakage rate by increasing the relative humidity of the entrapped air to above 50%. Thus, it is essential that the dosimeters be absolutely hermetically sealed. Leaks were found in many dosimeters produced by both manufacturers. In the meters from manufacturer A, water vapor can diffuse through the plastic diaphragm in which the charging pin is sealed. This condition can be a potential source of meter failure, especially when these instruments might be stored at high relative humidities.

In addition to water vapor and defective dielectric material, other less prevalent causes of failures were found for some dosimeters: (1) inability to charge at low temperatures (<50°F), (2) failure of the charging pin to disengage from the electrometer unit after the unit had been charged, (3) inability to charge the fiber (fiber stuck to anvil), (4) failure of the fiber to maintain a fixed position when the device is removed from the charger, and (5) defective sealing.

To eliminate the electrical-leakage problem, the following recommendations were made to the Office of Civil Defense:

1. that phenolic-type conducting plastics no longer be used,
2. that all plastic meter components and the metal case be thoroughly dehydrated,

3. that a more stringent quality control be maintained in the production and handling of the dielectric film,
4. that a desiccant unit be included in the dosimeter,
5. that all meters be absolutely hermetically sealed.

EDISON GAMMA-RAY SURVEY METER

A prototype gamma-ray survey meter was manufactured by the Thomas A. Edison Research Laboratory under OCD Contract No. OCD-PS-64-13 for the investigation and development of a low-cost gamma radiation survey meter.⁹ The instrument consists of a high-voltage supply, a radiation detection tube, and a microammeter. The radiation level is read from a meter which indicates the average of the current pulses from the radiation detector. Thus, the complications of a count rate meter are avoided.

Limited performance tests were made at ORNL since the instrument had been calibrated previously by the National Bureau of Standards. The instrument was checked using gamma radiation sources from 1" to 2" r/hr; it functioned properly after some minor repairs had been made.

From these tests and other considerations, it is concluded that the instrument in its prototype form is not ready for quantity production.

Edison Radiation Detector Tube

The radiation detector in this instrument is an Edison tube originally developed to measure ultraviolet radiation from 2200 to 2900 Å. Since it is capable of operating as a G-M tube, the Edison tube in this instrument is functioning as a G-M tube operated in the current mode. The circuit of this instrument is similar to circuits that use a conventional G-M counter tube operating in the current mode. (Although the manufacturer states⁹ that this tube, with symmetrical electrodes and no organic quench-gas filling, has characteristics that would allow its operation with an ac power supply, the survey meter is equipped with a dc high-voltage supply.)

The design of the Edison tube is not optimum for use as a gamma radiation detector. For example, "special" materials that enhance the sensitivity of the tube to ultraviolet radiation would not be required. Further, if the Edison tube were fabricated from soft glass and with conventional feed-through bases instead of the "special" materials, assembly would be easier and the cost would be lower. Consideration of this tube for production in large quantities would require redesign of the tube to yield a higher sensitivity to gamma radiation and a lower production rejection rate.

⁹ L. G. Figular, Final Report: Development of a Low Cost Gamma Radiation Survey Meter, Thomas A. Edison Research Laboratory (March 1964).

An evaluation of the Edison tube based on tests of the survey meter was reported previously.¹⁰ Some of the more significant problems were due to a lack of well-defined plateau characteristics and an unusual energy dependence of the tube. Beside these problems experienced with the prototype instrument, there are other considerations pertinent to this instrument that can be derived from operation of a G-M counter tube in the current mode:

1. Tube current is strongly dependent on the high voltage applied. An increase in voltage will increase the charge per pulse and will also change the effective volume of the tube with a resulting increase in the number of pulses. The dead time of the tube is also a function of voltage which, in turn, affects the nonlinear response at the high end.
2. The series anode resistance and the shunt capacitance greatly affect the tube response in terms of charge per pulse, dead time, and whether or not satellite pulses will occur.
3. Temperature effects, energy dependence, tube size, and tube ruggedness must also be considered since they affect the response.

Power Supply

The high-voltage power supply was designed with a drooping regulation characteristic and a manual voltage adjustment to achieve a desired nonlinear scale reading and to reduce cost. The overall efficiency of the power supply is poor, resulting in a short battery life. To increase the battery life, the supply could be made responsive to the current demand. The desired drooping voltage characteristic of production units could be better obtained by using a well-regulated supply and by adding a series resistor in the output to obtain the desired voltage droop.

Meter

Specifying a low cost meter that would match the nonlinear characteristics of the detector tube would be a problem. It would probably be necessary to calibrate the detector, high-voltage supply, and meter as a unit.

Calibration of a large number of instruments requiring the matching of component parts, each having nonlinear responses, to get a desired composite characteristic is a slow and tedious procedure. This is usually done by trying different values of shunt capacitors and series resistors with the detector in a gamma-ray field up to 100 r/hr until the correct values are found.

¹⁰H. N. Wilson, ORNL, "Evaluation of the Thomas A. Edison Research Laboratory Gamma Radiation Survey Meter," letter from C. J. Borkowski to J. W. Downs (USNRDL), May 27, 1965.

MISCELLANEOUS INSTRUMENT TESTING ASSISTANCE

ORNL evaluated instruments for OCD upon request, assisting in the solution of specific problems or aiding in determining the applicability of new instrument concepts to OCD needs. Some of these evaluations are discussed below.

A type FC counter was proposed in 1961 by the Geophysical Measurements Corporation for measuring high-level gamma radiation. ORNL tested a model of this instrument for the effect of prolonged exposure to high gamma radiation on calibration, stability, linearity at low levels of radiation, and the rise time and amplitude of the output pulse. The reported results¹¹ showed considerable nonlinearity in the response of the instrument between 1 and 10 mr/hr. A major advantage of this instrument over ion chamber and electrometer instruments is that leakage, which normally occurs in outdoor installations, cannot develop because the chamber is hermetically sealed. One disadvantage is that an intense radiation source is required to demonstrate that the instrument is functioning properly.

In 1961, ORNL evaluated the performance of Victoreen and Anton survey meters, CD-700. The results¹² indicated that the instruments performed satisfactorily and within specifications. The power supply in the Victoreen instrument was inefficient and had an unbalanced battery drain.

In 1963, ORNL evaluated a proposal made by Electro-Neutronics, Inc., regarding changes in the CD-700 survey meter. ORNL concurred¹³ with the proposed changes to the circuit which would affect the meters, increase the sensitivity to G-M tube output pulses, and reduce the effect of high-temperature leakage by changing the type of transistor used. Recommendations made by ORNL would eliminate unnecessary circuit components and improve the resolving time of the instrument.

ORNL studied CDV-717 radiological survey meters built by Victoreen.¹⁴ The manufacturer had trouble in meeting response time requirements because it was difficult to construct an ion chamber with a capacitance low enough which when added to the other input capacitance would have an RC product of less than 3 sec, and at the same time meet other specifications. This problem was discussed in detail in a report by ORNL, which stated that a less stringent requirement for the instrument response time would be a satisfactory solution and that the instrument would perform satisfactorily.

¹¹Letter from F. M. Glass to R. B. Martin, Sept. 8, 1961.

¹²Letter from F. M. Glass to R. B. Martin, Nov. 7, 1961.

¹³Letter from F. M. Glass to R. B. Martin, Nov. 7, 1963.

¹⁴Letter from C. J. Borkowski to James Kerr, July 17, 1964.

METAL-OXIDE SEMICONDUCTOR FIELD-EFFECT TRANSISTORS

Under the research contract ORNL investigated metal-oxide semiconductor field-effect transistors (MOSFETs), also known as insulated-gate field-effect transistors, and their possible use in applications now employing vacuum-tube electrometers. Increased reliability and reduced cost of an instrument using a MOSFET instead of an electrometer-tube might be achieved owing to reduced power-supply requirements.

Most MOSFETs have characteristics similar to the pentode vacuum tube. The transconductance g_m of typical commercial MOSFETs is between 200 and 10,000 micromhos. One three-terminal device in a TO-5 case contains a MOSFET integrated with a bipolar transistor; the transconductance of this device is 10^6 micromhos at a bias of 150 ma and 20 v. Both p- and n-channel devices are available with operation in either the depletion or the enhance-ment mode. The typical input-gate resistance of MOSFETs is greater than 10^{14} ohms. Input capacitance ranges from 1 to 15 pf for present devices. The input leakage current for an average MOSFET is less than 10^{-14} amp; it has been reported that some of the better units have leakage currents less than 10^{-16} amp. The gain-bandwidth figure-of-merit for most devices is 100 to 200 MHz. However, two companies offer MOSFETs having gain bandwidths greater than 1000 MHz.

It appears that MOSFETs may be useful in a wide range of circuitry, from electrometers to high-frequency amplifiers. However, MOSFETs have several disadvantages which must be considered when designing these circuits. These are:

1. The insulating layer of SiO_2 between the gate and channel is quite thin (typically less than 3000 Å), and excessive electrostatic transients can cause the SiO_2 layer to rupture. The gate must be protected in circuits where transients exceed ± 75 v.

2. When a MOSFET is operated at a high temperature ($> 100^\circ\text{C}$) and a positive gate voltage, ion migration in the bulk of the oxide layer may result in a permanent drift in the output characteristics g_m and I_{drain} . In general, no noticeable change is observed at temperatures below 60°C or under negative gate voltages. The recent innovation of silicon nitride (Si_3N_4) as the insulating layer¹⁵ offers hope for improvement of MOSFETs concerning the ion drift problem.

3. The noise of MOSFETs appears to be predominantly a flicker effect out to very high frequencies. MOSFETs currently available have noise voltages considerably higher than junction FETs. However, for most portable instruments having limited bandwidths, such as electrometers, noise is not a primary consideration.

¹⁵T. Maguire, "Silicon's New Wonder Drug," Electronics, 39 (1), 156-164 (Jan. 10, 1966).

Instability of MOSFET characteristics is now generally attributed to the presence of positive ions in the oxide layer between the metal gate and semiconductor channel of the transistor. The ions are generally believed to be due to either adsorbed water vapor or sodium contamination. The severity of this problem has been reduced by carefully restricting the possibility of contamination during the oxide growth cycle. The relaxation time constant of the ion motion may be $\geq 10^3$ sec. The influence of the ion charge is most predominant for transistors with a positive gate voltage, i.e., either an n-channel MOSFET operating in the enhancement mode or a p-channel transistor operating in the depletion mode.

The temperature characteristics of MOSFETs are now understood much better. A zero-temperature coefficient bias current has been predicted¹⁶ which is directly related to the total number of surface charges at the oxide-semiconductor interface. There is usually good agreement between theoretical predictions and experimental results.

Theoretical analysis and experimentation has shown that there is an optimum bias for which the total gate leakage current is zero; this occurs in the enhancement region of operation at a gate-to-source V_{GS} such that

$$V_{GS} \approx - \frac{V_P}{2} ,$$

where V_P is the pinch-off gate voltage.

For a given MOSFET, the gate leakage current can be made less by heating the transistor to approximately 100°C with a negative voltage on the gate and allowing it to remain at this temperature for several hours. After the transistor is cooled, the gate leakage current is reduced from its original value. The cause of this effect might be that the positive-ion charge in the oxide becomes bound to the gate-oxide interface when the transistor is heated and remains bound when the transistor is cooled.

Low current sensitivity of an amplifier having MOSFETs in the input stages is limited primarily by the gate leakage current I_G flowing in the circuit. Experimental data recently obtained at ORNL¹⁷ indicate that, for those MOSFETs that can operate in both depletion and enhancement modes, there is an optimum bias which will reduce I_G to zero. Tests on a 2N3796 n-channel MOSFET, which can operate in both enhancement and depletion modes, show that it can be biased in the $V_{DS} - I_D$ region such that leakage current from gate-to-source (or gate-to-substrate) is cancelled by the leakage current from gate to drain.

¹⁶E. J. Kennedy, A Study of the Theoretical and Practical Limitations of Low-Current Amplification by Transistorized Current-Feedback DC Electrometers, Ph.D. thesis, University of Tennessee, 1966, and ORNL-TM-1726 (to be published).

¹⁷E. J. Kennedy, "Gate Leakage Currents in MOS Field-Effect Transistors," Proc. IEEE, 54 (8), 1098-99 (Aug. 1966).

Gate leakage current measurements on p-channel enhancement-mode MOSFETs show that I_G does not change radically as the drain voltage V_D is changed. The predominant leakage is due to the gate-to-source voltage V_{GS} (or the gate-to-substrate voltage, since $V_{source} = V_{substrate}$). Since in enhancement-mode MOSFETs the gate-to-source voltage cannot change sign and is usually greater than 5 v, the two currents cannot be made to cancel one another and the advantage of an $I_G = 0$ condition is not attainable.

To evaluate MOSFET characteristics and their application in electrometer circuits, a current-feedback electrometer¹⁸ with MOSFETs in a differential input stage was built. Results of tests using two of the lowest leakage, commercially available MOSFETs in the input stage showed that the electrometer had the following characteristics:

1. The current sensitivity ranged from 1×10^{-5} to 1×10^{-14} amp full scale.
2. The output voltage drift over a 43-hr period was within $\pm 6\%$ of full scale on the most sensitive range (1×10^{-14} amp).
3. The output peak-to-peak noise was less than 7% (6 mv) of full scale on the 1×10^{-14} amp range.
4. The output voltage change for a $+10^\circ\text{C}$ change in temperature was within $\pm 2\%$ of full scale on the 1×10^{-14} amp range.
5. The input leakage current was less than 1×10^{-15} amp.
6. The amplifier open-loop voltage gain was 300.
7. The amplifier open-loop bandwidth was 1 kc.
8. The amplifier steady-state power requirements were 5 ma at +14 v and 4.2 ma at -14 v.

Two new nuclear instruments were developed using MOSFETs in the input stages: a dc current integrator, ORNL model Q-2895,¹⁹ and a portable ionization chamber survey meter, ORNL model Q-2898.

The dc current integrator operates in a manner similar to that of more conventional current integrators in that the voltage across a storage capacitor in the input circuit is monitored by a MOSFET electrometer operational amplifier whose output triggers a discriminator at a given voltage level. The discriminator generates a reset pulse which operates a current switch and removes a fixed charge from the integrating capacitor. At the same time, the discriminator pulse drives a scaler that counts the number of times the operation is repeated and indicates the total integrated current applied to the instrument. The instrument has full-scale

¹⁸E. J. Kennedy, "Metal-Oxide-Semiconductor Field-Effect Transistors in Electrometer Applications," Instrumentation and Controls Div. Ann. Progr. Rept. Sept. 1, 1965, ORNL-3875, pp. 13-14.

¹⁹F. M. Glass, et al., "A New Approach to Direct Current Integration," paper presented at the 13th Nuclear Science Symposium, Boston, Mass., Oct. 19-21, 1966, sponsored by the IEEE.

ranges from 1×10^{-11} to 2×10^{-4} amp with a repeatability of 500 ppm. The total input leakage current is less than 1×10^{-13} amp.

The portable ionization chamber survey meter also has MOSFETs in a differential current-feedback electrometer circuit. The input terminal of the electrometer is connected directly to a 500-cc ionization chamber. The survey meter requires two 1.5-v "D" cells to furnish power for a dc-to-dc converter.

MOSFETs are currently available from ten companies in the United States and two abroad. Several of these devices have passed the initial developmental and sampling phases and are now in full production, with registered JEDEC 2N numbers. Prices, which originally were about \$50 each in lots of 1-99, are now \$12-30, with the expectation of continued reductions as additional types and greater quantities are marketed.

MOSFETs will be useful in future design of instruments for civil defense applications, since circuits designed to replace similar vacuum-tube circuits will not require regulated filament voltage supplies and will not experience the accompanying drain on supply batteries.

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