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HEMISPHERIC SEARCH DETECTOR

Progress Report No. 10

December 9, 1949

Under

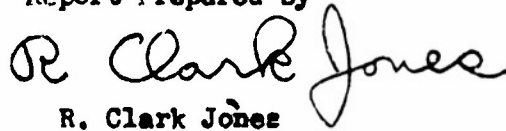
U. S. Navy Contract No. N0bsr-42179

Submitted by

Polaroid Corporation
Research Department
Cambridge 39, Massachusetts

(Project RC-5)

Report Prepared by


R. Clark Jones
Project Leader

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of 22 Copies

Approved for Distribution



E. R. Blout
Associate Director of Research

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HEMISPHERIC SEARCH DETECTOR

Progress Report No. 10

December 9, 1949

Introduction

The major effort during the remainder of the period of this study contract is being devoted to the construction of a prototype of the hemispheric search detector. Some of the details relating to the prototype are described in the attached report (Enclosure 1) of a meeting in Washington on September 21, 1949.

An outline of the activities to be carried out during the remainder of the duration of this contract is as follows:

I. Electronic Design and Construction

- A. Preamplifiers
- B. Compressing amplifiers
- C. Synchronous rectifiers
- D. Detector power supply
- E. Power supply for the electronic system
- F. Special amplifiers to drive the multichannel recorders
- G. Mechanical commutators

II. Mechanical Design

- A. The chopper for the PbSe system
- B. Capsules for the thermistor detector
- C. Basic casting
- D. Spherical mirrors
- E. Slip rings
- F. Rotation drive
- G. Contactor to indicate azimuth
- H. Windows

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III. Procurement

- A. Thermistor detectors
- B. PbSe detectors
- C. Windows
- D. Motors
- E. Mirrors
- F. Selayne
- G. Multichannel recorder

IV. Theoretical Studies

- A. A correlation and systemization of the sensitivity of photoconductive cells
- B. Study of the noise equivalent power obtained with various geometrical detector strip configurations and with the geometry of the chopper.

V. Mechanical Shop Construction

- A. Items under II

1. Electronic Design and Construction

It has become increasingly apparent that the major problem involved in the design and construction of the hemispheric search detector lies in the electronic field. Work has been carried on since the middle of September on the electronic design. A report on this activity, by Mr. Lincoln Baxter is attached (Enclosure 2). It will be noted in his report that substantially all of the attention so far has been given to the preamplifiers and to the high gain, low noise level, low frequency compressing amplifier (items A and B). It will also be noted in his report that it has been necessary to construct a certain amount of additional equipment in order to test the amplifiers which have been constructed because oscillators, meters, etc. are not readily available which are well adapted for operation in the frequency range $1/2$ to 3 cps. It is believed that the preamplifiers and compressing amplifier for the PbSe channel will be similar in design.

Information has been supplied by Mr. J. R. Flegal of Bell Telephone Laboratories about the various copper oxide varistor units manufactured by Western Electric. One of these units has been tentatively selected for use in obtaining the desired compression characteristic of the compressing amplifier (see Enclosure 9).

The major difficulties so far in the way of obtaining a low noise level amplifier to operate at approximately one cps have been microphonics and flicker effect in the amplifier tubes. One way of eliminating the flicker effect is to modulate the signal up to a high frequency where the flicker effect is much less prominent. In order to explore these possibilities, visits were made to RCA Laboratories and Bell Telephone Laboratories on December 1 and 2. Summaries of the matters discussed at these meetings are attached as Enclosures 3 and 4.

II. Mechanical Design

Since the middle of October, a considerable amount of design work has been done on the mechanical aspects of the hemispheric search detector. The design work done so far has been concerned with items A, C, D, E, and F. As a result of the work done on the mechanical design, a number of decisions have been made as follows:

1. A separate detector of the position of the sun will probably be used. A small lens and a photocell associated with a simple amplifier should suffice. This sun detector will be used to close shutters over the entrance pupils of the optical systems whenever the sun approaches a position where its image could fall on the detectors. The sun shutter elements will be semicircular in shape and the complete shutter will consist of two of these elements. The shutter will operate inside of the sealed optical system in the case of the PbSe system and will operate outside of the sealed optical system in the case of the thermistor system.

2. The slip rings will be placed where they will be easily accessible.

3. Preliminary shields will be placed about the amplifier housing and the various motors will be shielded magnetically.

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4. It was decided to use a reflecting spherical mirror large enough only for the four channels to be constructed. Similarly, the cylindrical mirror on the PbSe system will be large enough only for the four channels.

5. The azimuth angle will be indicated on the recorder by contactors placed to provide a pulse every 90° of rotation with a somewhat longer pulse at the 360° position. Selsyns will be used only as indication of the elevation angle and this indication will be dispensed with if it introduces difficulty.

6. The obscuration of the entrance pupil of the optical system by the rotating chopper in the PbSe system has been found to be greater than previously expected because of the oblique passage of the light which reaches the edge of the detecting elements. For this reason it was decided that the use of a double strip system in the PbSe channel was out of the question and that a single strip must be used. Even with a single strip, the obscuration by the chopper wheel amounts to about 30 percent. Consideration is being given to the use of a slightly greater numerical aperture to offset partially this loss of light.

7. A dull black paint will be applied to all non-reflecting surfaces inside of the optical system.

Attention is called to the situation described in Enclosure 5 that the capsules for the thermistor detector must be designed and constructed by Polaroid Corporation.

III. Procurement

Considerable difficulty has been experienced so far in connection with the effort to procure the thermistor detectors for the channel employing these detectors. A meeting was held at BTL on September 30, 1949 (see Enclosure 5) at which it was determined that the construction of the desired thermistor detector seemed reasonably straightforward. Two methods were discussed by which the detectors might be procured: (1) A task order on the existing contract (NObs-2440) between the Bureau of Ships and Western Electric. (2) Negotiation of a contract between Western Electric and Polaroid. In a letter from the Bureau of Ships dated October 10, 1949, it was stated that the first method was out of the question because of limitation of funds available under Contract NObs-2440.

Accordingly, a meeting was held with officials of the Western Electric Company in New York on October 14 (Enclosure 6). During this meeting a statement of the scope of the work desired was worked out by those present at the conference and by discussion with Mr. Anderson by telephone. It was suggested by the Western Electric

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representatives that the work desired be placed in a purchase order on Western Electric by Polaroid Corporation. An unofficial purchase order accordingly was submitted to Western Electric on November 1 and a copy of this purchase order was submitted to the Bureau of Ships for approval. This approval has not yet been obtained.

On November 28, however, a telephone call was received from Mr. Selover of Western Electric in which Mr. Selover stated that it had been decided by consultation between Western Electric and the Bureau of Ships that the procurement of the thermistor detectors could be handled on an unclassified basis. Mr. Selover further stated that a consequence of this decision was that the detectors must be procured through the Graybar Electric Company, which company maintains offices in Boston. This information was later confirmed in a letter from Mr. E. N. Poole of Western Electric.

With regard to the procurement of the lead selenide detectors, visits were made to the Armour Research Foundation and to Dr. Cashman at Northwestern University on October 5. The discussions carried out at these meetings are summarized in Enclosures 7 and 8.

Dr. Cashman decided that the detectors were feasible to make and he agreed to start work on about November 1, provided that he receive such instructions from the Bureau of Ships. Dr. Cashman was requested to produce these detectors on Contract NObs-45068 in a letter dated October 13 from the Bureau of Ships to Dr. Cashman.

Considerable attention has been given to the problem of the cylindrical window for the PbSe channel. Silver chloride would undoubtedly be satisfactory for this purpose, but simpler and perhaps more rigid and less expensive windows are under study. Some interesting high lead content glasses have been produced by the Bureau of Standards under the direction of Mr. C. H. Hahner, some of which have reasonably high transmission in 2 mm thicknesses out almost to 5 microns.

Correspondence has been carried out with Mr. Harold G. Vogt of the Corning Glass Works. It appears that Corning makes no glasses which transmit well out to 4 microns. According to information supplied by Mr. Vogt, it appears that fused quartz would provide a satisfactory window for the PbSe detectors. Accordingly, inquiry is now being made into the cost and feasibility of a suitable fused quartz window.

IV. Theoretical Studies

A proposal of a simple method of comparing the sensitivities of various photoconductive cells was communicated in a letter to Dr.

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Cashman on November 9. The substantive content of this letter has been issued in the form of a report dated November 30 (Enclosure 10). An application to results on 19 different lead sulfide cells obtained by the Naval Ordnance Laboratory is described in a report dated December 6 (Enclosure 11).

If the proposal turns out to be sound, it is the writer's opinion that the adoption of the reference condition proposed in Enclosure 10 would materially expedite the evaluation of the work now being carried out on various photoconductive cells.

V. Mechanical Shop Construction

Ample time and facilities will be available in the mechanical shop for the construction of the components of the hemispheric search detector.

List of Personnel

Lincoln Baxter, II, Electronic Physicist
John A. DeYoung, Electronic Engineer
Murry N. Fairbank, Mechanical Engineer
R. Clark Jones, Senior Physicist
Sidney B. Whittier, Designer

List of Attachments

1. Minutes of an RC-5 Meeting in Washington on September 21, 1949, R. Clark Jones, September 26, 1949.
2. Progress Report on RC-5: Concerning the Work on Circuit Development from September 15, 1949, to December 8, 1949, Lincoln Baxter, II, December 8, 1949.
3. Visit to RCA Laboratories on December 1, 1949, R. Clark Jones, December 7, 1949.
4. Visit to Bell Telephone Laboratories at Whippany on December 2, 1949, R. Clark Jones, December 8, 1949.
5. Minutes of an RC-5 Meeting at Bell Telephone Laboratories on September 30, 1949, R. Clark Jones, October 3, 1949.
6. Minutes of a Meeting at Western Electric Company on October 14, 1949, R. Clark Jones, October 19, 1949.

7. Minutes of an RC-5 Conference at Armour Research Foundation on October 5, 1949, R. Clark Jones, October 12, 1949.
8. Minutes of an RC-5 Meeting with Dr. Cashman on October 5, 1949, R. Clark Jones, October 13, 1949.
9. Visit to Bell Telephone Laboratories on September 30, 1949, R. Clark Jones, October 4, 1949.
10. Proposal of a Simple Method of Describing and Comparing the Properties of Photoconductive Cells, R. Clark Jones, November 30, 1949.
11. An Application of the Proposed Reference Condition C, R. Clark Jones, December 6, 1949.

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Minutes of an RC-5 Meeting in Washington on September 21, 1949

R. Clark Jones

September 26, 1949

A meeting was held at the Navy Department in the morning and afternoon of September 21, 1949, attended by:

Harry Dauber, Bureau of Ships
John S. Kelly, Bureau of Ships
Elkan R. Blout, Polaroid Corporation
R. Clark Jones, Polaroid Corporation

Mr. George Brown, Army ERDL, attended the afternoon meeting.

Morning Session

The purpose of the meeting was to discuss the activity to be carried out in connection with the extension of Contract NOber-42179 (RC-5). This report records some of the facts obtained and decisions made.

A number of groups are manufacturing photoconductive cells at present, including:

Armour
Cashman
Cetron
Photo-mbo
Photoswitch
RCA

Mr. Woodside recommended that the cells for this contract be obtained from Dr. Cashman if possible. (The writer now has an engagement to visit Dr. Cashman in Chicago on the afternoon of October 5.)

It was reported that the Bureau of Standards is now setting up photoconductive cell test facilities. The writer emphasized, however, the need of setting up test facilities at Polaroid to test the cells that are contemplated for use. This is desirable because it is much simpler to test a photoconductive cell for a specific use than it is to obtain complete information on the cell. Our test facilities would permit the determination of the, say, signal-to-noise ratio of the detector for a given power input when the tem-

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perature of the source is, say, 100°, 150°, 200°, and 300° C, when the radiation is chopped at 200, 400, and 800 cps, and when the signal is a twelfth-second pulse.

The systems to be constructed shall contain four elevation channels and, subject to a later contrary decision, both the warm and hot systems will be constructed. The outputs of the four channels shall be recorded on a multichannel recorder. This recorder should record also the elevation angle and the azimuth by means of selsyns. There will thus be no cathode ray presentation and no switching tubes involved. The mechanical structure shall be capable of continuous rotation about a vertical axis and manual adjustment of the elevation angle. The construction should be sturdy and such that the unit may be tested outdoors, but the unit will probably never be mounted on a ship and it will not be necessary for the unit to pass shock tests.

The electronic system will not distinguish between hot and cold targets.

The system should be designed holding in mind the ultimate weight and space restrictions involved in the contemplated submarine application, unless this requirement involves a sacrifice in the signal-to-noise ratio. In particular, however, thermocouple or bolometer transformers will not be used because their weight is clearly out of the question in the final application.

Mr. Lewis Nelson of the Bureau of Ships will send us information on the glass which is suitable for the large window on the photoconductive system.

It was not decided whether the equipment would be constructed to operate on 60 cycle or 400 cycle power. Mr. Kelly will look into the availability of 400 cycle power at Fishers Island.

It was recommended that the writer return to the Bureau of Ships those reports which he is now not using actively.

Afternoon Session

In the afternoon session, attended also by Mr. Prown, the Army requirements for a hemispheric search detector were discussed. The tentative Army requirements were quite similar to those on the device now being designed. The general size of the apparatus and the 15 second period of rotation were acceptable. The primary differences were that a somewhat larger picture element would be acceptable (a picture element 10° square was suggested), and that the weight requirement was virtually non-existent. The device must be transportable on a truck.

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Progress Report on RC-5

Concerning the Work on Circuit Development
from September 15, 1949, to December 8, 1949

Lincoln Baxter, II

December 8, 1949

A little less than one week was spent reading the reports of the study contract.

It was decided to attempt to construct the circuit for the heat detector first. If the system employing a switching tube at the output is used, an amplifier having a pass-band from 0.5 to 3 cycles per second and a gain of about 10 million times or 130 db is required. The noise level desired is about 1 meg Johnson noise equivalent to about 1/10 microvolt.

In order to test this amplifier, an oscillator covering the range of 0.5 to 3 cps was required. An attempt was made to modify a resistance capacity audio oscillator to operate at these frequencies but this circuit was abandoned because the stability and waveform were very poor at the low frequency, probably because of the short time constant of the ballast lamp filament as compared with the frequencies it was desired to produce.

A relaxation oscillator using a VR105 followed by four stages of filtering and some amplification was then designed and constructed. Some experimental consideration was given to the use of 884 or 2090 thyratron tubes but the VR105 was more stable. It was found possible with the system using the VR105, by ganged switching of oscillator and filter resistors, to build an oscillator with a frequency variable in eight steps from 0.3 to 5 cps, with the output voltage variable from 0 to 16 volts and independent of frequency. The waveform as viewed on the 208B oscilloscope was very close to sine wave. When it was decided later to use a push-pull design for the amplifier, a phase inverting system was added to this oscillator, since it was found that the center tap of the push-pull signal and the oscillator chassis had to be grounded to avoid picked up noise and hum.

Several modifications of a single ended amplifier were designed and constructed using 4 stages of amplification with 4 pentodes, the first stage triode connected. First 6AG5 then 6AK5's were used. Great difficulties in obtaining isolation of stages from power supply and each other were encountered and degeneration in

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cathodes and screens (bypassing at these low frequencies requires condensers of prohibitive size) made it too difficult to obtain the required gain. The leakage current of condensers made it difficult to design any varistor circuits to obtain the desired gain compression of the amplifier. The best single ended amplifier constructed had a gain of about one million times or 120 db and a noise level of about one microvolt, equivalent to 100 mega Johnson noise. This amplifier had to be operated from several batteries and used regeneration to neutralize the reduced gain due to cathode degeneration. This regeneration made it even more difficult to adapt compression circuits of the types considered to the amplifier.

A study was made of data on Western Electric oxidized copper, copper alloy, Germanium, and silicon carbide varistors. The Chile copper thallium alloy varistors in the 1/16" diameter size seem most suitable. A number of graphical studies were made of the compression characteristics of various combinations of these alloy varistors of the 3/16" and 1/16" sizes in resistance networks and amplifier circuits. It was tentatively decided to work on the basis of 4 units with a gain of 100 between each.

It was decided that a push-pull amplifier system offered many advantages which would probably more than compensate for the increased number of components of the amplifier. A push-pull amplifier was designed and constructed using 6AU6 tubes for the last three stages and a 12AX7 for the first stage. The 12AX7 was found to be excessively noisy and was abandoned. The remaining three stages were found to have about the same equivalent input noise in the 1/2 to 3 cps bandwidth as the single ended system, but the power supply, gain, and adaptability to varistor design problems are greatly simplified in the push-pull system.

Microphonics were found to be very serious even when the chassis was mounted on sponge rubber; so it was decided to suspend it from the ceiling on a spring having a period of vibration of about one second. It was found that the microphonics extended all the way down to the lowest frequency the amplifier would pass and that for any motion faster than about 1/2 cycle the oscilloscope trace would reproduce the motion of the chassis. It seemed extremely unlikely that tube elements would vibrate at this rate; so pick-up from external fields was suspected. The first of the three stages in use was electrostatically shielded without producing any noticeable change. Then it was discovered that the first tubes would pick up the motion of steel pliers brought near them but not a brass rod; so magnetic fields were suspected. Magnetic shielding was found to prevent almost completely the low frequency motion sensitivity. Reducing the B potential on the first of the three stages to about 100 volts reduced the higher frequency microphonics to the point where the amplifier mounted on sponge rubber was useful for measuring noise in a preamplifier stage which was mounted on another chassis. 6AU6's,

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6SH7's, and 6AC7's were tested in push-pull arrangements. With larger currents and potentials the 6AU6 and 6SH7 were less noisy than the 6AC7 but decreasing the plate voltage and current of the 6AC7 improved its signal-to-noise very much more than it did for the other types, so that at about 25 volts on the plate, 45 volts B, the 6AC7 was about one-half as noisy as the other types. The equivalent input noise of some arrangements with the 6AC7 was estimated to be approximately 0.5 microvolts or less in the 1/2 cps to 3 cps band. This is equivalent to the Johnson noise of about 25 megohms or less.

It was decided that a more accurate method of estimating the noise was required, since an estimate by eye of the average peak-to-peak values on the oscilloscope might be considerably in error. Methods using diode rectifiers at the output of either the amplifier or at the plates of the oscilloscope were found to give too low an impedance and altered the oscilloscope indications noticeably. A push-pull infinite impedance detector using a 6SL7 was constructed and connected across the vertical deflection terminals of the cathode ray tube. The output of this detector was averaged by an RC network with a 20 second time constant and this average value measured on an RCA volt-ohm-mill Jr. which was modified to give a 3 volt infinite impedance scale. The meter was adjusted to give a full scale reading on 0.8 volt rms sine wave at input of the oscilloscope and was found to be linear for sine wave amplitudes greater than about 0.08 volt rms.

By using 2VR105 tubes to regulate the output of a commercial regulated power supply at 210 volts for the last two stages and a cathode follower to further regulate this at 105 volts for the first stage, it was found possible to operate the three stage push-pull amplifier from the a.c. power without increasing the noise. This was desirable as the battery supply previously used showed signs of getting weak.

Several tubes which have been suggested by various sources as being low noise or low microphonics have been ordered and obtained. They are Western Electric 348A and 403B, Victoreen 5800, RCA 5693, and 6AT6. It is planned to begin tests on these as soon as experiments are completed now being made to see if it is possible to reduce flicker noise by feedback designed to hold the cathode current constant, as suggested by Mr. A. W. Vance of R.C.A.

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Visit to RCA Laboratories on December 1, 1949

R. Clark Jones

December 7, 1949

A conference was held at RCA Laboratories on December 1 attended by

A. W. Vance, RCA
Lincoln Baxter, Polaroid
R. Clark Jones, Polaroid.

The purpose of the visit was to obtain information on techniques usable to obtain amplifiers with very low noise level and frequencies of about one cps.

Mr. Vance reported that in connection with the Typhoon Project a d.c. amplifier employing a commutator had been constructed whose noise level in a bandwidth of 0.025 cps was 10^{-11} to 10^{-12} ampere. With an input impedance of one megohm this corresponds to a noise level of from 1 to 10 μ volts. This noise is roughly constant current independent of the impedance level. That is to say, it acts as though it were produced by a current generator. Mr. Vance suggested that the source of the noise was a variable Volta effect due to impurities on the surfaces of the commutator. Among the considerations important in designing a low level, high impedance commutator are the use of a special solder whose Volta potential relative to copper is small and the avoidance of insulating surfaces exposed to the moving parts.

Leeds and Northrup manufactures a single pole double contact breaker designed for operation at 60 cps. The resonance, however, is broad. This unit employs a polarized drive. RCA manufactures for its own use in connection with the Typhoon Project a single pole double throw breaker operating at 386 cps. The resonance in this unit is also broad and it employs a non-polarized drive. That is to say, it is driven with an alternating current whose frequency is 193 cps. At impedance levels of about one megohm Mr. Vance felt that the RCA unit was perhaps somewhat superior to the Leeds and Northrup unit.

Mr. Vance reported that Leeds and Northrup in Philadelphia is carrying on work on commutators for high impedance circuits, and suggested that we get in touch with Albert J. Williams, Leeds and Northrup Company, 4901 Stenton Avenue.

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Mr. Vance suggested an ingenious scheme for increasing the voltage level right at the commutator so that a higher voltage level would be available for driving the amplifier. He suggested that the signal voltage be connected through the commutator to an inductor. Then when the circuit is broken, the inductance will give a high voltage peak whose amplitude is proportional to the signal voltage. If one uses gating to eliminate the noise during all periods except those during which the contact is opening, a relatively low noise level should result. Mr. Vance also suggested a simple way of obtaining this gating: Introduce a fixed d.c. voltage in series with the signal voltage; then the noise between the inductor pulses may be removed simply by clipping off the noise peaks.

All of the commutator methods discussed so far have the effect of translating the low frequency signal as modulation of a high frequency signal. The high frequencies are much more easily amplified because of the absence of the flicker effect which is so bothersome at low frequencies. Mr. Vance made another ingenious suggestion that may permit the elimination of the flicker effect. The flicker effect is believed to consist of spontaneous fluctuations in the emission of the cathode. Mr. Vance suggested the use of a feedback circuit to hold constant the total cathode current of the tube and to obtain gain by virtue of the fact that the control grid would then vary the ratio of the currents received by the screen and plate. Presumably this procedure will lead to a relatively high level of shot noise, but since shot noise has a flat spectrum this effect will not be of deep concern at the very low frequencies. More specifically, Mr. Vance suggested the use of a pentagrid converter, with grid No. 1 used to maintain the total cathode current constant and grid No. 3 used to introduce the signal to be amplified.

Mr. Vance further suggested the use of a deflection tube whose total cathode current could be held constant by feedback methods. In this connection he suggested that we write to Mr. E. W. Harold with respect to the possible use of such tubes. Mr. Vance further suggested that Raytheon is now making a number of special tubes for the International Business Machine Company. These tubes have many grids and sharp cutoffs and might be useful for our problem.

Mr. Vance suggested the use of a somewhat excessive heater voltage (7 volts instead of 6.3, for example) in order to obtain a somewhat greater emission.

Mr. Vance referred us to an article on the contribution of shot effect to the noise in ordinary vacuum tubes (RCA Review, April, 1941).

Part of the day was spent in examining the Typhoon Project computer and a brief unsuccessful experiment was made in the effort to lower the noise level in the Typhoon d.c. amplifiers.

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Visit to Bell Telephone Laboratories at Whippany on December 2, 1949

R. Clark Jones

December 8, 1949

On the day after the conference at RCA Laboratories with Mr. A. W. Vance a discussion was held at the Whippany installation of Bell Telephone Laboratories attended by:

W. E. Ingerson, BTL
H. G. Och, BTL
Lincoln Baxter, Polaroid
R. Clark Jones, Polaroid.

The purpose of the visit was to obtain information on techniques usable to obtain amplifiers with a very low noise level and at frequencies of about one cps. Mr. Och explained at the beginning of the discussion that the Laboratories group which he represented had not been concerned with commutators working at very low levels, and suggested that we ought to see Mr. Vance at RCA.

We were shown different mechanical commutators. The first one was manufactured by Daven and was labeled the "2937 network," serial No. D30444. This commutator consisted of two decks, each with 24 contacts. If the alternate contacts in each are grounded, the two decks together are capable of handling the input and output commutation for 12 channels simultaneously. (Thus for 18 channels, two decks each with 36 contacts would be required.) The noise level obtained with this commutator was 10 to 20 μ volts in a bandwidth of about one cps at a rotational speed of 5 rps. It was emphasized, however, that no serious effort had been made to reduce the noise level.

For low level work Mr. Och recommended the Daven unit modified by the use of wider contacts for the input circuit than for the output circuit and by individual shields placed about the two sections.

The second commutator shown to us was a unit manufactured by BTL with a primary requirement in mind of long life rather than low noise level. This commutator was the equivalent of a two deck system with 12 contacts on each deck.

A discussion was held with regard to the importance of grounding every other contact rather than just one contact in each deck. The BTL group believed that the use of alternate grounds greatly improved the stability of the other channels when one channel was overloaded.

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In a subsequent discussion with Mr. H. C. Rorden, BTL (a former associate of the writer), Mr. Rorden described a low noise level amplifier which he had recently constructed. This amplifier employed four 348A tubes in parallel at the input in order to minimize the noise level of the input tubes. Mr. Rorden suggested, however, that the 1620 tube is almost as good as the 348A for this purpose. He suggested that we write Mr. H. C. Montgomery with regard to the possibility of obtaining a schematic circuit of the amplifier and a curve of the noise level versus frequency. Mr. Rorden also mentioned a reference to an article by Bogel on low frequency low level amplifiers. Mr. Rorden will send the writer the detailed reference.

We were shown the analogue computer which BTL is constructing for its own use. This computer employs the commutated d.c. amplifier involved in the discussion.

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Minutes of an RC-5 Meeting at Bell Telephone Laboratories
on September 30, 1949

R. Clark Jones

October 3, 1949

A meeting was held at the Murray Hill Laboratory of Bell Telephone Laboratories during the morning of September 30, 1949, to discuss the feasibility of obtaining thermistor detectors suitable for use on the RC-5 device. Present were:

A. E. Anderson, BTL
J. A. Becker, BTL
J. J. Kleimack, BTL
R. Clark Jones, Polaroid

At the beginning of the meeting the writer described in outline form the proposed application of the thermistor detector. At the conclusion of this description Dr. Becker emphasized that BTL would perform as a supplier of units with performance specified by Polaroid, and that BTL would in no way share responsibility for the overall performance in the proposed application.

The performance desired by Polaroid is as follows:

Sensitive area: 5.3 mm x 16 mm
Time constant: 0.08 second
Number of units needed: 8, plus a few spares

There was considerable discussion of the means that might be employed to obtain the desired time constant. The simplest way to obtain the desired time constant would be to support the thermistor elements only at the contacts and thus to let the sensitive element be air-backed. An air-backed unit, however, has a pronounced microphonic response due to the "swish" effect. If the air were removed, the time constant would be too long, and if the flake were backed with a solid, such as quartz or glass, the time constant would be far too short. It was decided that a low pressure of helium was the best answer to the problem. There was some uncertainty as to whether such a unit would be microphonic because of the mechanical vibration of the sensitive element.

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The proposed method of construction which was evolved during the discussion is as follows: From 4 to 8 flakes, each 7 mm long, would be bridged over a gap between two insulating supports, which gap is 5.3 mm wide. Depending on the width of the strips, from 4 to 8 strips would be used to cover a gap length of 16 mm.

The following summary of the technical situation was agreed to by all those present. It seems feasible for BTL to make by present techniques a helium-backed unit of the desired time constant and area, which, however, may be too microphonic for the final application. Removal of the microphonic response seems probable, but does require development.

One of ways discussed, by which the microphonic response might be removed, was to use a solid backing of a high porous material such as, for example, very porous sintered glass. Or, the thermistor flake might be supported at one or two points across the gap.

The method of electrical interconnection of the separate strips making up the detector and the choice of thermistor material was left for later decision. Two thermistor materials are available: The No. 1 material in a thickness of 10 microns has a resistance of 3 megohms per square and the No. 2 material 0.3 megohms per square at room temperature. Dr. Becker emphasized that one must consider seriously the problem of cooling of the capsule in which the element is mounted.

If BTL should go ahead with this development, it would expect Polaroid to design and supply the capsules in which the thermistor flakes would be mounted. In this connection it was agreed that a 9 mm internal width and a 4 mm internal depth would be adequate. Provided that the walls of the capsule are not too thick, these dimensions should permit placing the 5.3 x 16 mm strips side by side with a separation substantially equal to the width, namely 5.3 mm.

The matter of financing the proposed development by BTL was next discussed. Mr. Anderson emphasized that because of the pressure of internal work, the development could not be done until funds were available and the contract signed. In principle two methods of procedure seem open:

- A. Negotiation of a contract between Western Electric Company and Polaroid Corporation.
- B. Supplying of funds through the present contract with the Bureau of Ships.

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Mr. Anderson thought that from the point of view of both BTL and Polarcid, method B was preferable, because not only would the contract involved in method A be difficult to negotiate, but it would undoubtedly take a long time and the contract could probably not be negotiated in less than six to nine months.

If BTL starts work on this development, its program will consist of two rather distinct parts, first the provision of engineering services to study the feasibility of various designs and to design the first detecting element. The second part of the development would be the actual production of the units to be supplied. Mr. Becker remarked that when the number of units of a given kind exceeds ten, there is a provision in the Bureau of Ships contract that it should yield to a commercial Western Electric contract. Mr. Kleimack suggested the following time schedule with the emphatic provision that it represented a probable time schedule, that the schedule could in no way be guaranteed, and that if unexpected difficulties in construction arose the time would be substantially longer: Two months to construct the first suitable unit and another two months to produce the eight units required plus a reasonable number of spares.

The question of probable costs was not discussed.

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Minutes of a Meeting at Western Electric Company
on October 14, 1949

R. Clark Jones

October 19, 1949

A meeting was held in the Western Electric Company offices at 120 Broadway during the afternoon of Friday, October 14, 1949, for the purpose of arranging the details of a proposed contract between Western Electric Company and Polaroid Corporation. Present at this meeting were:

Lea F. Hescok, Western Electric Company
E. N. Poole
L. E. Selover
R. Clark Jones, Polaroid Corporation.

The purpose of this meeting was the arrangement of a contract by which Polaroid would obtain from Bell Telephone Laboratories 10 to 12 thermistor bolometers of the type required for the RC-5 project.

The major part of the meeting was devoted to a discussion of the project itself and a discussion of the general type of contractual arrangement. After considerable discussion it was decided that the best method would be for Polaroid to place a purchase order with Western Electric for engineering services as described below. This purchase order would carry the proviso that the cost of the engineering services should not exceed \$10,000. If the work at Bell Telephone Laboratories should proceed to the point where all of the \$10,000 has been used up, then Bell Telephone Laboratories should cease further work until further arrangements have been made between Western Electric Company and Polaroid Corporation.

After this decision was made a scope of the purchase order was quickly written up and checked with Mr. A. E. Anderson by telephone. The following scope thus has the approval of Mr. A. E. Anderson and the four people at the meeting:

Scope

Purchase from Western Electric Company of engineering services of the Bell Telephone Laboratories, said engineering services to be aimed at the following two objectives: (1) the investigation of the feasibility of various designs and fabrication of the first Thermistor Bolometer, (2) the fabrication of 10 to 12 additional Thermistor Bolometers.

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Technical Requirements:

- (1) Sensitive area 5.0 to 5.5 mm by .16 to .18 mm
- (2) Time constant 0.05 to 0.12 second
- (3) Under normal operating conditions the noise in the 1/2 to 3 cps band is not to exceed 1.5 x Johnson noise.
- (4) Suitable housings will be furnished by Polaroid Corporation. (The Bell Telephone Laboratories will furnish consulting services on the design and fabrication of these housings.)
- (5) The Thermistor flakes will be fabricated, mounted in the housing and the housing sealed by the Bell Telephone Laboratories.
- (6) Other considerations shall be subject to mutual agreement between the Western Electric Company, the Polaroid Corporation, and the Bell Telephone Laboratories.

end of scope

After the purchase order is drawn up, it must be approved by Western Electric Company and by the Bureau of Ships before it has final status and before work can be begun at Bell Telephone Laboratories.

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Minutes of an RC-5 Conference at Armour Research Foundation
on October 5, 1949

R. Clark Jones

October 12, 1949

A meeting to discuss the use of photoconductive cells in the RC-5 hemispheric search detector was held on the morning of October 5 at the Armour Research Foundation in Chicago at 35 West 33rd Street. (Note: This location is a \$1.25 taxi ride from the Loop, and may also be reached by taking a south-bound Rapid Transit to the 35th Street station and then walking back to 33rd Street on the catwalk. The Foundation is about 600 feet west of the Rapid Transit line.) The visit consisted of three rather distinct parts: a meeting in Mr. Betz's office, a discussion in Mr. Richardson's office, and a meeting in Mr. Parkley's laboratory.

The meeting in Mr. Betz's office was attended by Mr. H. T. Betz, Mr. R. F. Humphreys, and Mr. E. I. Perrine. After the writer gave a brief description of the RC-5 project, Mr. Betz explained that the group in the Physics Department was not producing photoconductive cells, but was instead interested in procuring them and expected to obtain them from Dr. Cashman. Mr. Betz inquired whether our project involved detecting the modulation of the signal. I said no, and we both agreed that the range would be substantially less for detection of the modulation compared with the detection of the presence of the signal. The writer mentioned the NOL Memorandum 9929 containing an experimental study of 19 lead photoconductive cells. The Armour Foundation was not aware of this report and the writer agreed to send them the detailed reference.

After this meeting the writer had a detailed discussion with Mr. Don E. Richardson with regard to some work which the latter has done in measuring the properties of lead sulfide cells, which work is described in the Armour Progress Reports No. 8 and No. 13. The writer found Mr. Richardson's results very interesting; in particular he was interested in the uniformities which Mr. Richardson found. Even more particularly Mr. Richardson has found that for a number of different types of lead sulfide cells operating over a wide range of temperatures, the cells all satisfy approximately the following relation:

$$k = 7.5 (\tau R)^{3/4},$$

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where k is the sensitivity of the cell in ohms per ohm per watt per square centimeter, τ is the time constant of the cell in seconds, and R is the resistance in ohms. This relation is extremely interesting. Very unfortunately from my point of view, however, Mr. Richardson did not have available a corresponding study of the noise of these detectors so that no conclusions may as yet be drawn about the way that the signal-to-noise ratio in the reference condition of measurement depends on the time constant.

After the discussion with Mr. Richardson the writer moved over to the Chemistry Department to attend a meeting with Mr. J. E. Barkley and Frank Ticulka of that department. Present also were several members of the Physics Department. Mr. Barkley explained that Armour Research Foundation had a contract with ERDL for the preparation of cooled lead sulfide cells and that the department had also prepared a small number of uncooled lead selenide cells. The writer inquired how a sample of these cells could be obtained, and was informed by Mr. Barkley that it would probably be impossible to obtain even one of them except by an arrangement by which the Armour Research Foundation would produce a few for our use. Accordingly, the writer requested Mr. Barkley to send him an estimate of the cost of a contract for the securing of two to four uncooled lead selenide cells with a sensitive area approximately 3 mm x 3 mm. Mr. Barkley described the best lead selenide cells produced by them so far as having a 40 db signal-to-noise ratio when there were 45 volts across the cell and 45 volts in the load resistor; when the source was at a temperature of 500° K, was one centimeter in diameter, and was 40 centimeters from the cell; for a cell which had a sensitive area of 3 mm x 3 mm; when the radiation was chopped at 450 cps and the signal-to-noise ratio was measured in a bandwidth of 9 cps. A corresponding figure under the same test conditions for a lead sulfide cell at room temperature would be about +50, and at dry ice temperature, from 70 to 80.

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Minutes of an RC-5 Meeting with Dr. Cashman
on October 5, 1949

R. Clark Jones

October 13, 1949

A meeting to discuss the possibility of obtaining uncooled lead selenide detectors suitable for use in the RC-5 hemispheric search detector was held in the office of Dr. Cashman at Northwestern University in Evanston, Illinois, during the afternoon of October 5, 1949. (Note: There is a variety of ways to reach Dr. Cashman's office from downtown Chicago. One may take a C. & N. W. train to Evanston and then transfer to the North Shore line and get off at Noyes Street station. Or one can take a Rapid Transit train to Howard Street and then transfer to the North Shore at Howard Street. Or one can take a North Shore car anywhere on the Loop and get off at Noyes Street. From the Noyes Street station one walks three blocks east to the Technology Building. Dr. Cashman is in Room 127, conveniently reached through the south court door.)

After the writer described briefly the RC-5 project a rather detailed discussion followed of the method of fabricating an uncooled lead selenide cell suitable for our use. Dr. Cashman stated that up to the present time all evaporated lead photoconductive cells are sensitive to exposure to the atmosphere, particularly if one wants sensitivity for the longer wavelengths. In this connection Dr. Cashman stated that the cells manufactured by Continental Electric Company do employ an activation method that yields a low sensitivity in the longer wavelengths and that these cells can accordingly be opened to the air. On the other hand, both Eastman and British Thomson Houston have prepared cells by chemical means which are sensitive to the longer wavelengths and which can be opened to the atmosphere. The writer was surprised to learn that Eastman Kodak is making photoconductive cells.

Because of the difficulty with regard to exposure to air, it does not seem feasible at the present time to prepare the unit of rather large area desired by us by placing adjacent to one another a number of units of smaller area which had been prepared separately. Dr. Cashman did suggest, however, that developments during the next few months might make it possible to expose sensitive lead selenide cells to air. Dr. Cashman, after some thought and discussion, decided that it would probably be feasible to prepare the cells in a quartz capsule, using a procedure similar to one already in use by him.

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In response to the writer's question, Dr. Cashman explained that graphite electrodes were about the only type of electrodes which can be used in the evaporated types because graphite does not combine with sulphur or selenium, as do practically all metals at the high temperatures required to sensitize the cell. Dr. Cashman showed the writer two reports by him dated January 8 and January 22, 1949, prepared on Navy Contract NObs-45068, and indicated that he had a copy of each which he could send to the writer upon authorization. The summary of these two reports contains a good deal of quantitative information about the signal and noise of the lead selenide cells prepared by him.

The following is a verbatim copy of the specifications and time schedule agreed upon with Dr. Cashman:

Lead Selenide Cell Uncooled

Sensitive area, 5.0 mm to 5.5 mm by 16 mm to 18 mm.

Maximum area of housing = 11 mm x 26 mm.

Maximum depth: approximately 1.5 in.

Eight units required, plus a reasonable number of spares.

Time Schedule

Dr. Cashman could start work on about November 1. By the use of present techniques, except for the modifications involved in the large area and the small clearance, he would expect to have a housing in two weeks, including a layer of questionable sensitivity. He would expect to be able to supply to us 10 to 12 sensitive units by January 1. This schedule is subject to approval by the Bureau of Ships.

Dr. Cashman believed that he could supply in these units a lead selenide surface as sensitive as the surface described in the January 8 report cited above. He furthermore indicated that he would supply an uncooled lead sulfide cell whose sensitivity would be as good as the lead selenide cell in the January 8 report at 200° C. The uncooled lead sulfide cell, however, would be less sensitive for sources of lower temperature and would be more sensitive for sources of higher temperature.

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With regard to the local variations of sensitivity, Dr. Cashman stated that with our large scanning spot 2.5 mm in diameter he expected that the sensitivity would be the same within 3 db over the entire area of the detector.

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Visit to Bell Telephone Laboratories
on September 30, 1949

R. Clark Jones

October 4, 1949

After the meeting on thermistor detector elements (described in the writer's report dated October 3) was over, the writer took advantage of his presence (he hopes not improperly) at Murray Hill to discuss briefly with some of his former associates two of the other problems involved in the RC-5 program.

Compressing Amplifiers

The writer talked with J. C. Lozier and J. R. Flegal about non-linear elements which might be suitable for use in compressing circuits. Both of these people emphasized the usefulness of copper oxide rectifiers for this purpose and emphasized also the particular advantage of copper oxide rectifiers containing a small quantity of thallium. Mr. Flegal provided the writer with three sheafs of data on non-linear elements, on copper oxide units, on silicon carbide units, and on germanium units, which will be of the greatest usefulness in the design of the compressing amplifier for the RC-5 project.

Mechanical Commutators

The writer talked with Mr. R. I. Dietzold and W. E. Ingerson about mechanical commutators suitable for use in connection with d.c. amplifiers operating with input levels equaling Johnson noise. Mr. Ingerson mentioned two projects which involve such commutators. The first is a project in the Whippany Laboratory of Bell Telephone Laboratories under the direction of W. H. C. Higgins. The second is the Typhoon project at RCA under the direction of Mr. Vance. Mr. Ingerson described also a commercially available Leeds and Northrup relay which is suitable for use with very low level circuits.

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Proposal of a Simple Method of Describing and Comparing
the Properties of Photoconductive Cells

R. Clark Jones

November 30, 1949

Introduction

This report contains the suggestion of a simple method of describing the responsivity-to-noise ratio of photoconductive cells, in such a way that the signal-to-noise ratio obtainable in a given application is easily calculable and in such a way that the number of specific numerical assumptions (involved in the description in the reference condition of measurement) is probably the irreducible minimum: a frequency ratio of $\omega = 2.718$, and a reference area of one square centimeter.

This proposal was stimulated by the awkwardly large collection of numbers ordinarily required in order to state fully the conditions of measurement of a given photoconductive cell. For example, a cell was recently described to me as having "a signal-to-noise ratio of so much when there were 45 volts across the cell and 45 volts in the load resistor; when the source was at a temperature of 500° K, was one centimeter in diameter, and was 40 centimeters from the cell; the cell has a sensitive area of 3 mm x 3 mm; the radiation was chopped at 450 cps, and the signal-to-noise ratio was measured in a bandwidth of 9 cps."

If now a number of different investigators use different values of the parameters given above, it is clear that it will be quite difficult for the various investigators to compare results.

Now, there are two possible ways out of this difficulty. One is for every investigator to use the same experimental parameters. The other is for each investigator to reduce his results in such a way that numbers are obtained which are directly compar-

able. I understand that some progress has been made with regard to the former possibility. The proposal here, however, relates entirely to the latter possibility. I should like to propose a method of reduction by which one should obtain the same numerical value from a given cell, even though the cell is tested under various experimental conditions with different values of the parameters mentioned in the quotation above.

Naturally enough, the starting point of this reduction was the similar task of reduction carried out with respect to thermocouples and bolometers in two recent publications (J. Opt. Soc. Am. 39, 327-343, 344-356 (1949)). The reduction in these reports consisted of three distinct parts. First the sensitivity of the detector was reduced to the value it would have if its area were one square millimeter. Secondly the signal-to-noise ratio was reduced to the value it would have if the noise equivalent bandwidth were equal to the bandwidth of the detector itself as determined from its time constant. Thirdly a figure of merit was defined on the basis that the sensitivity resulting from the first two steps should be proportional to the time constant. By this means a figure of merit was obtained by which one could directly intercompare different detectors. Furthermore, the figure of merit carried the implication that any of the detectors considered could be reconstructed to have a given area and a given time constant and that the figure of merit would then be the same. Thus if two different detectors were each reconstructed to have the same final area and time constant, the detector with the higher figure of merit would give superior performance after reconstruction.

There are two reasons why the procedure described in the references cited is not immediately applicable to photoconductive cells: (1) With photoconductive cells, the responsivity in volts per watt depends, among other things, on the wavelength of the radiation or on the temperature of the source, whereas this is not the case for thermocouples or bolometers. (2) Over the useful range, the noise power per unit bandwidth (the noise power is defined as the mean square noise voltage) is inversely proportional to the frequency, whereas with bolometers and photocells the noise power per unit bandwidth is substantially independent of the frequency.

The complication represented by item 1 in the preceding paragraph is an essential complication and cannot be avoided. That is to say, whatever figure of merit is finally defined, it must necessarily be a function of the wavelength or of the temperature. The complication represented by item 2, however, is not an essential one and may be treated as in the following section.

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Noise of Photoconductive Cells

The essential feature of the noise in the output of the photoconductive cells is that the noise power depends on the ratio of the frequencies at the upper and lower end of the passband, rather than on the difference of these frequencies in the ordinary case of flat noise. This fact may be shown as follows:

Let N be the noise power per unit bandwidth, that is to say, the mean square noise voltage per unit bandwidth. Let η be the total noise power. Then, in general, the relation between η and N is as follows:

$$\eta = \int_0^{\infty} N(f) df. \quad (1)$$

In the special case in which an amplifier intervenes between the cell and the noise meter which provides flat amplification of the frequencies between f_1 and f_2 , and which rejects all other frequencies, the above expression becomes

$$\eta = \int_{f_1}^{f_2} N(f) df. \quad (2)$$

Now let f_s be the signal frequency, and let N_s be the noise power per unit bandwidth at the frequency f_s . Then in the case of photoconductive cells one has

$$N(f) = f_s N_s / f. \quad (3)$$

Upon substituting Eq. (3) and Eq. (2) and performing the integration, one finds

$$\eta = f_s N_s \log_e f_2 / f_1. \quad (4)$$

Equation (4) confirms the statement made above that the total noise power depends only on the ratio of f_2 to f_1 .

Now let us consider the case of flat noise defined by the statement that the noise power per unit bandwidth N is in-

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dependent of frequency. One then finds from Eq. (2)

$$\eta = N_s (f_2 - f_1). \quad (5)$$

At this point it has become evident that in the reduction of the experimental results it will be desirable to reduce the experimentally determined sensitivity to the case in which the noise has some specific fractional bandwidth. In my earlier consideration of this subject I considered that the natural choice would be the octave, that is to say, a frequency ratio of 2. More recently, however, I have come to realize that a frequency ratio equal to $e = 2.718$ (where e is the base of Naperean logarithms) is the better choice. If the frequency ratio has this value, Eq. (4) becomes simply

$$\eta = f_s N_s, \quad \frac{f_2}{f_1} = e. \quad (6)$$

That is to say, the total noise power η has the value it would have if the noise power per unit bandwidth at the signal frequency were extrapolated to a bandwidth equal to the signal frequency by the use of the familiar flat spectrum relation (5).

The Proposal

Let F_N be the experimentally determined noise equivalent flux per unit area as measured with a given signal frequency f_s and with an amplifier whose passband extends from f_1 to f_2 . Let A be the area of the detector in square centimeters, and let the measurement refer to a stated wavelength for a stated source temperature. Furthermore, let S_N be the corresponding noise equivalent power. The quantities S_N and F_N are related simply by

$$S_N = A F_N. \quad (7)$$

In order to simplify the writing of equations in the remainder of this report it is assumed that the radiation incident upon the cell is characterized by wavelength rather than by temperature, but it should be held in mind that the symbol λ can be replaced by the temperature T of the source in any of the equations which follow.

Now let the noise equivalent power $\mathcal{S}(\lambda)$ in the reference condition C be defined by the following equation:

$$\mathcal{J}(\lambda) = S_N(\lambda) / (A \log_e f_2/f_1)^{\frac{1}{2}} \quad (8)$$

or

$$\mathcal{J}(\lambda) = F_N(\lambda) \left(\frac{A}{\log_e f_2/f_1} \right)^{\frac{1}{2}} \quad (9)$$

In the very important special case in which the frequency ratio f_2/f_1 does not differ substantially from unity, one has

$$\log_e f_2/f_1 \rightarrow \frac{f_2 - f_1}{f_1} \rightarrow \frac{\Delta f}{f_s}, \quad f_2 - f_1 \ll f_1, \quad (10)$$

provided that the signal frequency f_s lies between the frequencies f_1 and f_2 . Equations (8) and (9) now become

$$\mathcal{J}(\lambda) = S_N(\lambda) \left(\frac{f_s}{A \Delta f} \right)^{\frac{1}{2}} \quad (11)$$

$$\mathcal{J}(\lambda) = F_N(\lambda) \left(\frac{A f_s}{\Delta f} \right)^{\frac{1}{2}} \quad (12)$$

The function $\mathcal{J}(\lambda)$, defined by the above two equations, or alternatively Eqs. (8) and (9), has the following advantages: The number obtained is independent of the signal frequency used in the test, and it is independent of the bandwidth of the amplifier used in making the test. It is furthermore independent of the area of the detector, provided that one assumes that the intrinsic sensitivity of the surface is independent of the total area.

Thus if one plots $\mathcal{J}(\lambda)$ as a function of λ , one obtains a single function which characterizes the intrinsic sensitivity of the detector. No further numerical information whatever need be given. The quantity $\mathcal{J}(\lambda)$ is the noise equivalent power that would be actually measured if the area of the detector were one

square centimeter, and if the frequency ratio of the amplifier used in the measurement were equal to $e = 2.718$. Accordingly, the only two numerical assumptions involved in the reference condition of measurement C are the frequency ratio of e and the area of one square centimeter. Thus if one wishes to be more specific, one can refer to the "reference condition C (e, cm^2)".

Ground Rules

The preceding section has contained the basic idea of the reference condition of measurement. The proposal, however, is not sufficient to insure that all workers will obtain the same numbers. In order to obtain this further assurance it is necessary to agree on a number of additional ground rules.

1. I strongly recommend that the signal voltage, the noise, and the heat signal itself always be measured in terms of their rms value, and that furthermore in the case of the signal voltage and the heat signal, the rms value of the fundamental component be employed. The reasons for this choice seem to me fairly cogent. First, the rms value of the noise voltage is the only reasonable way to measure noise. To be sure, the average value of the absolute deviation from the mean yields a value only 11 percent lower than the rms value, but this value does not enter simply into any fundamental theoretical formulae. The peak noise values which are sometimes stated are to be deplored, since it is difficult to determine the rms value from the peak value, even when the conditions of measurement of the peak value are thoroughly defined. Then, since the rms value must be used for the noise, it is only natural to employ the same measure for the heat signal and for the signal voltage. It is particularly important to employ the same measure for the heat signal and for the signal voltage, since only in this case does the sensitivity in volts per watt reduce at low frequencies to the steady state response in volts per watt. If the rms measure is employed throughout, the reference condition C may be written even more explicitly as "reference condition C ($e, \text{cm}^2, \text{rms}$)."
2. The instantaneous heat signal is to be measured as the difference between the radiation of the source to the cell and the radiation from the cell to the source. This correction is particularly important in the case of low temperature sources.

3. The cell should be measured with a load resistance equal to the dark resistance of the cell.
4. The current through the cell should have the value which maximizes the signal-to-noise ratio.
5. The units in which S_N and δ are measured should be agreed to by common consent. Among the possible choices of ergs per second, microwatts, and watts, the watt family has the obvious advantage that the symbol sec need not be written. Furthermore, the unit watt is easily reduced to smaller dimensions as in μ watt and $\mu\mu$ watt.

Discussion

The statement that the noise equivalent power $\delta(\lambda)$ in the reference condition C is independent of the signal frequency, and the noise equivalent bandwidth used in the measurement depends on two assumptions:

- (1) The assumption that the responsivity of the cell in volts per watt is independent of the signal frequency.
- (2) The assumption that the noise power per unit bandwidth N is inversely proportional to the frequency.

The first condition is evidently equivalent to the assumption that the signal frequency is small compared with the cutoff frequency of the cell as determined by its time constant:

$$f_s \ll \frac{1}{2\pi\tau} \quad , \quad (13)$$

where τ is the time constant of the cell. The second assumption is equivalent to the assumption that the current noise of the cell is large compared with the Johnson noise of the cell and is thus equivalent to

$$f_s \ll R_1^2 f_1 \quad , \quad (14)$$

where R_1 is the ratio of the current noise voltage of the cell to the Johnson noise voltage at the frequency f_1 . These two conditions will almost always be satisfied in the normal condition of

measurement of the cell, but it does not always follow that these conditions will be satisfied for any contemplated application of the cell, that is to say, if one uses Eqs. (11) or (12) backward in order to obtain the actual noise equivalent signal S_N . Under some contemplated conditions of use it is necessary to confirm that the conditions (13) and (14) are simultaneously satisfied.

These considerations naturally raise a question of just how one treats the sensitivity of the cell for frequencies which do not satisfy (13) and (14). At first it might seem as though one could apply one criterion to the range of frequencies in which the noise is primarily current noise and another criterion to the range in which the noise is primarily Johnson noise. Unfortunately, however, this is not the case, since as soon as the frequency rises to the point where current noise is no longer the dominant noise, then clearly an improved signal-to-noise ratio will be obtained by increasing the cell current. Accordingly, for frequencies so high that (14) is not satisfied, it is necessary to redetermine for each frequency the optimum cell current. On the other hand, it is fortunately true that the optimum cell current will be independent of the wavelength or temperature of the radiation. Accordingly, it should be possible to supplement the curve of $\delta(\lambda)$ as a function of λ (which curve holds for frequencies satisfying (13) and (14)) by a supplementary curve which displays as a function of frequency the factor by which $\delta(\lambda)$ must be increased. Thus two separate curves should suffice for the complete description of the sensitivity of a photoconductive cell as a function of signal frequency and signal wavelength or temperature. On the other hand, the state of the art has certainly not advanced to the point where the second type of curve is easily measurable.

There is a detail relating to the noise question which may be of some interest. Suppose that one wishes to use experimentally a passband in the amplifier corresponding to a frequency ratio of 2.718, which passband is to have the additional requirement that the width of the passband is to be equal to the signal frequency. In this case the upper and lower frequency limits of the amplifier are uniquely defined. The lower limit of the passband should be $0.581 f_g$, and the upper limit should be $1.581 f_g$. It is easily confirmed that these two frequency limits satisfy the condition that their difference is f_g and their ratio is e .

Note Added December 7

The above material is substantially that contained in a letter to Professor R. J. Cashman dated November 9. Although no written reply has yet been received from Dr. Cashman, Dr. Cashman in-

dictated in a telephone conversation on November 28 that he had some question about the legitimacy of the assumption involved in Eq. (3) above, namely the assumption that the mean square noise voltage per unit bandwidth is inversely proportional to the frequency. Accordingly, this must be considered as an open question subject to further investigation. The writer does have a rather strong prejudice that Eq. (3) is correct. It is well known that the recently developed transistor has a noise spectrum of the type represented by Eq. (3), and Christensen and Pearson¹ find that the noise spectrum of carbon microphones as well as carbon resistors also has a spectrum indicated by Eq. (3). The only experimental study² of photoconductive cells which treats the noise spectrum and which is available to the writer indicates that the noise spectrum between 50 and 500 cycles is in accord with Eq. (3), but that the noise spectrum falls off more rapidly at higher frequencies. In this case, however, Mr. L. G. Mundie indicates in a letter dated December 2, "We agree with your observation that the noise spectrum curve in Plate 6 does seem to fall off abnormally fast above 1000 cps. This is probably due to excessive capacity somewhere in the cathode follower circuit. No pains were taken to remove this capacity, as no further measurements were made at frequencies above 90 cps. Had we used frequency response curves to determine the time constants, this capacity would, of course, have been intolerable."

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¹ C. J. Christensen and G. L. Pearson, Resistance fluctuations in carbon microphones and other granular resistances, B.S.T.J. 15, 197-223 (1936) (Monograph B-922).

² L. G. Mundie, E. M. Pell, and L. W. Jones, An experimental study of nineteen lead sulfide photoconductive cells, December 9, 1948 (NOLM 9929).

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An Application of the Proposed Reference Condition C

R. Clark Jones

December 6, 1949

In order to illustrate the usefulness of the proposal contained in the writer's report dated November 30, 1949, the proposal will be applied to the specific results contained in the Naval Ordnance Laboratory report NOLM 9929.* This report contains detailed measurements of the noise and the responsivity of 19 different lead sulfide cells. In the case of 9 of these cells, measurements were made with the cell at room temperature and at dry ice temperature.

In connection with this report, the writer wishes to acknowledge a very gracious and very helpful letter received from L. G. Mundie dated December 2, 1949, in which a rather large number of detailed questions are answered with respect to the report cited. A number of quotations from this letter are used below.

The data actually used in this report are contained in Table I and Plates 7 through 34 of the NOL report. More specifically, there is used the noise equivalent power per square centimeter at the wavelength of peak sensitivity as given in Table I and the corresponding values for other wavelengths were obtained from the curves in Plates 7 through 34. The noise equivalent power per square centimeter for 200° C black body radiation as given in Table I has also been used.

The values of the noise equivalent flux stated in Table I of the NOL report must be subjected to minor corrections in order to obtain the rms power per unit area which is equivalent to the rms noise. Let F_N' be the noise equivalent flux stated in Table I of the NOL report. Then F_N' should be multiplied by** $0.45 = 2^2/\pi$,

* L. G. Mundie, E. M. Pell, and L. W. Jones, "An experimental study of nineteen lead sulfide photoconductive cells," December 9, 1948.

** "Our 200° C heat signal consisted of a flux of 13.7 microwatts per square centimeter interrupted in a square wave manner. This figure represents the difference in flux density received by the cell from the black body and the (room temperature) chopper blade. The rms value of the fundamental component would indeed be obtained by multiplying this peak-to-peak value by 0.45."

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and must further be multiplied by* 1.128. Accordingly, one has

$$F_N = 0.508 F_N' . \quad (1)$$

The cells were measured at a frequency of 90 cps and with a bandwidth** of 5 cps. The factor $(A/\log_e f_2/f_1)^{\frac{1}{2}}$ therefore has the value:

$$(A/\log_e f_2/f_1)^{\frac{1}{2}} = 4.24A^{\frac{1}{2}} . \quad (2)$$

Upon substituting Eqs. (1) and (2) above in Eq. (9) of the writer's November 30 report, one finds:

$$\lambda = 2.15A^{\frac{1}{2}} F_N' . \quad (3)$$

The values of λ for the wavelength of peak sensitivity and for 200° C black body radiation were computed from the results in the NOL Table I and are given in Table A of this report.

It may be noted in Table A that the noise equivalent power in the reference condition C is stated to be given in watts. It may be argued that the correct unit is not watt, but rather watt/cm. The writer, however, prefers to think of the area A which appears in Eqs. (2) and (3) above not as the area in square centimeters, but as the ratio of the area of the actual detector to the area of a detector which has an area of one square centimeter; from this point of view the area A is thus dimensionless.

* "For the signal voltage, we used the direct meter indication, and for the noise voltage we averaged the indication of the meter. When one takes noise measurements over a bandpass as narrow as is obtained with this wave analyzer, however, it is seen that the fluctuations are such a large fraction of the reading itself that this averaging process is rather difficult and inaccurate. We found, for example, that one observer might read the noise as much as 20% higher than another observer from the same meter fluctuations. This inaccuracy could, of course, have been reduced by using a broader bandpass, at the cost of reducing our signal-to-noise ratio. In any case you are right -- our readings would have to be multiplied by 1.1284 to give the rms noise."

** "The wave analyzer used was a General Radio Model 736A, not 548A, as reported. A more careful study of the gain curve supplied with the instrument seems to indicate a bandwidth of 5.2 cps; thus as you suggest, 5 cps is a better figure than 6 cps."

The noise equivalent power in the reference condition C is plotted as a function of wavelength in Figs. 1 and 2. In these figures the detectors are identified by the plate number given in column 3 of Table A. The results for the cells which were cooled to dry ice temperature have even numbers from 18 to 34; all of the other curves correspond to measurements with the cell at room temperature. It should be noted in these figures that the noise equivalent power decreases as the ordinate increases. This method of plotting has been used in order that the curves should have their normal appearance. The noise equivalent powers in the reference condition C for the 200° C black body are plotted in Fig. 3.

At any given wavelength the reciprocal noise equivalent power in the reference condition C may be considered as a figure of merit for the various detectors. That is to say, the higher a given detector appears (for a given wavelength) in Figs. 1 and 2, the greater is the intrinsic merit of that detector at that wavelength. The ordinates in the figures, however, have more than relative value, as illustrated in the next paragraphs.

By inverting Eq. (3) in the writer's November 30 report, one finds:

$$S_N(\lambda) = \Delta(\lambda) (A \log_e f/f_1)^{\frac{1}{2}}. \quad (4)$$

This relation will now be used in the solution of the following sample problem. Consider a hypothetical cell with an area of 0.1 cm² whose noise equivalent power in the reference condition C is the same as the cooled ARL cell B-434, denoted by the number 20 in Fig. 1. If this cell is chopped at 200 cps and the passband of the amplifier has a noise equivalent bandwidth of 10 cps, what rms-signal to rms-noise ratio will be obtained with a steady incident power of 1 μwatt on the cell at a wavelength of 2.4 μ?

The rms power incident upon the cell is therefore given by

$$\text{rms power} = 0.25 \text{ } \mu\text{watt}. \quad (5)$$

From Fig. 1, one has

$$\Delta(2.4) = 2.0 \times 10^{-11} \text{ watt}. \quad (6)$$

The conditions of the problem further yield:

$$\begin{aligned} A &= 0.1 \\ \log_e f/f_1 &= 0.05. \end{aligned} \quad (7)$$

Upon substituting Eqs. (6) and (7) in Eq. (4), one obtains

$$S_N(2.4) = 2.05 \times 10^{-12} \text{ watt.} \quad (8)$$

The solution of the problem is now practically at hand. One has the following general relationship:

$$\frac{\text{rms signal}}{\text{rms noise}} = \frac{\text{rms power}}{\text{rms noise equivalent power}} \quad (9)$$

Since the numerator and denominator on the right are given respectively by Eqs. (5) and (8), one obtains in the output of the detector an rms-signal to rms-noise ratio given by

$$\frac{\text{rms signal}}{\text{rms noise}} = 2.2 \times 10^5 \quad (10)$$

Acknowledgment

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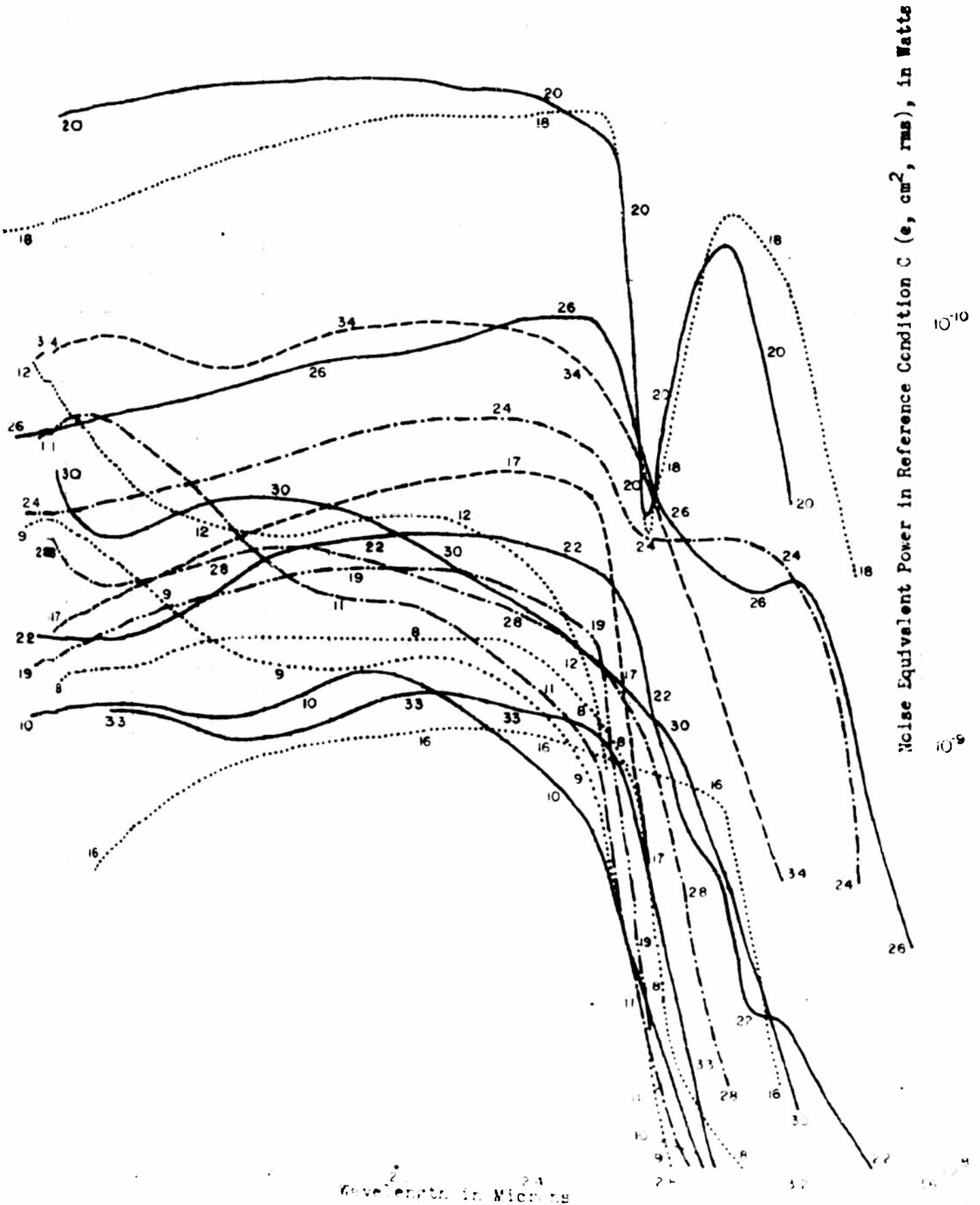
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TABLE 3

Manufacturer and Cell No.	Cell Tem- perature	Plate No.	δ_N = noise equivalent power in reference con- dition C(e, cm ² , rms) at wavelength of peak sen- sitivity in watts	δ_N = noise equivalent power in reference condition C(e, cm ² , rms) for 200° C black body radiation, in watts
Cover Dual				
EV-1-1	25° C	7	9.67×10^{-8}	$> 2.56 \times 10^{-5}$
Cover Dual				
EV-1-10	25° C	8	5.84×10^{-10}	4.56×10^{-7}
Cover Dual				
EVN1-22	25° C	9	3.10×10^{-10}	9.67×10^{-7}
Cover Dual				
EVN1-23	25° C	10	6.92×10^{-10}	8.58×10^{-7}
Cover Dual				
EVN4-15	25° C	11	1.83×10^{-10}	6.92×10^{-7}
RCA				
PG-568-88	25° C	12	2.94×10^{-10}	4.34×10^{-7}
RCA				
PG-568-107	25° C	13	3.57×10^{-9}	2.08×10^{-6}
ARL				
125	25° C	14	2.15×10^{-9}	9.89×10^{-7}
ARL				
156	25° C	15	2.15×10^{-9}	7.30×10^{-7}
ARL				
3	25° C	16	9.45×10^{-10}	1.33×10^{-6}
ARL	25° C	19	3.93×10^{-10}	2.28×10^{-7}
B-434	-80° C	20	2.69×10^{-11}	1.35×10^{-8}
ARL	25° C	17	2.30×10^{-10}	1.55×10^{-7}
B-465	-80° C	18	3.18×10^{-11}	1.35×10^{-8}
ARL	25° C	21	2.69×10^{-9}	2.11×10^{-6}
C-30	-80° C	22	3.27×10^{-10}	
ELAC	25° C	23	2.69×10^{-8}	$> 8.92 \times 10^{-5}$
ST23DH-427	-80° C	24	1.72×10^{-10}	5.31×10^{-7}
ELAC	25° C	25	1.20×10^{-8}	$> 3.20 \times 10^{-5}$
RD-55-567	-80° C	26	9.89×10^{-11}	5.03×10^{-8}
Farrand	25° C	27	4.00×10^{-8}	$> 9.03 \times 10^{-6}$
80	-80° C	28	3.55×10^{-10}	1.55×10^{-7}
Farrand	25° C	29	3.22×10^{-8}	$> 9.03 \times 10^{-6}$
95	-80° C	30	2.71×10^{-10}	1.74×10^{-7}
Farrand	25° C	31	7.09×10^{-8}	$> 9.03 \times 10^{-6}$
105	-80° C	32	1.55×10^{-9}	2.97×10^{-6}
Cashman	25° C	33	7.78×10^{-10}	8.70×10^{-7}
	-80° C	34	1.03×10^{-10}	4.34×10^{-8}

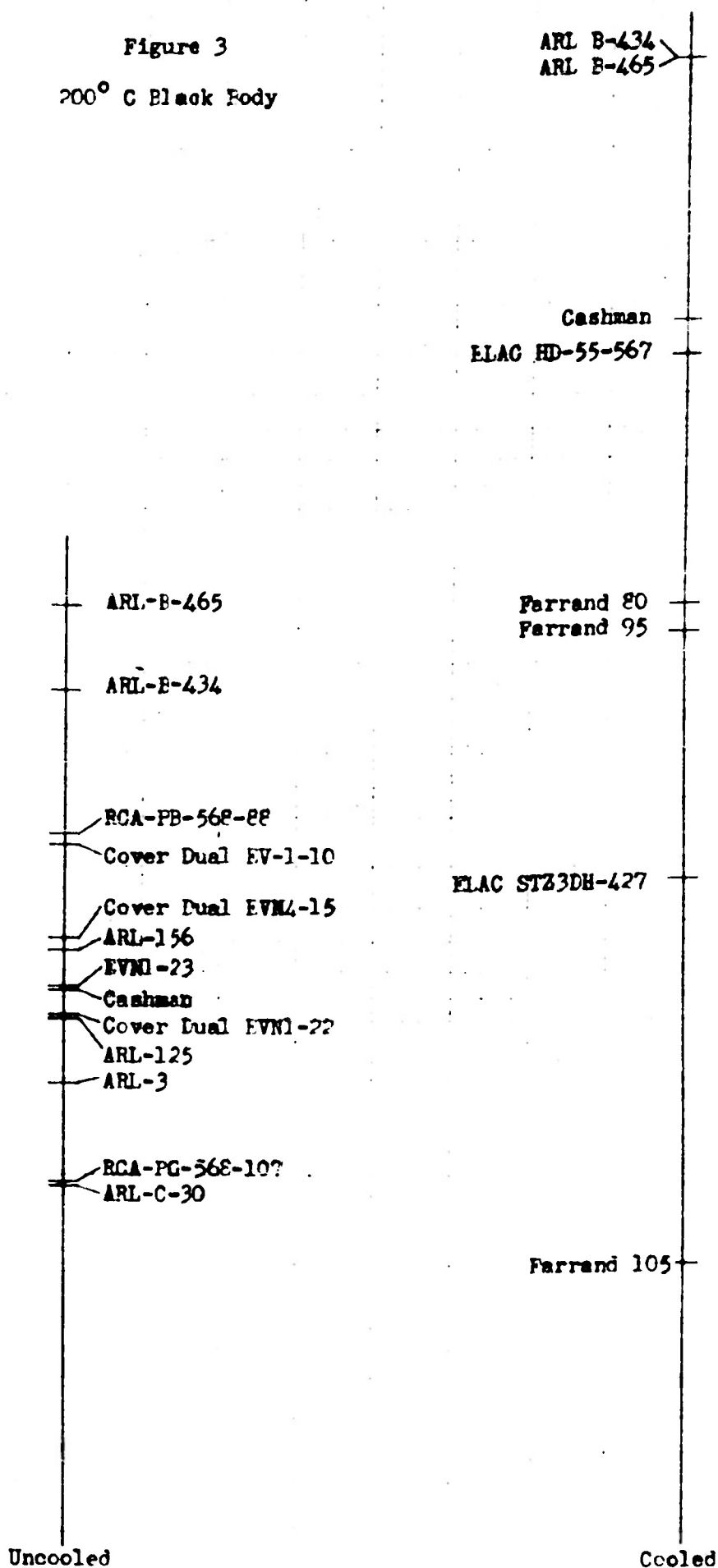
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Figure 1



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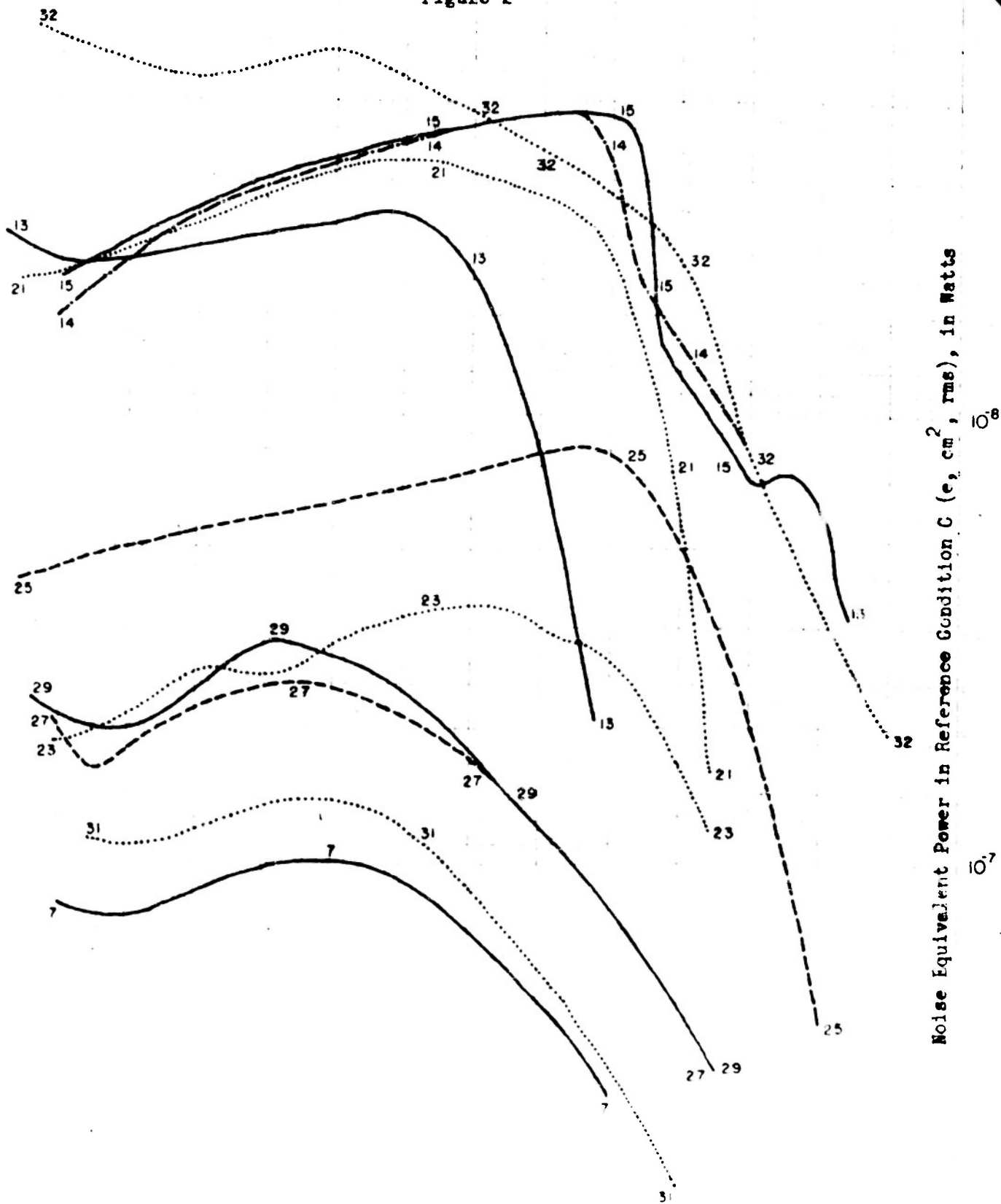
Figure 3
200° C Black Body



Noise Equivalent Power in Reference Condition C (e, cm², rms), in Watts

10⁻⁷10⁻⁶10⁻⁵

Figure 2



Noise Equivalent Power in Reference Condition C (e, cm^2, rms), in Watts

Wavelength in Microns

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