COO-323-41

SPECIAL PROBLEMS IN NUCLEAR INSTRUMENTATION

Final Report

For period ending July 31, 1978

John J. Spokas

Physical Sciences Laboratory
Illinois Benedictine College
Lisle, Illinois 60532

October 31, 1979

NOTICE

This report was prepared as an account of work sponsored by the United States Government. The Unites States and the United States Department of Energy, their employees, and their contractors and subcontractors as well as their employees neither make any expressed or implied warranty; nor assume any legal liability and responsibility for the accuracy, completeness, and usefulness of; nor represent that privately owned rights would not be infringed by the use of any apparatus, product, and process disclosed.

Prepared for

The U.S. Department of Energy

UNDER CONTRACT NO. EY-76-S-02-0323

DISCLAIMER

I. INTRODUCTION

This report will review and summarize the significant accomplishments of the project, Special Topics in Nuclear Instrumentation, which was supported in part by the U.S. Department of Energy under Special Research Support Agreement EY-76-S-02-0323. The program was initiated on September 1, 1954 with support provided by the U.S. Atomic Energy Commission under Contract AT(II-1)-323 and with Francis R. Shonka as the sole principal investigator.

The program was expanded on April 1, 1956 to include the project, Ionization in Gases, for which William P. Jesse served as the principal investigator. Ionization in Gases was terminated on August 31, 1972 upon the retirement of William Jesse from full-time research. Jesse's annual report dated June 30, 1969 contained a comprehensive review of the total accomplishments under this particular project up to that time. A final report for Ionization in Gases, Report COO-323-29, was filed on August 25, 1972 and adequately covered the subsequent progress. Consequently Ionization in Gases will not be considered further in this report.

Shortly after the death of Francis Shonka on October 11, 1970 John J. Spokas assumed the role of principal investigator for Special Topics in Nuclear Instrumentation. John Spokas served in this capacity at a level of about 90% until the termination of the agreement on July 31, 1978. No other investigators received support under the contract. The principal investigators were aided in diverse ways by other scientists thru numerous collaborations. To be sure, these collaborations also benefited the other scientists and their programs.

The annual report under U.S. Atomic Energy Commission Contract AT(11-1)-323 dated June 30, 1969 included a comprehensive review of the total accomplishments which had been achieved under the project, Special Topics in Nuclear Instrumentation, from its inception until that time. Therefore this report will be confined to those important advances which have been made from July 1969 until the termination of the project on July 31, 1978.

Activities of the concluding period of the contract are noted separately in the following section. A major component of the project has been the development of special conducting plastics to meet the special needs of radiation dosimetry. The work in this area during the period covered by this report is summarized in Section III. The most critical application of the special plastics which have been developed under this contract is in the construction of ionization chambers. Ionization chambers provide the most practicable means of accurately measuring absorbed dose and exposure. The many important advances which have been made under this contract in the design and fabrication of ionization chambers will be reviewed in Section IV. The final section will cover the work in related areas such as electrometers and low-noise signal cables for use with ionization chambers. A list of patents and publications for the period covered by this report will be found at the end of the report.

II. PROGRESS REPORT: 1 September 1977 to 31 July 1978

The principal activities during the concluding period of the contract include: the preparation and study of a new conducting tissue-equivalent (muscle) plastic mixture; the design, construction, and evaluation of a planar chamber; a comprehensive review of the density of all the successful conducting mixtures which have been developed here in the Physical Sciences Laboratory; and the writing of a technical report, "Preparation and Properties of Conducting Solid Mixtures", Report COO-323-40. Each of these activities will be summarized below.

At a photon energy of 30 KeV, A150 fails to match soft human tissue by 15 % or so (see Conference Paper COO-323-33). A new formulation was designed by Lowell Anderson of Memorial Hospital in consultation with us which matches soft tissue precisely with respect to photons of energy equal to 30 KeV. The new formulation has been designated A180 and contains the following components by mass:

TPX (polymethyl pentene)	67.6%
MgO	17.7%
Carbon Black	13.5%
CaF_2	1.2%

By using the polymer, TPX, whose specific gravity is .830 it was possible to adjust the concentrations in order to achieve a resultant density very near to that of soft tissue. The calculated density of 1.067 g/cm^3 is to be compared to the measured value of 1.0565±.0005 g/cm^3.

Since A180 contains only a single polymer component there is no problem of miscibility of different polymers in the preparation of the mixture. Mixing mainly is to achieve a high degree of homogeneity in the dispersion of the inert components as well as a high and stable electrical conductivity. Mix- was accomplished in the Shonka reciprocating extrusion mixer operating at a speed of 130 rpm and at a temperature of 525 ^{0}F. At 525 ^{0}F this mixture has a consistency comparable to that shown at the mixing temperature by other formulations which have been successfully prepared with this equipment.

Although this represents the first experience with TPX no problems were encountered in mixing A180. The working temperature of A180 is the highest thus far encountered. Since TPX was not available in powdered form it was necessary to first grind TPX to a sufficiently small mean particle size in order to obtain reasonable initial homogeneity.

Seven separate attempts were required in order to successfully cast a block of A180 of 14 inches diameter and 2 inches thickness. The first problems encountered were inadequate heating power and non-uniform mold temperatures. These problems were rectified by the addition of two cartridge heaters to the mold base. The poor thermal conductivity and higher flow temperatures of A180 also require that the mold be held at the requisite temperature for significantly longer than A150. Furthermore, to avoid fractures and distortions in the block the cooling rate must be decidedly less than that which would result by merely terminating heating power.

A molding schedule which was found to yield well-formed blocks is the following. The mold is first brought to 500 °F. When this temperature has been achieved throughout the mold, the pressure in the mold is increased to 2 kpsi. After holding these conditions for at least 3 hours the mold is permitted to cool to 350 °F while the pressure is maintained at 2 kpsi. Three hours after the commencement of cooling, heating is terminated and the pressure reduced to essentially zero. It has subsequently been determined that the room temperature resistivity ranges from 100 to 1000 Ω-cm for A180 formed according to this schedule.

The phantom and planar chamber needed for the planned neutron dosimetry studies were completed. The chamber is constructed almost entirely of A150.

It is fully guarded having a collecting gas volume in the form of a circular disk 2 cm in diameter and 1 mm in thickness. The front window has a thickness of 0.5 mm. The chamber is fitted with two tubes for gas inlet and exhaust. A low-noise triaxial cable is connected directly to the chamber. Thus the chamber has no stem.

Except for the cable and gas tubes the outside dimensions of the chamber are 4.8 cm in diameter and 1.0 cm in thickness. A 14-inch A150 phantom disk has been machined to hold the chamber with the window flush with the top surface of the disk. The chamber can be positioned at different depths in the phantom by merely re-arranging the phantom plates. Two identical chambers have been made one of which is to serve as a spare.

A third planar chamber following much the same design has also been fabricated. This chamber is arranged to take disks of 1.5 inches diameter as the outer electrode. The disks can be readily mounted on the chamber. The chamber was intended for evaluative measurements on different materials with respect to their suitability for use as chamber electrodes. The collector, guard, and outer electrode support ring were made of the Shonka air-equivalent plastic, C552. C552 was chosen since it shows relatively large electrical conduction and is very rugged mechanically. The demountable chamber has been tested and successfully used to demonstrate the suitability of A180 for chamber electrodes.

The density has been determined for each of the successful mixtures which have been designed under this contract as well as for five Nylon-polypropylene-carbon test mixtures. The results are summarized in the technical report (COO-323-40) which was written during this period and will not be duplicated here. Previously reported measurements were re-analyzed and a new value was obtained for the effective density of the carbon black, a common ingredient in all of the mixtures. The new value for carbon black is 1.944 g/cm^3 compared to the previous value of 2.008 g/cm^3.

Even with the new lower value for carbon, the calculated densities of the mixtures are generally higher than the measured ones. Perhaps the effective density of carbon black is less than the latest value which has been determined for it. It may also be that carbon black, as well as the other inert powders used in the various mixtures, shows different densities when dispersed in different hosts.

For the last several months of the contract the entire effort focussed exclusively on the preparation of a comprehensive report documenting all the readily available information on the important mixtures which had been achieved up to the present. Unfortunately there was no opportunity to obtain any accurate quantitative information concerning the electrical conductivity of any of the mixtures.

The report describes the particular approach which characterizes the Shonka plastic mixtures. Of major importance in obtaining the excellent properties of the final product is the special machine in which the mixtures are blended. The machine, a reciprocating extrusion-mixer, is described in detail in the report. Since the machine operates continuously rather than for a batch at a time, a high degree of homogeneity and consistency can be achieved in addition to intensive mixing.

Defining compositions are given in the report for all the successful formulations. The particular conditions under which different formulations have been prepared are noted. What is known concerning molding and welding characteristics is also given. The photon attenuation and photoelectric cross-sections which have been calculated are included in the report as well as the results of the density measurements which were mentioned above.

III. CONDUCTING PLASTICS

The major thrust of the work under this contract has constantly been the development of special conducting plastics which are needed for accurate dosimetry by ionometric means. By concentrating on and by making advances in the actual blending process, Francis Shonka achieved stable plastic mixtures of unusually high uniformity and electrical conductivity. A new concept in plastics blending equipment emerged from these considerations. This concept was given expression in a novel reciprocating extrusion mixer. Only one such device has been constructed. Since its completion this machine has been used exclusively in the Physical Sciences Laboratory in the preparation of various conducting plastic mixtures.

A significant concern after the death of Francis Shonka was whether the capability of producing quality conducting plastics as Francis Shonka did might have been lost. The available information appeared to be meager. However by paying close attention to the operation of the special Shonka plastics mixer, an understanding of the machine and its operation has been achieved. Consequently, not only has it been possible to duplicate the standard Shonka formulations A150 (muscle), B100 (bone), and C552 (air) but a number of new mixtures have been successfully prepared with the same machine.

The study of the operation of the mixer led to the incorporation of several improvements in it. These include; reduction of the length of the main drive chain and converting to a stouter chain; reconstruction of the ball bearing spline shaft and fitting; introduction of a key to lock the drive sprocket to the shaft of the mixing screw; addition of dowel pins for locating the barrel positively with respect to both longitudinal displacements and rotations; a complete redesign of the feed screw drive mechanism; and installation of a more efficient hopper to hold the homogenized ingredients. A number of procedural items were found to be of significance in the mixing process. Some of these are: pre-mixing techniques; feeding strategies; use of blowers to cool the mixing chamber; and control of the general air flow in the vicinity of the mixer.

The main drive chain must withstand the shocks accompanying the repeated reversing of the direction of rotation. Frequent stoppages were occasioned by the breaking of the drive chain. First slack would develop as the chain stretched during use. With increasing slack in the chain, reversing of direction produces ever increasing impulsive tensile stresses leading ultimately to the breaking of one or more chain links. This problem has been almost entirely eliminated by: re-arranging the drive motor so as to reduce the length of chain; converting over to a stouter chain (from a 1/2-inch pitch No. 41 to No. 40 roller chain); and regularly checking the chain and removing any slack which may develop in it.

The mixing screw is connected to a ball bearing spline shaft by means of a chain coupler. The spline shaft permits the screw to move axially somewhat over four inches as the screw rotates alternately clockwise and counter clockwise. The original shaft of the spline was in two parts held together by means of twenty small set screws. This proved to be a poor arrangement which rapidly worsened. The continual reversing would loosen the screws in a short time. Furthermore, the tapped holes were stretched and distorted as the screws were forced sideways back and forth. Subsequently the screws would be loosened in less time. Recognizing this degeneration and the number of set screws and the much time required to tighten them, a new one-piece spline shaft and matching fitting were built and installed on the mixer.

Originally a sprocket was secured to the shaft of the mixing screw by means of three set screws. The repeated starting and stopping required by the mixer cycle was more than this method of anchoring could withstand. Accordingly, a 1/4 inch key was introduced to lock the sprocket to the mixing screw shaft.

The extrusion force generated in the mixer is rather substantial. The mixing chamber itself must supply the reaction to this force and therefore will experience repeated forward thrusts. It is not surprising that the barrel would inch forward in its split collar type mounting brackets as a consequence of such thrusts. If the barrel were not reset periodically, the mixing screw would eventually make contact with the rear end plug and wear it away. The addition of a dowel pin in each of the two support brackets stopped both axial and rotational shifting of the mixing chamber.

There were a number of problems with the original feed drive setup. The feed had been operated intermittently. The feed would commence with the onset of extrusion and continue afterwards for several seconds. The length of time the feed operated was governed by a timer. A disk clutch driven by a pair of solenoids allowed control of the feed. The solenoids frequently burned out. Power for the feed screw was brought in thru a reducing right angle bevel gear. Wear and broken teeth on the gears and slipping of the gears on shafts were further problems encountered with the feed. A more powerful feed motor was introduced and was coupled directly to the feed screw by means of a roller chain. Considerable adjustment of the speed of the feed screw is readily accomplished now by substitution of sprockets of different sizes.

The ingredients of a given formulation are weighed in discrete amounts of 500 g or so and placed into gallon sized jars or cans. By rolling the containers for approximately 40 min the ingredients are homogenized while still in the powdered state. Some ingredients, though fine powders, are lumpy and remain so to some extent thru the rolling operation. The inclusion of a rod in the container during rolling has been found to be most effective in breaking all but the hardest lumps. The addition of spiral flutes to such rollers would seem to be a further improvement. The flutes would be left-handed on one half of the roller and right-handed on the other half. The fluted rollers would cause an axial movement of the powders during rolling either towards the center or away from the center depending upon their placement in the container. A higher degree of mixing would thus be achieved.

For some mixtures the feed screw is unable to force the ingredients into the mixing chamber. Two factors operate here. One pertains to the lack of friction of the powder. The second has to do with the volume of gas which is driven out of the powder. The main avenue of escape of gas is back along the feed screw and into the loading hopper. The escaping gas may force some powder with it thus countering the action of the feed screw. When such a situation is encountered it has been found that the addition of granular mixed material to the ingredients improves and regularizes the flow of material into the mixing chamber.

For some mixtures it has been found to be necessary to use some degree of forced cooling on the mixing chamber in order to maintain the correct operating temperature. In such cases the mechanical working of the material in the chamber generates more than enough heat to compensate for losses to the surroundings and for the heat carried away by the extrudate. Some formulations do not exhibit so much internal friction and in these cases heat must constantly be supplied to the chamber to maintain the desired operating temperature.

It has been found most helpful to maintain a positive airflow in the general vicinity of the mixer. This controls and confines the obnoxious fumes and vapors asscoiated with certain mixtures as well as the finely divided powders which must be handled. It is impossible to prevent some of the powder from becomming air-borne. Were it not for controlling of the airflow, such powder would diffuse and settle over a surprisingly broad area. Because the mixing operation is such a dirty one for a number of years it has been located in a improvised enclosure set up outdoors well removed from labs, offices, and shops.

Presently the mixing chamber and ball bearing spline journal are mounted on a discarded lapping plate. The same journal holds the thrust bearing which produces the extrusion force. The casting which provides a flat surface 18" x 24" on an edge is approximately 5/8" thick with ribs around the periphery as well as two intersecting ribs in the center and parallel to the edges. Though the plate would seem to provide a sound base for the mixer, the extrusion forces are so large as to cause the plate to buckle more than 1/8" during extrusion. The buckling produces a tranverse force between the barrel and screw resulting in appreciable drag on the screw and excessive wear of both barrel and screw. This problem would be eliminated by securing the barrel directly to the journal by means of four tie rods. No transverse forces would result from this arrangement and wear would be greatly reduced. An opportunity to effect this important modification has not yet presented itself.

Nine new formulations have been prepared. The first two are simply dispersions of carbon black in polypropylene. One mixture, E105, has 30 % carbon black and the second, E106, has 20 % carbon black. In all, five separate batches of these mixtures were made at mixing temperatures ranging from 350 to 400 °F.

Five of the new formulations represent a series of test mixtures to determine the compatability of polypropylene and nylon 11. The main interest in polypropylene and nylon 11 were as possible substitutes for polyethylene and nylon 66 in the standard muscle formulation A150. The atomic composition of A150 would be preserved by suitably adjusting the proportions of polypropylene, nylon, and carbon black. Such a new muscle would offer a more precise composition, greater heat resistance, and greater mechanical strength.

Each of these five test mixtures contain 13.6 % carbon black. The balance of the mixture is a different proportion of polyprolylene and nylon ranging from 0 to 100 %. These test mixture have been designated E100, E101, E102, E103, and E104 with the polypropylene/nylon fractions of 75, 50, 25, 0, and 100 % respectively. Two batches were prepared of each of the mixtures. One batch was blended at 350 °F and the second at 400 °F. Ten pounds were prepared of each of the first three mixtures and five pounds of the last two. The mixer did not respond well for those mixtures containing the heaviest nylon concentrations. For one thing feeding was sporadic and fiberous strands developed in the mixing chamber impairing extrusion.

Forty separate moldings have been made of these mixtures to provide specimens for evaluation. The specimens were compression molded in a 1 1/2" diameter mold at different temperatures ranging from 360 to 450 °F. Extensive density measurements show regular behavior for this system with the density varying linearly from 0.976 to 1.116 g/cm^3 with nylon-polypropylene ratio. Analysis of the density for these mixtures has lead to the value of 1.944 g/cm^3 for the effective density of carbon black. The practibility of mixtures of this type will depend on the outcome of further critical evaluations.

Two entirely new tissue substitutes have been reduced to practice and found to be suitable for the electrodes of ionization chambers. The first is designated B110 and was designed by David White of St. Bartholomew's Hospital, London in consultation with us. B110 was formulated as a substitue for the cortical bone composition given by Woodard (Health Phys. 8, 513(1962)). The composition of B110 is:

Nylon 66	32.07%
CaF_2	51.22%
Carbon Black	13.84%
Polyethylene	2.87%

It will be observed that B110 contains the same components as A150 and B100 but in quite different concentrations. B110 has the greatest concentration of inert ingredients of any successful mixture prepared previously in the Shonka mixer. The density of solid B110 has been found to be 1.77 g/cm^3.

The evaluation of mixtures was approached from several different standpoints. Compositions of various formulations have been established and calculations of photon interaction cross sections have been completed for a number of mixtures. Proper molding procedures have been determined and the density in solid form has been comprehensively studied. Several different welding techniques have been investigated and found applicable to particular conducting plastics.

A widespread confusion existed concerning the composition of A150. This was investigated and the results were reported in a paper read at the 1975 Meeting of the Radiation Research Society in Miami Beach (Conference Paper COO-323-33). The composition of two other muscle formulations were reported in the same paper. The total photon attenuation and photoelectric cross sections were calculated for photon energies between 10 KeV and 8 MeV. The cross sections used in the calculations were those compiled in the ENDF/B data file (G.L.Simmons & J.H. Hubbell, NBSIR 73-241 (1973)). This compilation is the most complete and up-to-date of which we are aware. These calculations were also included in the Miami Beach paper.

The composition of all the successful mixtures prepared under this contract were reviewed in the technical report, "Preparation of Conducting Solid Mixtures" (Report COO-323-40). The photon cross sections were calculated for many of the mixtures and comparisons were made with the particular substances being simulated. These results may be found in the technical report.

It seems reasonable that there would be no interaction between the inert powder and polymer hosts of the mixtures considered here. If possible interactions between different polymers present in the same mixture are neglected the density of the mixture would then be simply the specific volume averaged with respect to mass over the components of the mixture. Actual measured densities agree well with such calculated values (Report COO-323-40). The greatest disparities occur for A116 and B110 where the measured values are 4.3 and 3.8 % low respectively.

Proper molding conditions have been determined for casting large blocks of 14-inches diameter. The mold must be held at the appropriate forming temperature sufficiently long to insure achieving adequate temperatures throughout the volume of the block. Then, particularly for the thickest blocks, the cooling must be prolonged to yield uniform cooling throughout and an undistorted stress-free block. In the case of C552 the material must be held under pressure in order to force gas out (or possibly in!) which otherwise would result in voids in the interior. A 14-inch diameter block 2 inches thick of C552 shows a pattern of small spherical holes concentrated near the median plane if the pressure and temperature are not maintained long enough. For such a block, one hour at 400 ^{0}F and 2 kpsi is sufficient to eliminate these voids.

In the case of A150 the thermal conductivity is evidently relatively low and a 2-inch block must be held at the forming temperature, 300 ^{0}F for a much longer time. Here the problem is not one of voids but one of granularity due to failing to reach adequate temperatures in the interior. A more effective means to form such blocks is to extrude the material directly into the mold. Possible granularity is eliminated and the only concern is to limit the cooling rate to avoid fissures, distortions and stresses. Adequate forming temperatures are guaranteed throughout the piece since the mold is filled with plastic already plasticized.

In forming a block of A150 14-inches in diameter and nearly 4 inches thick the mold is filled at 300 ^{0}F. Three separate controllers are used to regulate the temperature of the mold. One sets the temperature of the base plate, another that of the sides, and the third that of the core pin or piston. These controllers are reset to 225 ^{0}F after the mold has been filled. Four hours or more later the heaters are turned off and the mold is permitted to equilibrate with the surroundings overnight.

Though several attempts were made, it proved impossible to extrude C552 into the 14-inch mold. C552 does not flow well at any temperature and at elevated temperatures one encounters decomposition of the plastic component. It appears that under hydrostatic pressure the decomposition may be accelerated. Each time extruding C552 into the mold was tried the connecting line between the extruder and mold ruptured.

In addition to compression molding, injection and transfer molding methods have been successfully used with many of the conducting plastic mixtures. One usually finds that molded parts are smaller by 1-2 % than the mold in which they were formed. The shrinkage is not completely isotopic but follows to some extent the geometry of the part. The precise degree of shrinking depends not only on the material but also on particulars of the molding cycle.

An after-shrinkage has been discovered in parts injection molded from A150. This shrinkage amounts to very nearly 1 %. Annealing the molded parts at 150 ^{0}F for 48 hours will cause the shrinkage to occur after which no further dimensional changes are noted. It is speculated that this effect is related to the volatile plasticizer which is employed in the manufacture of the nylon component of A150.

Several distinct welding methods have been found for joining conducting plastic parts. The methods include heat sealing, friction welding, capacitor discharge welding, ultrasonic bonding. Each method is capable of yielding mechanically rugged joints which can be vacuum-tight. A wire placed at the interface between two parts to be ultrasonically welded has proved to be an excellent means for attaching electrical leads to conducting plastic parts. These special techniques have been reviewed and illustrated with specific examples in the technical report, "Preparation of Conducting Solid Mixtures", (Report COO-323-40).

IV. IONIZATION CHAMBERS

The most critical need for conducting plastic substitutes is in the construction of ionization chambers. It is quite natural therefore that a significant effort has been devoted to the use of the special plastics which have been developed under this contract in fabrication of chambers for diverse applications. The recent work in this area will be reviewed in this section. Several new chamber designs have been achieved. One, having a thimble geometry and collecting volume of 0.5cc, is intended for routine depth dose evaluations of therapy radiation fields. This design is useful in characterizing photon, neutron, and electron beams. Two other chambers represent scaled-up versions of an earlier design due to Shonka and Wyckoff (Radiation Dosimetry Vol. 2 edited by Attix and Roesch p. 54 (1966)). A new planar design for fundamental measurements was described above in Section II. The usefulness as well as the reliability of several established chambers have been extended by better fabrication techniques, certain design changes, and added features. Most of the chambers which have been developed under this contract are available from Exradin, Inc. (Box Q, Warrenville, IL 60555).

The new thimble type chamber has been made in three versions, TE, Mg, and Air. An early drawing of the TE version is shown in Fig. 1. These chambers are gas-tight and are fitted with two gas ports in the base for gas inlet

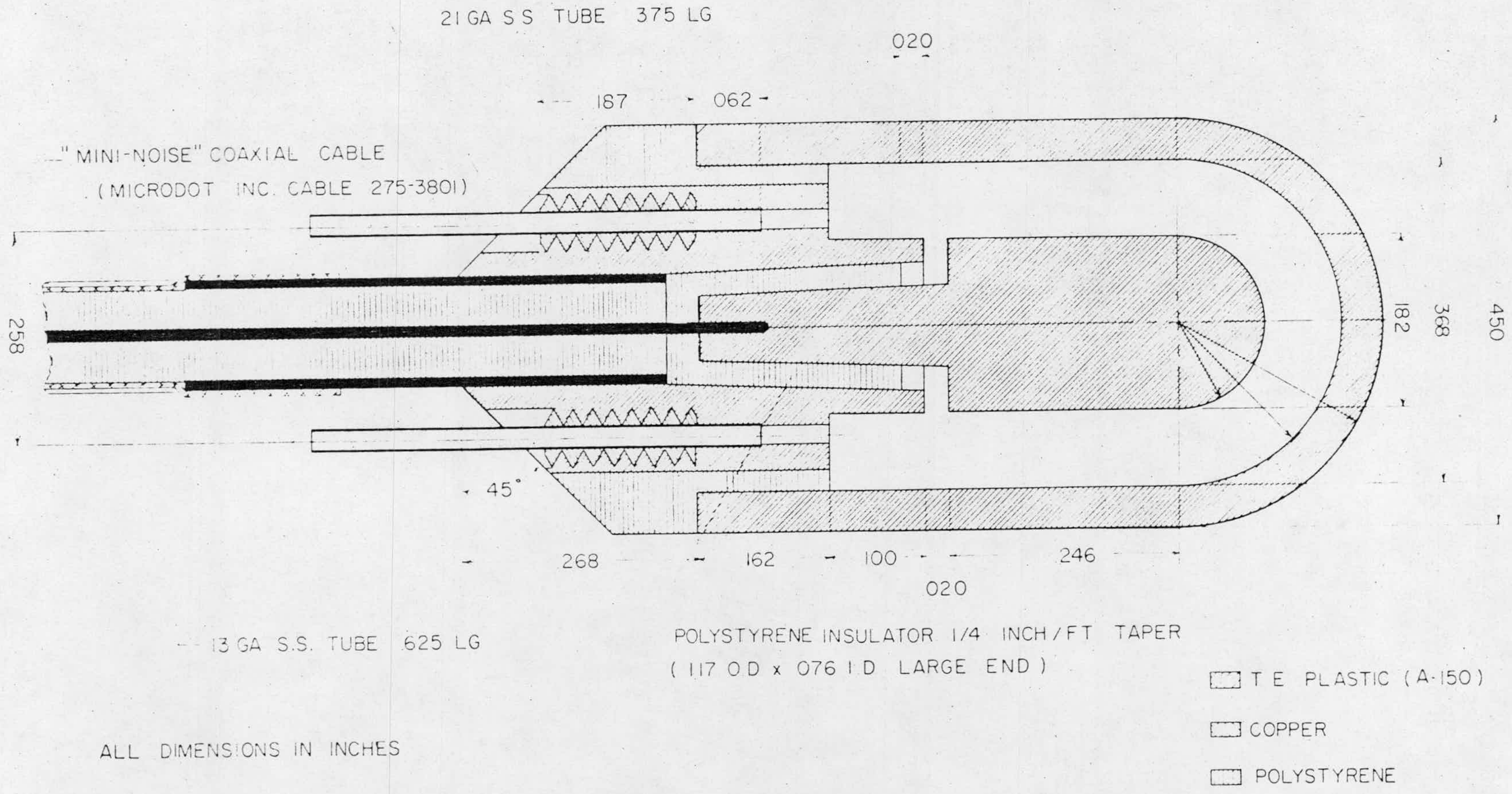

Figure 1. The 0.5 cm^3 thimble type TE Chamber.

and exhaust. The diameter of the collector was kept relatively large in order to reduce electric field variations in the collecting volume and thereby to achieve improved saturation characteristics. An extended guard provides a buffer region where the electric field is substantially higher but from which ions are drawn to the guard thus not contributing to the measured current. This serves to better define the "collecting volume", preserves good saturation behavior, and avoids soakage effects which would be founded in the dielectric polarization of the shell insulator.

More recently the collector-guard gap has been reduced to .005 inches and a triaxial cable attached directly to the chamber by means of a short piece of 17 gauge stainless steel tubing. The former cable was only a two conductor one and so an additional wire was needed to provide connection to the shell. The older cable was found to be inadequately shielded and to have radiation induced currents substantially greater than found in the newer cable.

The design is basically axially symmetric. The directional response measured in a well collimated Cobalt-60 beam shows variations within ± 1 % for all directions outside a cone centered over the stem and having a half angle of 60 ^{0}. Although the measurements were made on a TE chamber, the Magnesium and Air ones would be expected to show similar behavior.

In the case of the TE and Air versions, the HV or shell insulator is friction welded to the guard. In the TE chamber the materials are polyethylene and A150 and in the Air, polyvinylidene fluoride (Kynar) and C552. In the Magnesium chambers polyvinylidene fluoride is molded unto the Magnesium guard. In order to minimize the neutron response of the magnesium chamber, a thin Teflon washer covers the exposed surface of the shell insulation. Most recently, a Teflon collector insulator has been employed in all three versions of a 0.5 cc chambers.

The chief use of the Magnesium chamber is as a neutron insensitive chamber to be used along with the TE chamber in mixed fields in order to separate the individual photon and neutron doses. A series of measurements were made using four Magnesium chambers identical in all respects except that Teflon was used in two for the shell and collector insulator and polyethylene was used in the other two. The object of this study was to ascertain the possible contribution to the neutron response of polyethylene in these parts.

The four chambers were connected in a simple series arrangement in the gas-flow circuit. Argon was selected as the filling gas in order to minimize the neutron response of the chambers. The gamma response was determined for each chamber in a Cobalt-60 field. The response of each chamber at a fixed position in the neutron field of the Janus reactor at Argonne National Laboratory was then determined. The readings from each of the four chambers were normalized to those of a monitor which was kept in a fixed position. The determination of the neutron response was repeated with the order of the chambers in the gas circuit reversed. Finally, the Cobalt-60 responses were re-determined with the order of the chambers still reversed in the gas-flow circuit.

The results of these experiments were most interesting because of a significant unexpected result. The chambers with polyethylene indeed showed greater neutron response relative to those with Teflon as expected. The difference may be as much as 50 %. The unexpected result was the significant differences, on the order of 40 %, in the neutron response between chambers having the same type insulator. Clearly, something besides the type of insulator profoundly influences the neutron sensitivity of the chambers.

The four chambers employed in the experiments were fabricated from shells, collectors, and guards which were not made at the same time. Consequently, some had a higher degree of surface degradation than others. That the surface condition of magnesium affects the neutron sensitivity was confirmed in a separate experiment involving a parallel-plate chamber. A freshly machined magnesium surface was found to give a markedly lower response relative to one which had been machined several years earlier. It would seem that the surface condition can alter the neutron sensitivity of Magnesium-Argon chambers by at least 50 % and perhaps more than 100 %. Further experiments are needed to quantify this effect.

The ordering in the gas circuit did not reveal any clearly interpretable results. In the Cobalt-60 field the chamber in the first position showed a greater response by about 0.7 - 0.8 % than when in the last position. This is in the direction of an effect due to a pressure gradient along the circuit but the magnitude, though rather small, is much greater than that calculated from the actual pressure variations. In the Janus field the chamber in the first position showed a lesser response by 0.2 - 0.3 % than when in the last position. It would seem that the minor variations associated with position in the gas circuit are of the same order as the repeatability of the measurements.

Besides the effect due to pressure gradient there could be an effect due to an increasing contamination of the gas along the circuit. The higher contamination expected downstream should cause an increase in the response for both neutrons and photons.

The 16-liter and 8-inch spherical ionization chambers (Rose, J.E., and Shonka, F.R., Rad.Res. 36 384(1968)) had shown a relatively long stabilization time when used in measurement of background radiation levels. This effect has been identified as a voltage soakage effect which is founded in dielectric polarization of the shell-guard insulator. The insulator was re-designed in order to eliminate such effects completely. The re-design necessitated new fabrication methods and several such methods have been worked out.

The total elimination of soakage currents in these chambers allows the polarizing potential to be reversed between successive readings. Thus any offset currents which may exist in the input circuit of the electrometer, including cables and connectors, can be circumvented.

An improved method of friction welding the spherical outer electrode of these low-level chambers has been devised. Formerly an aluminum alignment form was set in one hemisphere. The form projected 1/8 inches or so out of one hemisphere to engage the other hemisphere during welding. The form was in pieces which could be disassembled and removed through the neck of the sphere after welding. The new method dispenses with the aluminum form. One hemisphere mounted on a stationary spindle is spun while the other is held fixed in terms of translation as well as rotation. The method has been successfully used on 8-inch chambers molded of A150 and C552. It is anticipated that the method will also work on the 16-liter (12 3/4 inches O.D.) chambers.

It is suggested that a further improvement in the quality of the equator weld in these chambers could be realized by molding a small step in the shells at the equator. The step would serve to guarantee alignment of the two halves and give the completed shperes much greater strength at the equator.

An air-equivalent transfer chamber was developed by Francis Shonka under this contract in collaboration with H.O. Wyckoff. This particular chamber is now known as the Shonka-Wyckoff chamber. A description of the chamber is given in Radiation Dosimetry, Vol.II (edited by Attix & Roesch, Academic Press, 1966 pp 54-55). Difficulty had been encountered with the cable attachment and the means of establishing electrical contact to the shell of the chamber. A new means of attaching the cable and of contacting the shell have been developed and reduced to practice. In both cases wire is imbedded in conducting plastic by ultrasonically welding two separate parts together. The method provides electrical contact of unsurpassed integrity and reliability and also a sturdy mechanical anchoring of the shell wires and of the cable.

Evidently all of the Shonka-Wyckoff chambers made previously did not conform to the description given in the reference noted above particularly with respect to details of the guard electrode. A number of these chambers show higher capacitance and soakage effects than would be expected according to the published chamber drawing. The latest version restores complete guarding to the chamber thus eliminating voltage soakage transients and yielding a chamber capacitance of approximately 0.45 pF.

The collecting volume, except for the collector electrode, of the original Shonka-Wyckoff chamber was spherical and of nominal diameter of 0.75 inches. Two versions were settled on and produced. One has an outer electrode of .010 inches wall thickness and is useful at energies as low as 20 KeV. The other has a wall thickness of .10 inches which provides adequate electronic equilibrium for Cobalt-60. Two new chambers were designed according to the Shonka-Wyckoff design. One has a nominal collecting volume of 30 cm^3 while the other, 100 cm^3. In these chambers the Shonka-Wyckoff design was followed precisely with every linear dimension scaled up by a factor of 2 for the 30 cm^3 design and 3 for the 100 cm^3 design except for the wall thickness.

The wall thickness was kept at .020 for both of the new designs. Because of the greater size of the chamber it was feasible to employ hollow collectors.

Figure 2 offers a scaled sectional drawing of the 100 cm^3 chamber. The improved means of wire and cable attachment which had been instituted in the Shonka-Wyckoff chamber has been incorporated in the two new chambers. There are two diametrically opposed breathing holes in the neck which insure rapid equilibration between the collecting volume and the ambient atmosphere. The larger size of these chambers made it possible to achieve a superior guard configuration wherein the collector has the same outside diameter as the guard and represents a smooth extension of the guard. This arrangement allows an extremely precise definition of the collecting volume.

The new chambers provide increased detectability over the original Shonka-Wyckoff chambers at the expense of spatial resolution. The integrity and reliability have not been sacrificed in the slightest. The 100 cm^3 chamber is expected to be particularly useful in verifying whether leakage from x-ray producing equipment is within the limits specified in the Radiation Control for Health and Safety Act of 1968.

A miniature TE chamber having a thimble geometry had been developed earlier for the accurate determination of depth-dose profiles. The chamber cavity has a cylindrical section which is capped by a matching hemispherical end. The collecting volume is approximately 0.05 cm^3. Some performance characteristics and drawings of this chamber are given in the technical reports TN71-2 (May 1971) and TN71-7 (December 1971) published by the Armed Forces Radiobiology Research Institute, Bethesda, Maryland. Significant improvements have been made in this chamber in the chamber guarding, the choice of cable which is intregal with the chamber, and in the method of establishing

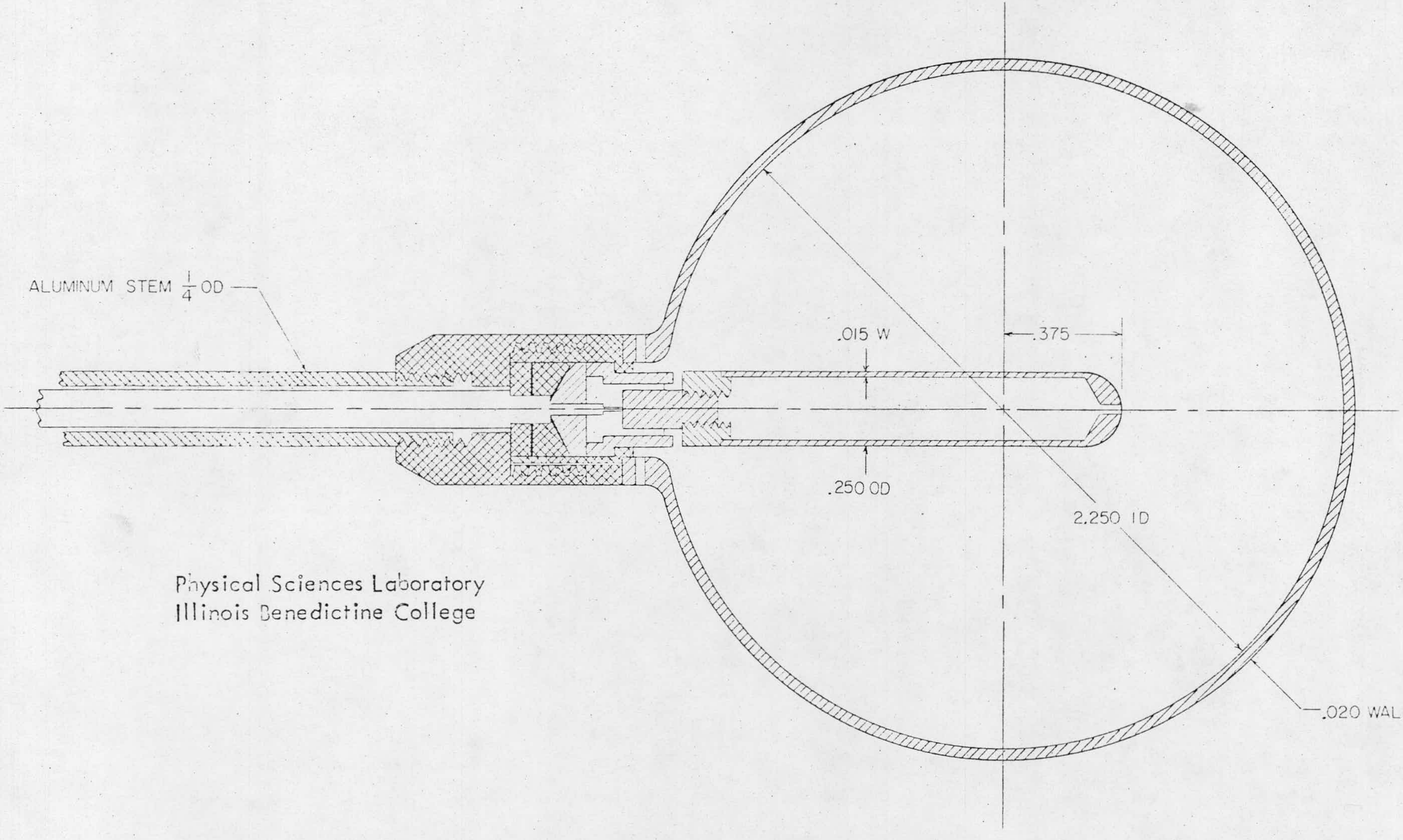

Figure 2. The 100 cm^3 air-equivalent Shonka-Wyckoff type chamber.

contact to the outer electrode. Furthermore the chamber has been made gas-tight and has been equipped with a pair of small tubes to allow a TE gas mixture to be circulated thru the chamber during dose measurements.

In order to achieve the improvements and the gas-flow feature the method of fabrication had to be drastically altered. However, the dimensions and shape of the collecting volume as well as the wall thickness of the outer electrode were preserved. The shell lead wire is imbedded in an ultrasonic weld. This approach has been used in other chamber designs with great success as noted above.

V. OTHER PROJECTS

The signifcant accomplishments on several additional projects will be reviewed in this section. The projects are; the further understanding of and improvements in the vibrating fiber electrometer, participation in INDI (International Neutron Dosimetry Intercomparison), and an investigation of the extraneous currents which originate in several different cables which are employed to carry ionization currents.

The vibrating fiber electrometer (Rev. Sci. Instr. 35, 1046 (1964)) has excellent sensitivity at extremely low levels and freedom from many of the common disturbing effects such as drifting contact potentials, impairment due to over voltage, and offset currents. The major limitations of the electrometer have been that it only allowed discrete measurements and that it required an operator.

The electrometer per se is essentially and simply a null instrument. A compensating signal must be provided separately to compare with that given by the experiment in progress. When the operator finds a value of compensation giving a null, that value corresponds to the value given by the experiment at the particular moment the null was obtained. A recording potentiometer has been successfully used to automatically provide the compensating signal which then maintains the electrometer at balance continuously.

The essential coupling between the potentiometer and electrometer is provided by a special photodetector which produces a voltage precisely syncronized with the motion of the quartz fiber of the electrometer. An image of the illuminated fiber is projected onto the photodector. The detector consists of two adjacent independent sections with the image of the fiber in the rest position equally divided between the two sections. The two sections are biased oppositely so that a positive signal represents a deflection of the fiber in one direction and a negative signal, in the other direction.

A description of such an electrometer system and of certain measurements carried out with it was included in a paper presented at the Second International Symposium on the Natural Radiation Environment, Houston, 1972 (Conference Paper COO-323-27).

The self-balancing vibrating fiber electrometer was found to have sensitivity, noise, and drift comparable with vibrating reed types. Furthermore, the radiation induced currents were found to be about eight times less for the vibrating fiber type. The reduced radiation response doubtlessly stems from the smaller gas volume surrounding the input conductor. It should be possible to re-design the input conductor and associated shielding in the reed instruments so as to greatly reduce the gas volume in communication with it and thus to reduce the radiation response of the instrument.

Vibrating quartz fiber electrometers have operated at 60 Hz with fibers which are heavily damped and whose natural undamped resonance frequencies are in the neighborhood of 250 Hz. Any asymmetry in the geometry and in the AC driving voltage impressed on the fixed electrodes will drive the fiber at twice the frequency of the drive voltage, 120 Hz. Unfortunately, the fibers are typically more responsive at 120 Hz than at 60 Hz. Thus AC balancing is a more critical concern than it would need be.

It has been proposed to operate the vibrating fiber electrometer at the resonant frequency of the fiber and to reduce the atmosphere surrounding the fiber so as to diminish damping and thus to sharpen the frequency response of the fiber. Operating in this manner would require lower driving voltages and AC balance would be reduced to a relatively minor concern. U.S. Patents, Nos. 3,851,248 and 3,924,184 have been issued covering these and related innovations.

Assistance was given to the team of Frank S. Williamson and Gordon Holmblad of Argonne National Laboratory during their participation in INDI. Three parallel-plate chambers, one polystyrene, one carbon, and one Magnesium, were reconstructed and laboratory tested for use in the intercomparison. Several of the 0.5 cm^3 TE and Magnesium thimble chambers discussed in Section IV were prepared for and used in INDI by the ANL team and by the team from the Armed Forces Radiobiology Research Institute (Bethesda). The ANL team was accompanied to Brookhaven and was assisted throughout the intercomparison experiments.

A key element in the ionometric approach to dosimetry is the cable which carries the ionization currents produced in the chamber to the measurement circuitry. In many situations the measurement circuitry is perforce rather far removed from the ionization chamber and the signal cable must be relatively long. It has frequently occurred in such cases that perturbing cable currents have interfered to such an extent as to seriously limit the range and accuracy of measurements. Indeed the .05 cm^3 TE thimble chamber developed from a .01 cm^3 version which suffered from the presence of interfering cable currents. The size of the chamber was increased in order to limit the errors caused by the interfering cable currents.

The cable that was in use at the time was a low-noise miniature type manufactured by Microdot, Inc. (Cable No. 275-3801). A cursory examination of the electrostatic shielding provided by this cable revealed serious deficiencies. Of course, such problems become more critical as one endeavors to observe smaller and smaller signals. As a consequence of this discovery and of the reports of disturbing radiation induced currents in the same cable, a comprehensive study of cables was initiated.

Guarded ionization chambers have three separate and distinct electrodes. Consequently a coaxial signal cable between such a chamber and the measuring instrument must be supplemented by an additional wire or cable. A triaxial cable would provide completely the necessary connections for guarded chambers. Accordingly, the cable study was concerned preferentially though not exclusively with low-noise triaxial types.

An initial report which covered these studies was given at the RSNA/AAPM meeting held in Chicago during November, 1976 (Conference Paper COO-323-39). Recently, a manuscript summarizing the experiments has been submitted for publication in Medical Physics. The manuscript also includes more recent experiments which focussed on radiation induced cable currents. Considerable variation in the magnitude of radiation induced currents were found among the cables investigated.

It was surprising to discover the inadequacy of the shielding in certain cables. A strange transient current was found on the central conductor of each cable which showed imperfect shielding. The transient accompanies a change of potential between the inner and outer shields of the triaxial cables. In the case of the one coaxial cable showing imperfect shielding, the transient accompanies a change of potential immediately surrounding the cable. The effect is similar to the soakage effect characteristic of incompletely guarded ionization chambers except that the cable effect is opposite in sign to chamber soakage effects.

PATENTS - 1 July 1968 to 31 July 1978

Miniature Coaxial Cable Connector, October 24, 1972, U.S. Patent No. 3,701,080.

Vibrating Fiber Electrometer, November 26, 1974, U.S. Patent No. 3,851,248.

Vibrating Fiber Electrometer, December 2, 1975, U.S. Patent No. 3,924,184.

PUBLICATIONS - 1 July 1968 to 31 July 1978

"Self-balancing Shonka Electrometer", Volume II p. 233, Proceedings of the Second International Symposium on Natural Radiation Environment, August 7-11, 1972, Houston.

"Tribute to William P. Jesse - IV The Days at Illinois Benedictine College," Proceedings of the Symposium on the Jesse Effect and Related Phenomena, Gatlinburg, November 9-11, 1973, Radiation Research 59, 340 (1974).

"Composition Variability and Equivalence of Shonka Plastic", Radiation Research Society, Miami Beach, May 11-15, 1975. Conference Paper COO-323-33 (1975).

"Energy Fluence and Exposure", Midwest Chapter American Association of Physicists in Medicine, May 21, 1976, Chicago. Conference Paper COO-323-35 (1976).

"An Investigation of Cables for Ionization Chambers", Radiological Society of North America/American Association of Physicists in Medicine, November 14-19, 1976, Chicago. Conference Paper COO-323-37 (1976).

"Composition of A150 tissue-equivalent plastic", with James B. Smathers, Victor A. Otte, Alfred R. Smith, Peter R. Almond, Frank Attix, William M. Quam, and Leon J. Goodman. Medical Physics 4, 74 (1977).

"The Measurement of Atmospheric Alpha Activity", North Central and Midwest Chapters American Association of Physicists in Medicine, May 7, 1977, Fontana, Wisconsin. Conference Paper COO-323-38 (1977).

"The Charge Induced by Displacement of an Ion", American Journal of Physics, 46, 1279 (1978).

"Preparation of Conducting Solid Mixtures", Technical Report COO-323-40 (1978).

"Study of Cables for Ionization Chambers", with Ralph D. Meeker. Submitted to Medical Physics (1979).