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NAVORD REPORT 2666

GAMMA RAY SOURCES AND TECHNIQUES FOR GAMMA RAY RADIOGRAPHY

26 FEBRUARY 1953

U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

NAVORD Report 2666

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ABSTRACT: A general review of radioisotopes used as radiation sources for industrial radiography is given along with production methods, measurement units, standards and nomenclature commonly associated with their use. The specific characteristics of commercially available radiation sources are discussed as well as elements expected to be available in the near future. Particular attention has been paid to the characteristics of various isotopes which determine their suitability for specific types of radiographic inspection. Complete information for the purpose of obtaining optimum radiographs for various object thicknesses and materials is provided. Information is likewise provided for the safe handling, storage and shipping of radioisotopes of various energies.

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1. NAVORD Report 2666 describes a laboratory investigation of optimum techniques for radiography with gamma ray sources. General information of value to radiographers, such as physical properties, shipment, storage and handling procedure, is included.

2. This work was carried out by the Technical Evaluation Department under Task NOL-199-52, Radioisotopes.

3. This publication is UNCLASSIFIED.

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NAVORD Report 2666

GAMMA RAY SOURCES AND TECHNIQUES FOR GAMMA RAY RADIOGRAPHY

INTRODUCTION

Radiographic Gamma Ray Sources

1. Natural gamma emitters, primarily radium and radon, have been used for industrial radiography since the introduction of the technique in 1930 (1). The use of these materials never became widespread because of their prohibitive cost and, in the case of radon, its short period of usefulness.

2. The construction during the war of high-flux neutron piles made possible the synthesis of gamma-emitting isotopes and these were made available by the Atomic Energy Commission in 1946 and 1947. Shortly thereafter the possibility of using some of these artificially produced isotopes for radiography was realized by Tenney (2) and others. Initially considered were cobalt 60 and tantalum 182 and today the use of cobalt 60 for radiographic work is increasing at a rapid rate. The number of isotopes available through the AEC and its Canadian counterpart have increased steadily, so that today about ten different isotopes suitable for radiography are available.

3. The ideal situation would find a series of gamma emitters available with a range of effective energies spanning the 100 Kev to 3 MeV portion of the gamma ray spectrum. Unfortunately, the radioisotopes now available do not completely cover this energy range, but there is reason to expect the gaps in the energy range to be more nearly filled in the future.

Advantages of Gamma Ray Sources

4. Readily available radioisotopes at a reasonable price permit the application of radiographic inspection techniques by those otherwise unable to afford it. The cost of radioactive isotopes, even when their limited period of usefulness

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(1) R. F. Mehl, G. E. Doan, and C. S. Barrett - Radiography by the Use of Gamma Rays - Transactions of A.S.S.T., Vol. 18, 1930, p. 1192.

(2) G. H. Tenney - Radioactive Isotopes as Sources in Industrial Radiography - Nondest. Test. Jour., Vol. 6, No. 4, Spring 1948, p. 7-10.

is considered, is low when compared to the initial and upkeep costs of x-ray generators. This is especially true when high energy gamma sources are being compared on a cost basis to high energy x-ray generators. The price of special handling tools and protective devices, essential accessories for radiography with radioisotopes, is also small when compared to the cost of safely shielding an x-ray generator.

5. Radioactive isotopes, together with their shielding containers, provide a small compact source of gamma radiation. They can be shipped very easily and moved about an industrial plant with little effort. This is a distinct advantage, especially in a crowded industrial plant, over a fixed x-ray generator.

Similiarity of Gamma and X-rays

6. It should be mentioned, before discussing radioactive constants, that the gamma radiation associated with many radioactive elements differs from high energy x-rays only in origin. Radiographically, no distinction need be made and high energy x-rays may be considered identical to gamma rays.

Measurement Units and Standards

Activity

7. The radiation emanating from radioactive elements and radioisotopes results from the spontaneous disintegration of the atoms of the element. This disintegration or break-down with the emission of an alpha or beta particle results in the formation of atoms of a new "daughter" element. The emission of gamma rays frequently accompanies the ejection of the alpha and beta particles, more often the beta particles. Early experimental work indicated that the rate of disintegration was logarithmic; that is, the number of atoms breaking down per unit of time is proportional to the total number of atoms present. The mathematical expression for the disintegration of a radioactive source is $N_t = N_o e^{-\lambda t}$, where

N_o = number of atoms at any arbitrary zero time

N_t = number of atoms remaining after an interval of time "t"

λ = decay constant or disintegration constant.

The decay constant is a specific property of a given radioelement and is independent of the physical condition or state of chemical combination of the element. For this reason, radioactive elements can be identified by their decay constants.

8. The rate of disintegration serves as a basis for quantitative measurements of radioactivity. The curie is the unit of measurement and is defined as the quantity of any radioactive nuclide in which the number of disintegrations per second is 3.700×10^{10}. Actually, the above definition is a new definition arrived at by an international council* convened to redefine the curie to avoid the confusion caused by the original definition. The initial definition of the curie was based upon the quantity of radon (the daughter element of radium) in equilibrium with one gram of radium. The number of disintegrations per second (3.7×10^{10}) used in the new definition is the generally accepted value for the disintegrations per second occurring in one gram of radium. In other words, the new definition permits the equating of one gram of radium to one curie.

Specific Activity

9. For practical purposes another expression, specific activity, is used to indicate the concentration of the radiation source. The specific activity of a given source is expressed as the number of curies per gram, with both stable and active isotopes considered in the weight. This definition gives pure radium a specific activity of one curie per gram. In industrial radiographic work, where the physical dimensions of the radiation source are important, the specific activity of a source is of great concern and very informative.

Half-Life

10. With disintegration progressing continuously in a radioactive source it is obvious that the radiation source is decreasing in quantity. If this decrease is too rapid the radioelement is unsuitable for radiographic work, regardless of its other characteristics. Although the decay constant previously mentioned indicates the rate of decay of a radioactive element, a more convenient term is commonly used. This is the half-life of a radioelement, or the time required for a given amount of the element to decay to half of its initial value. The ratio of N_t to N_o in the expression $N_t = N_o e^{-\lambda t}$ is then $\frac{1}{2}$ and T, the half life is equal to $0.693/\lambda$. This expression permits the determination of the half-life of a given element, if the decay constant is known. The half-lives of radioactive elements vary from fractions of a second to billions of years. When determining correct

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* Joint Commission on Standards - Units and Constants of Radioactivity - Paris, France, 17 Jul 1950.

radiographic exposure times the half-life of the source material must be considered and an appropriate correction factor applied. This is especially true for the shorter-lived elements. Radioactive elements with half-lives less than several months are not considered practical for radiographic work.

Detection and Measurement

11. Shortly after the discovery of radioactivity, it was noted that gases became electrical conductors, that is, they were ionized, when exposed to radiation. Alpha and beta particles are much more effective ionizing agents than gamma rays but all three do cause ionization. This property of radiation was utilized to design a great many radiation detectors and measuring devices. These instruments are readily calibrated for quantitative radiation measurements since the common unit of measurement, the roentgen, is defined as that amount of gamma radiation such that the associated corpuscular emission per 0.001293 grams of air (1 cc of air under standard conditions) produces, in air, ions carrying one electrostatic unit of quantity of electricity of either sign. Other instruments commonly used for the detection and measurement of radiation depend for operation upon changes in electrical properties or light emission by certain materials when exposed to radiation.

12. The sizes of radiation sources in general use are quite small so that the units of measurement commonly encountered are fractions of curies and roentgens. The milliroentgen and millicurie are used more often than the curie or roentgen in quantitative measurements.

Radium Emission

13. Radium sources generally used for instrument calibration will always emit the same amount of radiation under a definite set of physical conditions, as well as other radioelements. A point source of one milligram (one millicurie) of radium surrounded by one-half millimeter of platinum delivers 8.4 roentgens per hour at a distance of one centimeter. For other distances the number of roentgens delivered varies in accordance with the inverse square law. The radiation is, of course, directly proportional to the quantity of radium excepting radiation absorbed within the source.

Synthesis of Radioisotopes

Particle Bombardment

14. Very few of the natural occurring radioactive elements

meet the requirements of a radiographic source and none is abundant in nature. Radium, by far the most common source material, can be obtained only after a long, laborious refining process. Radium is recovered from uranium ore and over 2,900,000 grams of uranium ore must be processed to obtain one gram of radium. This, as well as the limited world supply has kept the cost of radium beyond the reach of many potential users. On the other hand, synthesized radioactive materials can be produced in relatively large quantities, either in an atomic pile or a cyclotron. In the cyclotron, radioactive elements are produced as the result of nuclear bombardment by accelerated charged particles, usually deuterons. The quantities produced in cyclotrons are small compared to pile production.

Pile Produced Isotopes

15. Practically all synthesized radioelements of interest to the industrial radiographer are pile produced as a result of neutron induced reactions. The isotope is produced by inserting the target material either as an element or compound into the pile and irradiating it with thermal neutrons. The time of irradiation varies from a day to several months, depending upon a number of variables. When the target material chosen is a compound the other element or elements of the compound must be selected to produce no radioactive isotopes, very short-lived radioactive isotopes or radicactive isotopes which can easily be separated from the required product. The target element undergoes one of a number of possible nuclear reactions with the resulting formation of a radioelement. Neutron absorption by the target element is usually accompanied by the simultaneous emission of a gamma ray, alpha particle or photon. The neutron-gamma reaction may yield an isotope of the target element or a decay scheme yielding a daughter element differing chemically from the target element. The neutron-alpha and neutron-proton reactions result in transmutations yielding isotopes differing chemically from the target elements.

Nuclear Cross Section

16. The probability of a nuclear reaction occurring in a specific element as the result of bombardment by sub-atomic particles, such as neutrons, is expressed by means of a quantity called the nuclear cross-section, the unit of which is the barn. The symbol for the barn is sigma, σ, and one barn is equal to $10^{-24}/cm^{-2}$/nucleus. With reference to neutrons, the total nuclear cross-section of an element A is the fraction of neutrons in a beam 1 cm^{-2} that is intercepted by a single nucleous of element A. The barn is

therefore expressed as $\sigma = \frac{B}{NI}$ sq cm/nucleus where I is the number of incident neutrons, striking in a given time, a one square centimeter area of the target material, containing N target nuclei and B is the number of these nuclei to undergo transmutation. The nuclear cross-section of an element is a specific property of the element and can readily be determined by measurement. If an element is placed in a neutron beam in the form of a sheet X cm thick and the neutrons striking the sheet per unit time are determined as well as the number emerging from the other side of the sheet, then σ can be calculated from the expression $\frac{I}{I_o} = e^{-NX\sigma}$, where

I_o = incident neutrons per unit time per sq. cm

I = emerging neutrons per unit time per sq. cm

X = sheet thickness in cm

N = target nuclei per cc

σ = total nuclear cross-section.

Resulting Activity

17. The specific activity of a radioelement resulting from thermal neutron irradiation in a pile can be predicted by use of the expression

$$S = \frac{0.6\,\sigma\phi}{3.7 \cdot 10^{10} \cdot A}\left(1 - e^{-.693t/T}\right), \text{ where}$$

S = curies/gm

ϕ = thermal neutrons /cm^{-2}/sec

σ = nuclear cross-section of target element for thermal neutrons

A = atomic weight

T = half-life

t = irradiation time.

Neutrons of low energy, about 1/40 ev, are considered thermal neutrons and are largely responsible for most of the nuclear reactions in the pile. Piles at Chalk River, Canada, operate with a neutron flux of 4×10^{13} neutrons /cm^{-2}/sec and those used in the United States for production

of radioisotopes operate at a lower neutron flux (1). This means that at the present time sources of greater specific activity can be procured from Chalk River than from the American piles.

Specific Characteristics

Radium - General Information

18. Radium, with an atomic number of 88 and an atomic weight of 226.05, is a metal with a melting point of 960° C and a boiling point of 1140° C. It has a valence of 2 and its specific gravity is approximately 5. It is a brilliant white metal, showing some luminescence, but alters its appearance rapidly in air and decomposes in water. It was first separated, in the form of a compound, from pitchblende in 1898 by the Curies. It is obtained commercially today in the form of the compressed sulfate with specific activities up to approximately 3 mc per cubic mm.

19. Actually radium, a member of the uranium series of radioelements, is an emitter of alpha rays which are of no value in radiographic work. References to radium sources mean, in all cases, radium in equilibrium with its decay products from which the gamma radiation is emitted. Although the decay rates of various substances vary greatly, all members of a radioactive series, except the parent, are being produced at exactly the same rates as those at which they are disintegrating. This condition, known as radioactive equilibrium, means that the amounts of all substances present in a series remain in the same proportion. Radon, the daughter element of radium and itself an alpha emitter, attains equilibrium with radium after a period of 30 days if sealed in a holder.

Radium Disintegration

20. The entire uranium series is shown in Table I. The branched or double disintegration which first occurs with radium A is characteristic of all radioactive series. Considering radium as the parent of the radium disintegration series, the following breakdown occurs:

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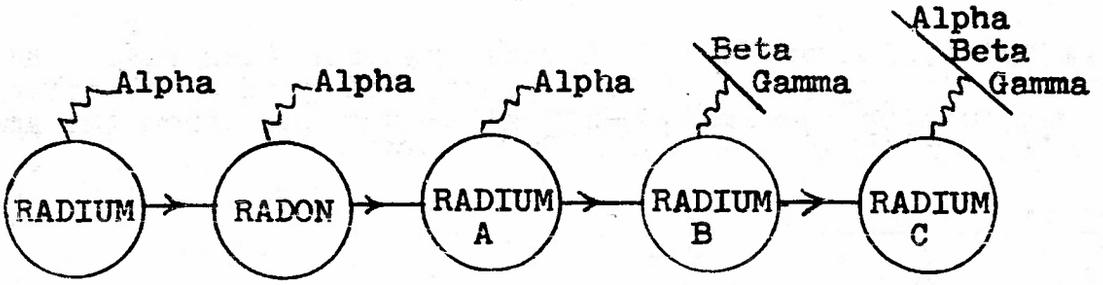
(1) National Research Council, Atomic Energy Project, Canada - Pile-Produced Isotopes.



As mentioned previously, no gamma emission appears in the series until the breakdown of radium B.

Activity and Half-Life of Radium

21. The accepted value for the number of disintegrations per second occurring in one gram of radium is 3.7×10^{10}. By definition of the curie this means that one gram of radium in equilibrium is equal to one curie. The half-life of radium is about 1590 years, so that in radiographic work the strength of a radium source may be considered constant and no correction factor is required. A 1 mg parent source of radium sealed in a platinum container with walls 0.5 mm thick will deliver by measurement, 8.4 roentgens per hour at a distance of one centimeter.

Energy and Half Value Layer of Radium

22. The gamma ray spectrum of radium is shown in Figure 1 (1). Although the peak gamma ray energy is about 2.2 MeV, there is a great deal of low energy gamma present. This characteristic permits the use of radium for radiography of thin sections of dense materials such as steel. It is useful for radiography of steel sections $\frac{1}{2}$" - $4\frac{1}{2}$" thick. The average energy of the gamma emission from radium is about 1.7 MeV. It should be remembered that the average energy of the radiation produced by an a.c. resonant transformer, 2 MeV x-ray generator is only 1.4 MeV.

23. The half value layer, that is the thickness of a material which reduces radiation intensities to one-half incident value, is frequently used to compare radiation characteristic of radioisotopes. The half value layer of iron for the radiation of radium is 0.90". Other half value layers are: lead - 0.51" and concrete - 3" approximately.

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(1) S. Glasstone - Sourcebook on Atomic Energy - 1950.

Cobalt 60 - General Information

24. Cobalt 60 is a pile produced radioisotope obtained by subjecting the stable element cobalt 59 to a neutron bombardment of low energy neutrons.

$$Co^{59} + n^{1} \rightarrow Co^{60} + \gamma^{o}$$

The neutron cross section is 22 barns (1). Cobalt is a white metal with a boiling point of 3000° C, a melting point of 1480° C and its specific gravity is 8.9. It is a hard, brittle metal which oxidizes readily and has a tendency to flake. This latter characteristic can prove hazardous from a standpoint of contamination, so it is customary to seal or plate cobalt sources.

Activity and Half-Life of Cobalt 60

25. The activity of a cobalt source depends upon a number of variables, as discussed previously, so the activity of a given weight of cobalt 60 may vary depending upon its irradiation history. Activities as high as 14 curies per gram (1) can be obtained and even greater specific activities should become available with the operation of high neutron flux reactors. This means that large radiation output is available from a physically small source, an ideal condition for radiography. A 2 curie cobalt 60 source in the form of a right cylinder may measure as little as 3.31 mm long and 3.32 mm in diameter. A 1 millicurie point source of cobalt 60 is calculated to deliver about 13 roentgens per hour at 1 cm. The ionization produced by 1 milligram of radium has been calculated to be 9.7 roentgens per hour at 1 cm, so that 1 millicurie of cobalt 60 may be considered equivalent to 1.34 millicurie of radium. Assuming a correction factor of 15% for the absorption in a 0.5 mm platinum radium capsule, an equivalence factor of 1.5 results. This factor of 1.5 is used to express the equivalence between a millicurie of radium and a millicurie of cobalt 60.

26. The half-life of cobalt 60 is 5.3 years and the disintegration results in the conversion of cobalt 60 atoms to the stable element nickel. The half-life of cobalt is long enough to justify considering it a constant size source for the duration of an exposure. However, periodic corrections of source strength should be made. Semi-annual corrections are sufficient and Table II gives the percentages of original strength remaining. Figure 2 gives the same information in a different form.

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(1) Isotope Branch, National Research Council, Atomic Energy Project, Canada - Pile-Produced Isotopes.

Energy and Half Value Layer of Cobalt 60

27. The gamma ray spectrum of cobalt 60 is shown in Figure 3. Unlike radium, cobalt 60 has only two lines, both in the same energy range. The lack of soft gamma radiation makes cobalt 60 unsuitable for the radiography of thin sections of high density material. Cobalt 60 is not suited for radiographic inspection of steel less than one inch thick. Cobalt also emits beta rays with an energy of 0.3 MeV, which are usually absorbed in the wall of the source container.

28. The half value layer of iron for cobalt 60 radiation is about 0.90" and of lead, 0.51".

Iridium 192 - General Information

29. Iridium 192, like cobalt 60, is a pile produced radioisotope. The stable element iridium 191 when exposed to a thermal neutron flux undergoes a simple neutron capture process resulting in the formation of iridium 192.

$$Ir^{191} + n^{1} \rightarrow Ir^{192} + \gamma^{0}$$

The neutron cross section for this reaction is 388 barns (1). A similar reaction involving the stable isotope iridium 193 occurs simultaneously but at a slower rate, resulting in the formation of iridium 194, another radioisotope. The cross section for this reaction is only 79 barns and the half-life of iridium 194 is only 19 hours, so that about a week after irradiation, the iridium source may be considered to be essentially made up of iridium 192.

30. Iridium is a metal with a boiling point of above 4800° C, a melting point of 2350° C and a specific gravity of 22.4. It is a white metal, extremely hard and brittle.

Activity and Half-Life of Iridium 192

31. The activity of an iridium source, as all pile produced radioisotopes, depends upon its irradiation history and other variables. Iridium sources with extremely high specific activities can be obtained from the presently operating piles. Activities as high as 1000 curies per gram are available (1), so that a 2 curie source of iridium measuring only 1 mm by 1 mm may be purchased. A one millicurie iridium source delivers 2.7 roentgens per hour at 1 cm. Due to the high

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(1) Isotope Branch, National Research Council, Atomic Energy Project, Canada - Pile-Produced Isotopes.

self-absorption of the iridium radiation, the gamma radiation external to the source is not directly proportional to the activity of the source. Because of this fact, the strength of iridium sources is frequently expressed in terms of external output, milliroentgen per hour at one meter, rather than in millicuries.

32. A number of values for the half-life of iridium have been published, varying by as much as 10%. Recent measurements indicate the half-life to be 74±1 days (1). Iridium 192 is a comparatively short-lived isotope and corrections for source strength must be made frequently. Weekly corrections should suffice for routine radiography. Information needed for correction of source strength is given in Table III and Figure 4 (1).

Energy and Half Value Layer of Iridium 192

33. The disintegration of iridium 192 is accompanied by the emission of both beta and gamma radiation. The gamma ray spectrum is composed of more than 17 lines of various energies, but a number of these are of relatively weak intensity (2). The six principal lines and their relative intensities are shown in Figure 5 (1). The low energy emission of iridium 192 makes it an ideal source for radiography of thin sections of steel ½" to 2".

34. The half value layer of lead for the gamma radiation of iridium is 0.08"; for steel it is approximately 0.5".

Characteristics of Other Sources

35. A number of other radioactive isotopes have been used for gamma ray radiography with varied success. Tantalum 182 is widely used as a substitute for cobalt 60. It is a pile produced isotope resulting from a simple neutron capture process.

$$Ta^{181} + n^{1} \rightarrow Ta^{182} + \gamma^{0}$$

Its neutron cross section is 20.6 barns and greater specific activities, 48 curies/gm, can be attained than with

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(1) A. Morrison - Iridium 192 for Gamma Ray Radiography - Jour. Soc. of Nondest. Test., Summer, 1951.

(2) J. M. Cork, J. M. LeBlanc, A. E. Stoddard, W. J. Childs, C. E. Branyan and D. W. Martin - Radioactivity Induced in Iridium by Neutron Capture - Physical Review, Vol. 82, No. 2, Apr 1951.

cobalt 60 (1). Its gamma ray spectrum is quite complex with over 40 components present. The principal lines are shown in Figure 6. The presence of low energy gamma rays results in slightly better radiographic contrast for thin sections of steel than do the almost monoenergetic rays of cobalt. The absorption characteristics of tantalum 182 are very similar to those of cobalt 60. The half value layer of lead is 0.5 inch and comparative exposure curves for the radioelements are given in Figures 7 (2) and 8. The chief disadvantage of tantalum 182 is the comparatively short half-life, which is only 120 days.

36. Europium 154 is another pile produced isotope which can be used in place of cobalt 60. Its neutron cross section is 125 barns, it can be quickly activated and sources of very high specific activity can be obtained. Sources with specific activities ten times greater than cobalt 60 can be obtained. Europium 154, like tantalum 182, results from a simple neutron capture process. Its gamma ray spectrum is rather complex, the principal lines being at .24, .28, .34, .40 and 1.6 MeV. An exposure curve for europium 154 is also shown in Figure 7 (2). The half-life of europium 154 is 5.4 years, almost the same as cobalt 60 (1). The soft components of gamma radiation present in the europium spectrum indicate that unlike cobalt 60, europium is usable for thicknesses of steel less than 1". The availability of europium sources is still limited, primarily because of the scarcity of the target material.

37. Several isotopes of the element cesium are suitable for radiography and their use is increasing rapidly. Cesium 137 is a fission product with a half-life of 37 years. Although its long half-life is desirable, the specific activity of cesium 137 has a definite limit, since it is a fission product, and is quite low compared to the pile produced sources already discussed. Cesium 137 is a beta emitter itself, but its breakdown results in the emission of gamma rays with an energy of 669 KeV. The radiation output of cesium is fairly low, a 1 millicurie source delivers about 3 roentgens per hour at 1 cm, which, coupled with its low specific activity, represent the chief disadvantages of cesium 137. Cesium 134, which is a pile produced isotope is also a gamma emitter. The half-life of cesium 134 is 2.3 years and the principal lines

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(1) Isotope Branch, National Research Council, Atomic Energy Project, Canada - Pile-Produced Isotopes.

(2) W. S. Eastwood - Gamma Radiography in United Kingdom - Neucleonics, Jul 1951.

of its gamma ray spectrum have energies of .57, .60, .79 and 1.35 MeV. The 1.35 MeV radiation is relatively weak, so that the gamma ray spectrum of cesium 134 lies between the spectra of iridium and cobalt. Specific activities as high as 16 curies per gram (1) are available; this is high compared to cobalt 60 (14 curies/gm) but low compared to the specific activities of iridium (1000 curies/gm).

38. There are no low energy gamma emitters commercially available at the present time suitable for radiographic inspection of light metals. Thulium 170, which is produced by thermal neutron irradiation of thulium 169,

$$Tm^{169} + n^{1} \rightarrow Tm^{170} + \gamma^{0},$$

has characteristics ideally suited for radiography of light metals. Experimental work has substantiated this belief (2). However, the scarcity of target material makes it impossible to obtain thulium 170 sources at the time of this writing. The half-life of thulium is 125±5 days, its excitation cross section is 105 barns and its effective energy is 83 KeV with no components of energy over 85 KeV (2)(3)(4). Thulium 170 is also a beta emitter and actually only 10% of the disintegrations are accompanied by gamma radiation, so that a 100 millicurie source is effectively only a 10 millicurie source (2). The half value layers of various materials for thulium radiation have not been determined with any accuracy.

39. In the past, due to the scarcity of radium, the medical profession in Europe made use of the thorium series of radioelements. Investigations of this series, shown in Table IV, indicated the disintegration of thorium C to be accompanied by very energetic gamma radiation. As a result of these investigations a number of radiothorium radiography sources were prepared. At the present time, however, radiothorium sources are not available in this hemisphere. Radiothorium, Th 228, has a half-life of 1.9 years and its disintegration

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(1) Isotope Branch, National Research Council, Atomic Energy Project, Canada - Pile-Produced Isotopes.

(2) R. West - A Low Energy Gamma Ray Source for Radiography and Thickness Measurement - Nucleonics, Sep 1951.

(3) J. S. Fraser - The Disintegration Scheme of Tm 170 - Physical Review, Vol. 76, Jul-Dec 1949.

(4) J. M. Cork, H. B. Keller and A. E. Stoddard - Radioactivity in Holmium 166, Thulium 170 and Lutecium 177 - Physical Review, Vol. 76, Jul-Dec 1949.

eventually yields thorium C which emits the desired gamma radiation during its transition to thorium D.

40. A number of the proposed disintegration schemes for the transition of thorium C to thorium D indicate the presence of gamma radiation with a peak energy of 3.2 MeV (1). More recent measurements have failed to prove or disprove the existence of a 3.2 gamma ray during transition but indicate that if it is present it occurs very infrequently during disintegration, probably accompanying less than 1/10 of 1% of the disintegrations. The presence of gamma rays with energies of .58 MeV and 2.62 MeV, respectively, has definitely been established (1). The 2.62 gamma radiation is appreciably higher than that available from radium or any other long-lived radioisotope. Because of the exceedingly high energy of the gamma radiation, radiothorium appears to be ideally suited for radiography of steel of thicknesses beyond the range of penetration of radium and cobalt 60 radiation.

41. Antimony 124 is another isotope that can be used for radiography. Its spectrum includes gamma radiation with energies of 2.0 MeV and 1.7 MeV, so that it has advantages over cobalt 60 and radium for radiography of thick steel sections. However, its short half-life, 60 days, and low specific activity, 5 curies per gram, outweigh this advantage (2).

42. Optimum radiographic techniques for radiothorium and thulium 170 sources cannot be determined until these sources become readily obtainable. Other radioisotopes, such as europium 154 and tantalum 182, are actually suitable substitutes for cobalt 60, radium and iridium 192 which will be discussed at greater length in the latter portion of this manual. A comparison of these various sources is given in Table V. Figure 9 illustrates comparative radiographic quality on a $\frac{1}{4}$" welded steel plate. Note the 2% penetrameter is not visible in the Co-Ra exposures.

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(1) R. E. Bell and L. G. Elliott - Search for a 3.20 MeV γ Ray in the Disintegration of Thorium C - Canadian Jour. of Research, Vol. 26, Sec. A, 1948.

(2) Isotope Branch, National Research Council, Atomic Energy Project, Canada - Pile-Produced Isotopes.

HANDLING AND RADIATION SAFETY

Effects of Overexposure

Energy Dependence

43. The harmful biological changes in the body which gamma radiation produces are the result of a complex process, still largely unknown. These harmful effects, however, are definitely related to the production, by the radiation, of ions in the body cells (1) and the damage is dependent upon the absorption of the radiation by the body cells (2). The absorption is directly related to the energy of the incident radiation; so that the body damage and the organs effected are dependent upon the quality of the ionizing radiation. The skin offers an example of the energy dependence discussed. A dose of 1000 roentgens is required to produce skin erythema or skin burn if the energy of the incident radiation is 1000 KV (3). If the energy of the incident radiation is only 100 KV, erythema will result from an exposure of only 270 roentgens (3), indicating more of the energy is absorbed in the skin as would be expected.

Immediate Effects of Overexposure

44. Total body exposure to high levels of radiation, 100-200 roentgens, are followed within a period of several days by radiation illness of a serious and incapacitating nature. Sufficiently high dosages, such as 400-450 roentgens, will prove fatal 50% of the time (2). Actually the exposure resulting from the use of radiographic sources is minute when compared to lethal dosage. The prime concern of users of radiographic sources should be the long time or cumulative effects of radiation rather than the effects of exposure to large single doses.

Long Time Effects of Radiation

45. The chief hazards resulting from the use of radioisotopes as radiographic sources stem from the possibility of receiving repeated small exposures exceeding tolerance dosage. The biological changes resulting from repeated overexposure are insidious and progressive. If continued over a

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(1) O. Stuhlman - An Introduction to Biophysics - 1943.

(2) V. H. Houghton - Biological Effects of Radiation - Radiological Defense, Vol. III.

(3) O. Glasser, E. Quimby, L. Taylor and J. Weatherwax - Physical Foundations of Radiology - 1944.

long period of time the accompanying biological changes may be irreversible and result in serious injury or death (1). The body is able to recover from damage by radiation, but not much is known of the process or of the rate of recovery, especially in the case of internal organs (2).

Permissible Dosage

Internal Radiation

46. The amount of a radioactive substance which can be tolerated within the body is dependent upon the element. Radiographic inspection, by means of radioisotopes does not subject personnel to any great extent to the danger of entry of radioactive materials into the body, except in the case of radium. Damaged radium capsules may permit the escape of radon, which after entry into the body will break down in the manner indicated in the uranium series, given in Table I. Radon is an extremely toxic gas, with the body unable to tolerate more than one millionth of a curie, so that radium sources should be periodically checked for leakage. The equivalent of .1 microcurie of radium is considered the tolerable limit for ingestion of other radioactive materials, but the danger is so remote it need not be considered.

External Radiation

47. The tolerance dosage is that level of radiation which the body can safely absorb over a long period of time. It is based on total body irradiation, but should be adhered to although in normal practice the entire body is rarely exposed to radiation. If the permissible dosage is exceeded in the course of normal radiographic setups, the cause should be determined and measures taken to prevent the recurrence of overexposure. The presently accepted permissible dosage rate is 300 milliroentgens per week (3)(4)(5). The rate within the

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(1) E. P. Cronkite - Diagnosis of Ionizing Radiation by Physical Examination and Clinical Laboratory Procedures - Radiological Defense, Vol. III.

(2) O. Glasser, E. Quimby, L. Taylor and J. Weatherwax - Physical Foundations of Radiology - 1944.

(3) National Bureau of Standards Handbook No. 47.

(4) Nav Med P-1325 - Radiological Safety Regulations - 1951.

(5) Minutes of Radiation Protection Committee - U.S., Great Britain and Canada - 29 Sep 1949.

weekly limits of exposure is inconsequential (1), although it is good practice to limit daily exposure to 100 milliroentgens.

48. The hands are the most likely portions of the anatomy to be irradiated during the process of radiography with radioisotopes. Fortunately, the hands are relatively insensitive to radiation. The tolerance dosage for the hands is 1500 milliroentgens or 1.5 roentgens per week (1)(2).

Detection and Measurement

49. Despite the harmful effect of ionizing radiation, the body itself is a poor detector of radiation. After exposure to as much as 25 roentgens it is difficult, if at all possible, to detect biological changes by clinical means (3). Because of the difficulty of detecting exposure to radiation by clinical methods, some type of instrumentation should be used and supplemented by the use of film badges when possible.

50. Film badges and developing facilities are available at many Naval installations and should be made use of, whenever possible. Film badges can easily be improvised if necessary. A small piece of film in a light tight holder worn during working hours will, when developed, have a density dependent upon the quantity of radiation to which it has been exposed. In order to interpret the film density in terms of radiation, it is necessary to make density measurements and to determine the response of the particular film to radiation of the wave length employed in radiography. The film can be calibrated by using the radiographic source itself.

51. It is not necessary to improvise film badges if detecting instruments are available. Pocket-sized ionization chambers known as minometers or dosimeters are readily available. These chambers can be carried during working hours and will indicate the exposure of the individual to radiation.

52. Portable survey meters employing ionization chambers or G-M tubes are also obtainable. These battery-operated devices indicate, instantaneously, the rate of exposure. They are

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(1) Nav Med P-1325 - Radiological Safety Regulations - 1951.

(2) Minutes of Radiation Protection Committee - U.S., Great Britain and Canada - 29 Sep 1949.

(3) L. O. Jacobson, E. K. Marks, E. L. Simmons, C. W. Hagan and R. E. Zirkle - Effects of X-rays in Rabbits, Part II, MMDC 1174.

ideally suited for surveying areas adjacent to the exposure area. If the exposure area is indoors, it is generally wise to survey the adjacent rooms to determine radiation level during exposure.

53. Areas above tolerance during exposure, as determined with a survey meter, should be blocked off and marked in some fashion for the protection of personnel not aware of the exposure.

Precautions

Distance-Time

54. When handling radioisotopes, it should be remembered that the intensity of the emitted gamma radiation behaves somewhat like visible light and obeys the inverse square law. That is; the intensity of radiation varies inversely with the square of the distance between the source of radiation and the point in question. Actually, there is some deviation from this relationship due to the absorption in air of radiation and also the presence of scattered radiations. These deviation however are of a minor nature.

55. The exposure received when dealing with radioisotopes is, as expected, directly proportional to the duration of the exposure. This makes speed a prime requisite when handling radioactive materials.

56. The time-distance dependence of exposure offers an excellent means of protection to personnel engaged in radiography with radioactive sources. The arrangement of the source, film and objects to be radiographed should be made so that the placement and removal of the source can be accomplished easily and quickly.

57. The radiation level at the surface of even a small source is quite high, so that radioactive sources regardless of size, should never be picked up or held in the hand. Tweezers, forceps or some kind of improvised handling tool should be used. A string or wire attached to the source holder is an excellent means of handling. Larger sources of the order of 1.5 to 2 curies may be placed in lead unidirectional mounts and handled with appropriate handling tools. The handling devices should never be so cumbersome or awkward that the time required to position or remove a source becomes excessive. Various handling tools and some source holders are shown in Figure 10.

58. When not in use radioactive sources are kept in lead containers which serve as storage, carrying and shipping boxes. The lead thickness of the containers is such that the radiation external to the case is of a permissible level. The lead shielding required for these containers is discussed at length in the latter portion of this manual.

59. Shielding of personnel handling the sources during initiation and termination of exposures is not necessary and often undesirable. The leaded gloves, aprons and other clothing worn by members of the medical profession during fluoroscopy are quite cumbersome and of little value when dealing with the radioisotopes used for radiography. The energies encountered in radiography are generally much higher than those employed for medical fluoroscopy. Even when handling low energy emitters the protection afforded by leaded clothing does not compensate for the impaired efficiency of personnel. When handling higher energy sources, the leaded apparel actually increases exposure of personnel because of the hazardous scattered and secondary radiation produced.

EXPOSURE FACTORS

General

60. The quality of a radiograph or gammagraph is determined by a number of factors. Definition, one of the chief factors, is influenced primarily by unsharpness due to scatter, geomtry, and film-screen combinations.

Unsharpness Due to Scatter

61. Unsharpness due to scatter is due primarily to the diffusion of the gamma rays in the absorber. Unsharpness measurements of "knife-edge" absorbers made in a manner described by Klasens (1) and illustrated in Figure 11 indicate the unsharpness due to scatter increases linearly with absorber thickness. The actual unsharpness values found using a cobalt 60 source are given in Table VI (2).

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(1) H. A. Klasens - Measurement and Calculation of Unsharpness Combinations in X-ray Photography - Phillips Research Reports, Vol. I, No. 4, pp. 241-249, Aug 1946.

(2) D. T. O'Connor, J. Hirschfield and D. Polansky - Development of the Cobalt Camera - NAVORD Report 1564, NOL, 1950.

Geometric Unsharpness

62. The unsharpness due to geometry involves both umbral and penumbral images. All of the more recent studies (1)(2) agree that the penumbral image is not dependable and therefore, not desirable. This indicates that a criterion for establishing optimum definition is the determination of a distance at which the umbral image of a defect is present or the limiting distance at which the umbral shadow vanishes. This relationship, illustrated in Figure 12, can be established as:

$$S + X = \frac{X\phi}{O} \qquad \text{where}$$

S = object-source of distance

X = absorber thickness

ϕ = source diameter

O = flaw diameter

Actually, it would be desirable to limit the size of the penumbral image, even though the umbral image is present. The distance required for this is in accordance with Figure 12.

$$S > \frac{\phi X}{U_g} \qquad \text{where}$$

U_g = penumbral image

63. In his paper on unsharpness, Klasens conclusively demonstrated that total film unsharpness is not equal to the sum of the various unsharpness values but must instead be expressed as the cube root of the sum of the cubes of the unsharpness due to film and geometry (3). Actually the

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(1) H. F. Kaiser, H. Friedman and R. Hafuer - Minimum Distance Requirements in the Gamma Radiography of One and Three Inch Steel Sections, Jour. Amer. Soc. of Naval Engrs., Vol. 54, No. 1, pp. 15-49, Feb 1942.

(2) J. A. Crowther, Ed., Members of the Industrial Radiology Group of the Institute of Physics - Handbook of Industrial Radiology - Edward Arnold & Co., London, Copyright 1945.

(3) H. A. Klasens - Measurement and Calculation of Unsharpness Combinations in X-ray Photography - Phillips Research Reports, Vol. I, No. 4, pp. 241-249, Aug 1946.

unsharpness due to scatter must be considered and the expression becomes (1):

$$U_{total} = \sqrt[3]{U^3_{geom} + U^3_{film} + U^3_{scatter}}$$

The largest term under the radical will dominate total unsharpness so that U_g need be no smaller and the expression for minimum distance for optimum radiography becomes:

$$S = \frac{\emptyset X}{U_{total}}$$

64. This expression clearly demonstrates the advantage and importance of using sources of small physical dimensions. As mentioned previously, sources of high specific activity are desirable for this reason and the chief advantage of cobalt 60 over radium as a radiographic source is due to its higher specific activity.

Exposure Techniques

Film and Screens - General

65. The choice of film and intensifying screens best suited for the radiographic inspection of a specific item is an important one. The finer grained films desirable for optimum definition and contrast are in most cases too slow to be usable with radioisotope sources. As a rule, Eastman Kodak Types A and F film, or film of comparable characteristics, are used and usually intensifying screens are used in conjunction with them to decrease exposure time. Table VII is a brief summary of the characteristics of some of the commercially available films.

66. It is common practice to "over develop" radiographs made with radioisotopes. This permits a given density to be achieved with a reduced exposure time. Slow and medium speed films such as Eastman Kodak Types A and M are developed eight minutes at 68° F, instead of the customary five minutes. This procedure cannot be used with fast coarse-grained films such as Eastman Kodak Type F film, because the increase in base fog density overweighs the advantage of increased development.

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(1) D. T. O'Connor, J. Hirschfield and D. Polansky - Development of the Cobalt Camera - NAVORD Report 1564, NOL, 1950.

67. Lead or chemical intensifying screens are used for reduction of exposure time. The rate of film blackening is increased with the use of lead screens by the electrons emitted from the lead as a result of the incident x-rays. Lead screens also improve film quality by reducing scattered radiation reaching the film. In the case of chemical screens, the blackening rate is increased by the light output of the screens which fluoresce when exposed to x-rays or gamma rays. The thickness of lead screen required for the greatest intensification is dependent upon the energy of the incident radiation. Figure 13 illustrates the results of measurements made of intensification factors of lead screens with a cobalt 60 source. The intensification factor was determined by taking the ratio of exposure time, to produce a given density, for the lead thickness under consideration and the exposure time for no lead. Although maximum intensification occurs with lead screens thicker than .005", commercially available screens of this thickness are acceptable. Measurements with radium and iridium 192 indicate screens of the same thickness are acceptable.

68. The speeds of the films are energy dependent to quite an extent. Film speed decreases with an increase in the energy of the incident radiation. Figure 14 illustrates the energy dependence for Eastman Kodak Type F film. The relative speed of films is fairly constant over the energy spectrum and manufacturers' literature can be used to determine relative film speeds. Chemical screen speeds are also energy dependent, with maximum screen efficiency at the lower energies of radiation.

Inherent Unsharpness of Film, Screens and Combinations

69. The inherent unsharpness of film, intensifying screens and combinations of these contribute to the loss of definition as well as other factors previously mentioned. Evaluation of inherent unsharpness values are given in Table VIII (1)(2). These measurements were made on radiographs exposed to a cobalt 60 source with a 1" steel absorber and with an additional $\frac{1}{4}$" lead absorber in the case of F film. It may be noted that the use of chemical intensifying screens results in a comparatively small increase in unsharpness. The speeds of the various screens are given in Table IX and the curves shown in Figure 15.

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(1) D. T. O'Connor, J. Hirschfield and D. Polansky - Development of the Cobalt Camera - NAVORD Report 1564, NOL, 1950.

(2) D. T. O'Connor and J. Hirschfield - Development of the Underwater Cobalt Camera - NAVORD Report 2100, NOL, 1951.

70. The speed ratings of chemical intensifying screens are dependent upon temperature. Reduction of screen temperature will increase screen speed appreciably. When reduction of exposure time is of great importance, this temperature dependence may be used to advantage. It is advisable to reduce the temperature of the film and screens together in the film holder to be used for exposure. Figure 16 illustrates the temperature dependence of Patterson 245 industrial screens.

Penetrameters

71. To indicate an absolute value of sensitivity achieved in a radiographic film, penetrameters are generally used on the object being radiographed. The common type of penetrameter consists of a flat plaque of the same material as the object being radiographed and of a thickness of a given percentage of the specimen thickness. The thickness is never less than .005"; usually a penetrameter with a thickness of 2% of the specimen thickness is used. The visibility of the metal plaque is a good index of contrast sensitivity. The penetrameters are made with three holes, whose diameters are 2, 3 and 4 times the penetrameter thickness. Visibility of these holes indicates the definition sensitivity achieved. When examining objects with severe thickness variations, penetrameter blocks can be used. These are placed under the penetrameter so that sensitivity is determined through the maximum and minimum thicknesses covered in the radiograph.

Filters

72. Filters, consisting of lead, are frequently used between the object and film holder to shield the film from scattered radiation. The thickness of the filter best suited for reduction of scatter is dependent upon the energy of the incident radiation. The usefulness of the filter depends upon the amount of scattered radiation present, quality of the incident radiation, the type of film being used and also to some extent upon the length of exposure.

73. Extremely long exposures may necessitate the use of filters, which would otherwise not be needed. Film with characteristics similar to Eastman Kodak Type M and A can usually be exposed without resorting to filters. Fast film such as Eastman Kodak Type F should always be exposed in conjunction with lead filters. Table X illustrates recommended procedure. Figure 17 offers a comparison of exposures made with and without filters. A 2% penetrameter is visible to the right of the weld on the filtered exposure. When fast, coarse-grained film such as Eastman Kodak Type F film is used, lead filters should be used in back as well as in front of

the film holder. Whenever possible the radiation source, film and object should be placed as far from the earth, floor and walls as possible. When lengthy exposures are to be made in a confined area, filters should be used regardless of the type of film employed. Filters should likewise be used whenever the subject is of irregular shape.

Decay Curves

74. As discussed previously, the various radioelements disintegrate at a fixed rate. With the exception of radium which, because of its extremely long half-life, may be considered to remain at constant strength, corrections must be made for the gradual reduction of source strength. Figures 2 and 4 and Tables II and III offer a ready means of determining source strength at any given time, in the case of cobalt 60 and iridium 192.

75. The technique and sensitivity curves shown in Figures 18 to 34 are simple means of expressing data collected by series of exposures and permit the predetermination of exposure time and resulting sensitivity for a given radiation source, absorber thickness and film screen combination. Exposure factor, the ordinate of the technique curves, is equal to the product of exposure time, in minutes, and source strength, in millicuries, divided by the square of the source-to-film distance in inches.

76. The dotted loops bearing percentage figures are sensitivity curves enclosing density ranges producing the indicated sensitivity when optimum exposure conditions (paragraphs 62 and 63) are met.

77. Examination of the curves indicates that neither cobalt nor radium is a desirable source of radiation for steel thicknesses less than 1 inch. This is due primarily to the predominance of high energy radiation in their energy spectrums. The low energy present in the radium energy spectrum makes it more suitable than cobalt 60 for work in this thickness range although iridium 192 is far superior to both over this thickness range. If a high energy source must be used on thin sections of steel or on low density materials, the use of a fine-grained film such as Eastman Kodak Type M with lead screens is recommended. This appreciably improves contrast sensitivity.

78. Figures 28 and 29, technique curves for iridium 192, demonstrate the effect of lead filters and the density contributed by scattered radition. The use of a .030" lead filter reduces the scattered radiation and improves film quality. The ordinate of the exposure curves for iridium

is expressed as exposure factor, as suggested by Morrison (1), and is equal to the product of source output, in mr per hour at 1 meter, and time in minutes divided by the square of the source to film distance in inches. This is done since iridium sources are rarely described in terms of millicuries.

79. Inasmuch as most of the curves are based on steel absorbers, a list of approximate equivalents is given in Table XI.

80. A device in which the radiation path is 1 inch of steel and 4 inches of aluminum would offer an equivalent steel thickness of 1 + .34 x 4 or 2.36 inches to the incident radiation.

STORAGE AND SHIPPING

Storage

81. Radioisotopes when not in use should be stored in lead safes or other containers designed to reduce radiation in the immediate area to a low level. The most practical storage container is one which can also be used as a part of a shipping container. Because of its low cost, lead is generally used in the storage container. Figure 35 shows the transmission of cobalt 60 radiation through lead. This curve may be used to determine the lead shielding required for the storage of a cobalt 60 source. Figures 36 and 37 are similar curves for the transmission of radium and iridium 192 radiation. Transmission curves for other radioisotopes can readily be prepared from half value layer data.

82. If film and radiation sources are to be stored in close proximity, special care must be taken to protect the film. The average storage time of the film will determine the radiation level that can be tolerated without increasing the base fog density of the film. The radiation required for a change in base fog density of 0.10 units for various film is given in Table XII.

Shipping

83. If a source of radiation is to be shipped by common

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(1) A. Morrison - Iridium 192 for Gamma Ray Radiography - Jour. Soc. of Nondest. Test., p. 26, Summer, 1951.

carrier, there are several regulations which must be met (1)(2). These regulations require that the shielded source be enclosed in a clearly marked wooden box whose surface radiation level shall not exceed 200 milliroentgens per hour. The shielding shall be such that the gamma intensity measured at a distance of 1 meter from any point on the source shall not exceed 10 milliroentgens per hour. To meet these conditions the following equations must be satisfied for a cobalt 60 or radium source:

$$(1)\quad 0.73\ RA_t/y^2 < 200$$

$$(2)\quad 0.73\ RA_t < 10 \quad \text{where}$$

A_t = the fraction of radiation transmitted through a lead shield T centimeters in thickness

R = Cobalt 60 strength in milligrams radium-equivalent

y = smallest distance in meters from the source to an outside surface of the shipping box

0.73 = calculated output (mr/hr at 1 meter) of 1 mg radium-equivalent of cobalt 60.

Solving equations (1) and (2) for y, indicates that to meet shipping requirements the shipping box must be constructed so that the distance from the source to any outside surface is 22.38 centimeters or 8.8 inches. A smaller dimensioned shipping box would require more lead shielding and therefore be more expensive. The most practical method of maintaining the required distance of 8.8 inches is to construct a shipping box with internal braces so that the source, in its lead shielding, is centered in the box. This type of construction permits the use of cubical shipping boxes 17.6" x 17.6" x 17.6". Figure 38 presents in graphical form the lead shielding required for various strength sources and for shipping boxes of various sizes. A curve for iridium 192 has been included so that Figure 38 may be used for radium, cobalt 60 and iridium 192 sources.

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(1) Interstate Commerce Commission of U. S. Docket #13666.

(2) Motor Carriers Explosives and Dangerous Articles Tariff No. 6, publishing ICC Regulations for Transportation of Explosives and Other Dangerous Articles by Motor, Rail and Water.

84. To facilitate handling, large metal handles should be attached to the shipping box. The inner lead shielding should likewise be enclosed in a wooden box with an attached strap or handle. Figure 39 illustrates a typical carrying case with lead shielding enclosed and a shipping box.

85. These regulations limit the shipment of radium and members of the radium family to 2000 millicurie per single outside container. Other radioisotopes are limited to 2700 millicurie per single outside container. If these limits are to be exceeded, clearance must be obtained from the Bureau of Explosives. The regulations also state that the radioactive material be packaged so that the container may remain 15 feet from unexposed film for 24 hours without producing any more film fogging than that produced by 11.5 milliroentgens of gamma radiation from radium shielded by $\frac{1}{4}$" of lead.

CONCLUSION

86. The radiographer faced with an inspection problem requiring the use of a radioisotope can, by utilizing the available information, select the film and radiation source best suited to his problem. In addition, he can determine optimum exposure variables such as source-film distance, exposure time, desired density, etcetera.

87. The recent increase in the use of isotopes with the promise of continued expansion warrants the familiarization by radiographers with gamma ray techniques, both exposure and handling techniques.

TABLE I

RADIOACTIVE DISINTEGRATION -

THE URANIUM SERIES

RADIOELEMENT	CORRESPONDING ELEMENT	SYMBOL	HALF-LIFE
Uranium I	Uranium	U^{238}	4.5×10^{10} yr.
↓			
Uranium X	Thorium	Th^{234}	24.1 days
↓			
Uranium X2	Protactinium	Pa^{234}	1.14 min.
↓			
Uranium II	Uranium	U^{234}	2.35×10^{5} yr.
↓			
Ionium	Thorium	Th^{230}	8.0×10^{4} yr.
↓			
Radium	Radium	Ra^{226}	1.62×10^{3} yr.
↓			
Radium Emanation	Radon	Rn^{222}	3.82 days
↓			
Radium A	Polonium	Po^{218}	3.05 min.
99.96% → Radium B (.04%)	Lead	Pb^{214}	26.8 min.
Astatine ←	Astatine	At^{218}	2 secs.
↓ Radium C	Bismuth	Bi^{214}	19.7 min.
99.96% → Radium C'	Polonium	Po^{214}	1.5×10^{-4} secs.
Radium C"	Thallium	Tl^{210}	1.32 min.
↓ Radium D	Lead	Pb^{210}	22 yr.
↓ Radium E	Bismuth	Bl^{210}	5.0 days
100% → Radium F (10^{-5}%)	Polonium	Po^{210}	140 days
Thallium 206	Thallium	Tl^{206}	4.23 min.
↓ Radium G	Lead	Pb^{206}	Stable

TABLE II

DECAY OF COBALT 60

YEARS	MONTHS	PERCENT
0	6	93.67
1	0	87.74
1	6	82.19
2	0	76.99
2	6	72.11
3	0	67.54
3	6	63.27
4	0	59.27
4	6	55.51
5	0	52.00
5	6	48.71
6	0	45.62
6	6	42.74
7	0	40.05
7	6	37.50
8	0	35.12
8	6	32.90
9	0	30.82
9	6	28.86
10	0	27.03

TABLE III

DECAY OF IRIDIUM 192

WEEKS	% ACTIVITY REMAINING
1 (7 days)	94
2	88
3	82.5
4	77
5	72.5
6	68
7	63.5
8	59.5
9	55.5
10	52
11	49
12	45.5
13	43
14	40
15	37.5
16	35
17	33
18	31
19	29
20	27

TABLE IV

RADIOACTIVE DISINTEGRATION -

THE THORIUM SERIES

RADIOELEMENT	CORRESPONDING ELEMENT	SYMBOL	HALF-LIFE
Thorium	Thorium	Th^{232}	1.39×10^{10} yr.
Mesothorium I	Radium	Ra^{228}	6.7 yr.
Mesothorium II	Actinium	Ac^{228}	6.13 hr.
Radiothorium	Thorium	Th^{228}	1.90 yr.
Thorium X	Radium	Ra^{224}	3.64 days
Th Emanation	Radon	Rn^{220}	54.5 secs.
Thorium A	Polonium	Po^{216}	.16 sec.
100% .014% → Thorium B / Astatine ←	Lead	Pb^{212}	10.6 hr.
	Astatine	At^{216}	3×10^{-4} secs.
Thorium C	Bismuth	Bi^{212}	60.5 min.
66% 34% → Thorium C' / Thorium C'' ←	Polonium	Po^{212}	3×10^{-7} secs.
	Thallium	Tl^{208}	3.1 min.
Thorium D	Lead	Pb^{208}	Stable

TABLE V

CHARACTERISTICS OF RADIOISOTOPES SUITABLE FOR RADIOGRAPHY

	RADIUM	RADIO-THORIUM	CESIUM 137	TANTALUM 182	IRIDIUM 192	COBALT 60	EUROPIUM 154	THULLIUM 170	CESIUM 134	ANTIMONY 124
AVERAGE ENERGY OF γ RADIATION (APPROX)	1.7 MEV	2.5 MEV*	.66 MEV	1 MEV	.28 MEV	1.2 MEV	1 MEV	.083 MEV	.68 MEV	1.2 MEV
PRODUCTION PROCESS	MINED & REFINED		FISSION PRODUCT	PILE PRODUCED						
ACTIVATION CROSS-SECTION (BARNS)				20.6	388	22	1200	**	25.6	1.1
HALF-LIFE	1590 YRS	1.9 YRS	37 YRS	120 DAYS	74 DAYS	5.3 YRS	5.3 YRS	125 DAYS	2.3 YRS	60 DAYS
H.V.L. LEAD	.51"	**	.39"*	.50"	.08"	.51"	.50"*	.04"*	.41"*	.58"*
AVAILABLE SPECIFIC ACTIVITY	LOW	LOW	LOW	MEDIUM	HIGH	MEDIUM	VERY HIGH	LOW	MEDIUM	LOW
SUITABLE THICKNESS RANGE IN STEEL	$\frac{1}{2}$"-4$\frac{1}{2}$"	-8"*	$\frac{3}{4}$"-2$\frac{1}{2}$"*	$\frac{1}{2}$"-4"	$\frac{1}{8}$"-2$\frac{1}{2}$"	1"-4"	$\frac{1}{2}$"-4"	LESS THAN $\frac{1}{2}$"	$\frac{3}{4}$"-3$\frac{1}{2}$"*	$\frac{3}{4}$"-6"*
PROCUREMENT	EASILY	HARD	EASILY				HARD		EASILY	
PRICE	VERY HIGH		MODERATE		LOW	MODERATE	HIGH		MODERATE	

*ESTIMATED **NOT KNOWN WITH ANY DEGREE OF ACCURACY

TABLE VI

APPROXIMATE VALUES OF UNSHARPNESS (U_s)

FOR VARIOUS STEEL THICKNESSES

STEEL THICKNESS (Inches)	U_s (SCATTER) (.001 Inches)
1	6.6
$1\frac{1}{2}$	8.2
2	9.6
$2\frac{1}{2}$	11.0
3	12.5
$3\frac{1}{2}$	14.0
4	15.5

TABLE VII

CHARACTERISTICS OF INDUSTRIAL X-RAY FILM

FILM TYPE	RELATIVE SPEED*	CONTRAST	UNSHARPNESS
Agfa Superay B	1.7	High	Fine grained
Agfa Superay A	1.9	High	Fine grained
Agfa Superay HI	4.2	Medium	Coarse grained
Dupont 504	11	Good	Coarse grained
Dupont 505	2	High	Fine grained
Dupont 506	9	High	Fine grained
Eastman Kodak M	30	High	Very fine grained
Eastman Kodak A	100	High	Fine grained
Eastman Kodak F	200	Medium	Medium grained

* Relative Speeds comparable only for films of same manufacturer

TABLE VIII

INHERENT UNSHARPNESS OF FILMS AND SCREENS

FILM-SCREEN	UNSHARPNESS (.001 Inches)
E.K. Type A	2.3
E.K. Type A and Pb Screens	3.0
E.K. Type F	5
E.K. Type F and Pb Screens	15
E.K. Type F and E.K. Detail Screens	18
E.K. Type F and Radelin TD	18
E.K. Type F and E.K. High Definition	18
E.K. Type F and Patterson Fluorazure	18
E.K. Type F and E.K. Fine Grain	19
E.K. Type F and Radelin T	19
E.K. Type F and Patterson Hi Speed Series 2	21
E.K. Type F and E.K. Ultra High Speed	22
E.K. Type F and Radelin TF	28
E.K. Type F and Patterson 245	28

TABLE IX

RELATIVE SPEEDS OF X-RAY INTENSIFYING SCREENS

E.K. Type F film, Cobalt 60 source, 1" Steel Absorber
5 minutes' development in E.K. Standard X-ray Developer

INTENSIFYING SCREEN	EXPOSURE FACTOR FOR DENSITY of 2.
No screens	482.0
Lead screens	160.2
Patterson Detail	91.0
Radelin TD	91.0
E.K. High Definition	67.5
E.K. Fine Grain	46.4
Patterson Fluorazure	44.6
Radelin T	28.6
Patterson Hi Speed (Series 2)	24.6
E.K. Ultra High Speed	19.6
Radelin TF	16.7
Patterson 245	16.4

TABLE X

USE OF FILTERS

ENERGY OF RADIATION	FILM-SCREEN	FILTER
High-Low	E.K. Type M	None required
	E.K. Type M + Pb	None required
High (Co^{60}, Ra)	E.K. Type A	None required
	E.K. Type A + Pb	None required
Medium-Low (Ir^{192})	E.K. Type A	.030" Pb front
	E.K. Type A + Pb	.030" Pb front
High	E.K. Type F	$\frac{1}{4}$" Pb - front & back
	E.K. Type F + Chemical	$\frac{1}{4}$" Pb - front & back
Medium-Low	E.K. Type F	1/32" Pb - front
	E.K. Type F + Chemical	1/32" Pb - front
High	E.K. Type F	1/16" Pb - front
	E.K. Type F + Pb	1/16" Pb - front
Medium-Low	E.K. Type F	1/16" Pb - front
	E.K. Type F + Pb	1/16" Pb - front

TABLE XI

STEEL EQUIVALENTS

Steel	1.00	Water	0.13
Lead	1.4	Copper	1.14
Aluminum	0.34	Explosive (1.65 gm/cc)	0.21
Brass	1.07	Wood (Oak)	0.09

TABLE XII

RADIATION REQUIRED FOR INCREASE OF FILM DENSITY OF 0.10 UNITS

Cobalt 60 Radiation

FILM	RADIATION (mr)
E. K. Type F	40
E. K. Type M	1050
E. K. Type A	350

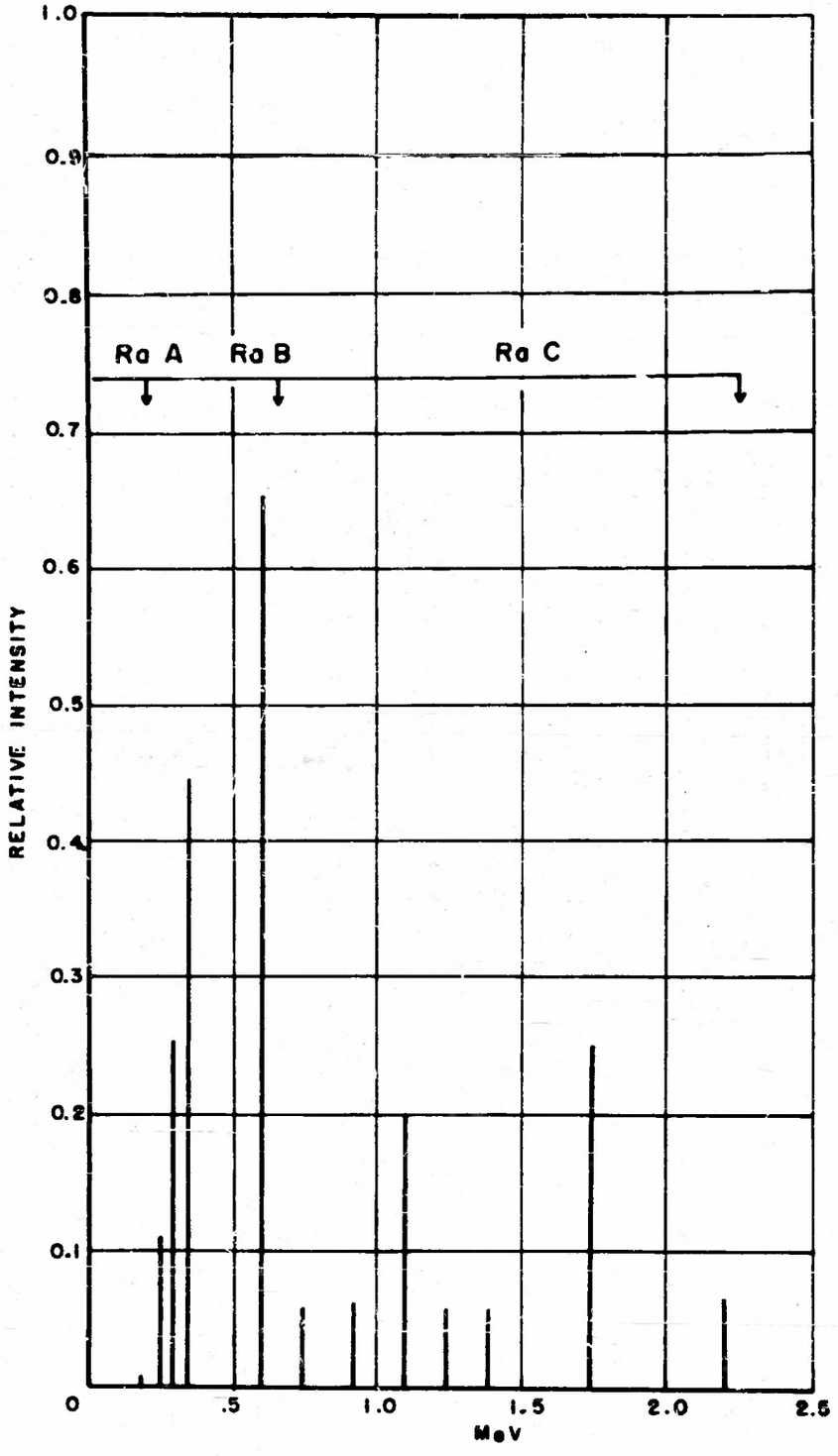


FIG.1 GAMMA RAY SPECTRUM OF RADIUM

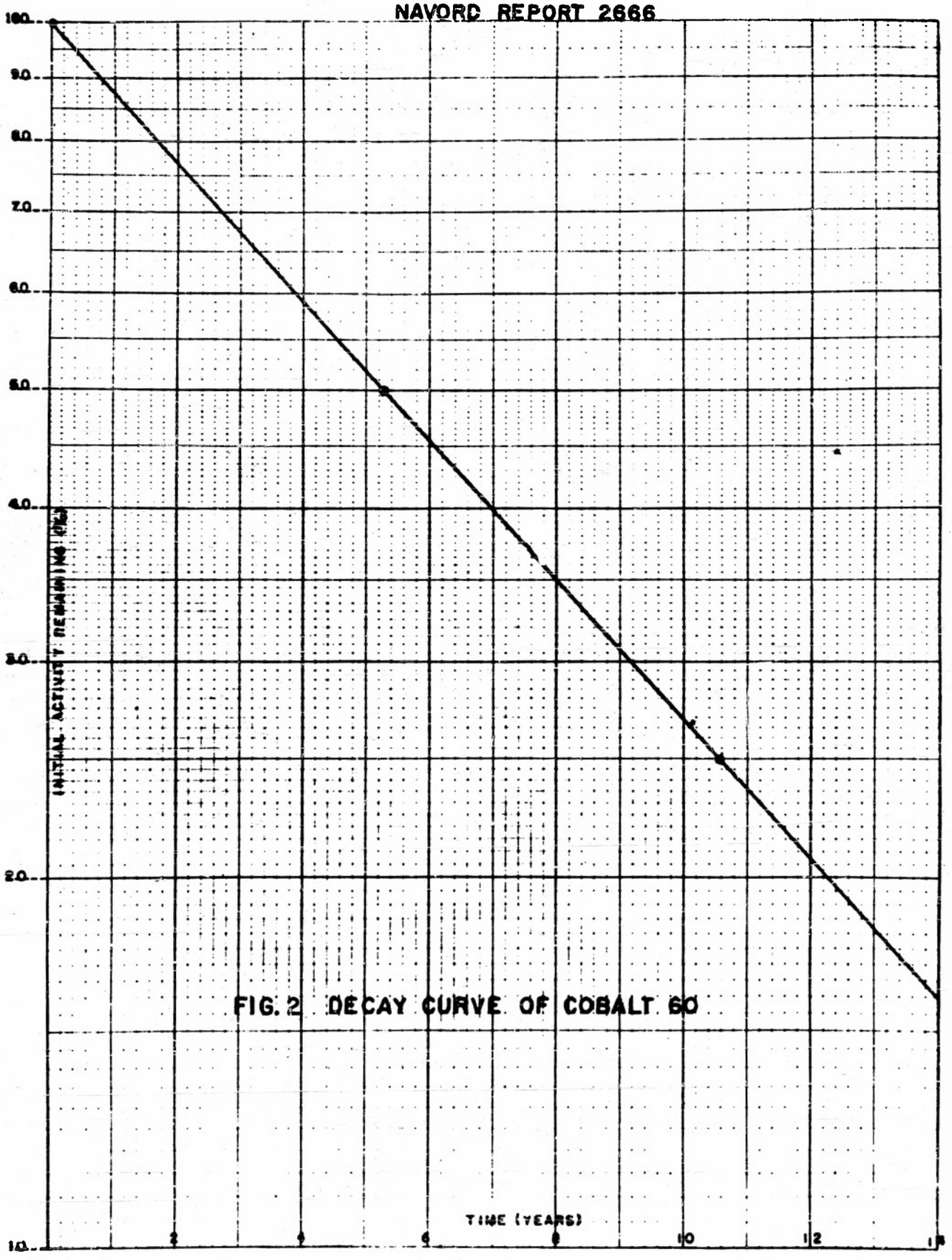


FIG. 2 DECAY CURVE OF COBALT 60

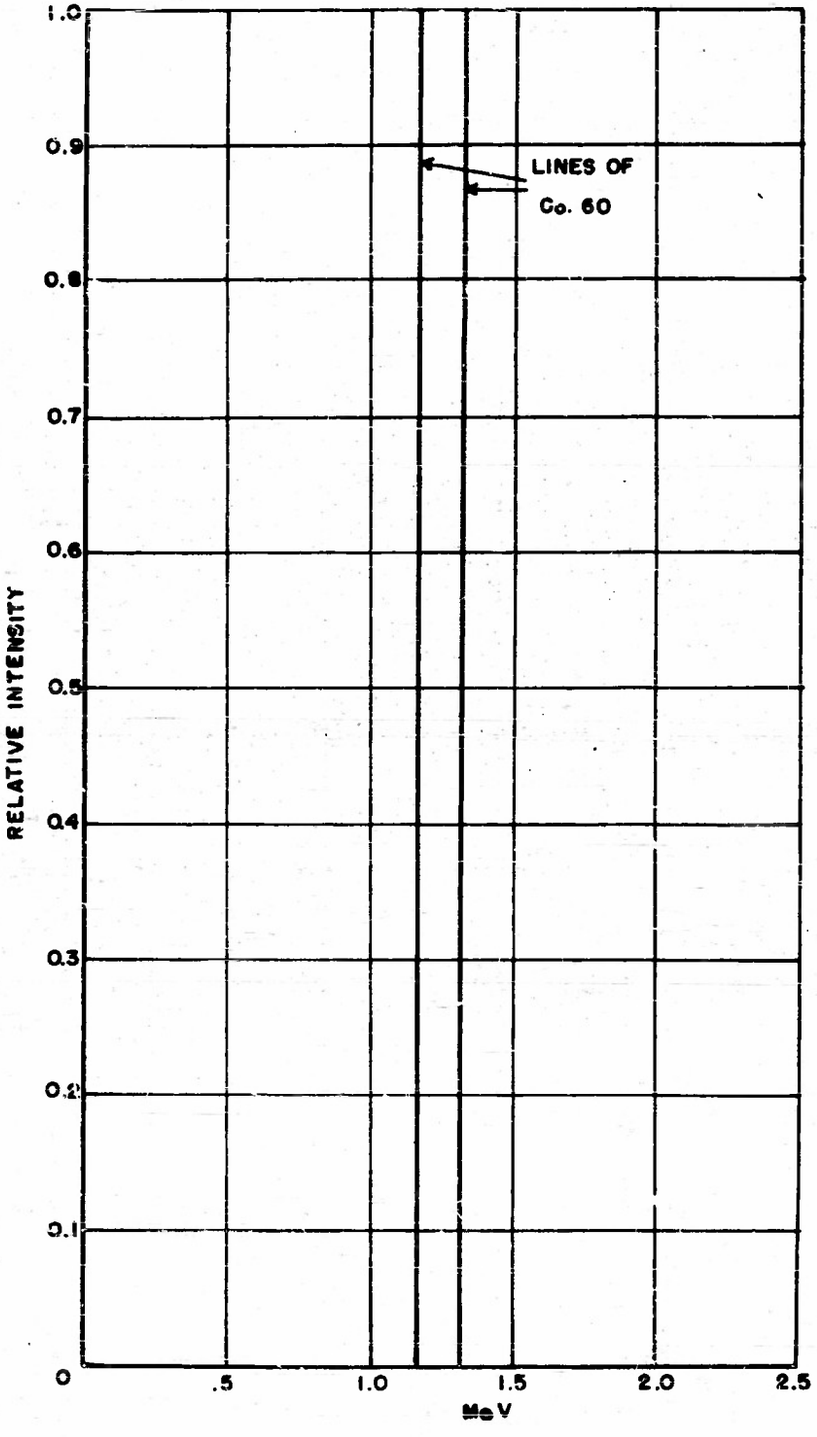


FIG. 3 GAMMA RAY SPECTRUM OF COBALT 60

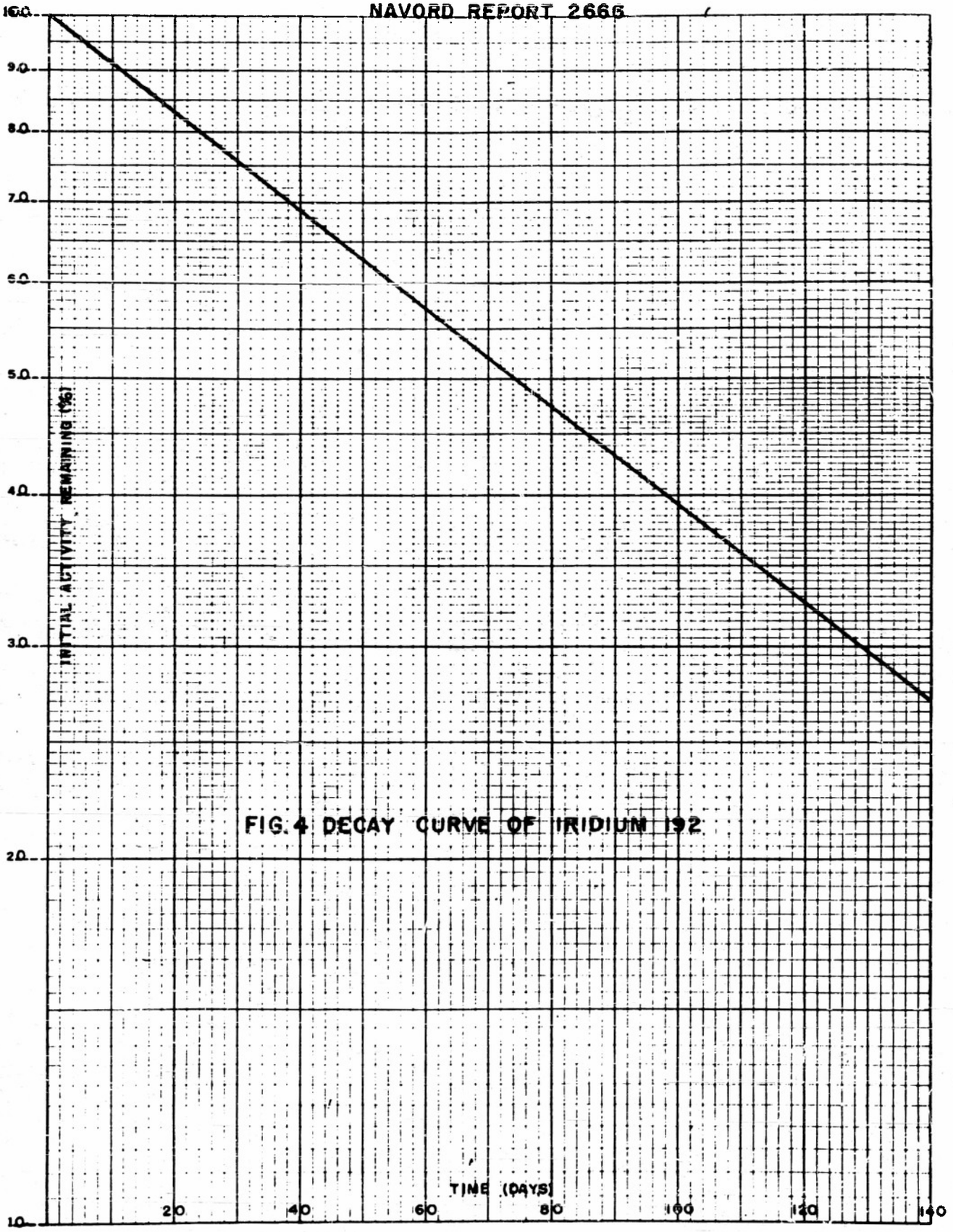
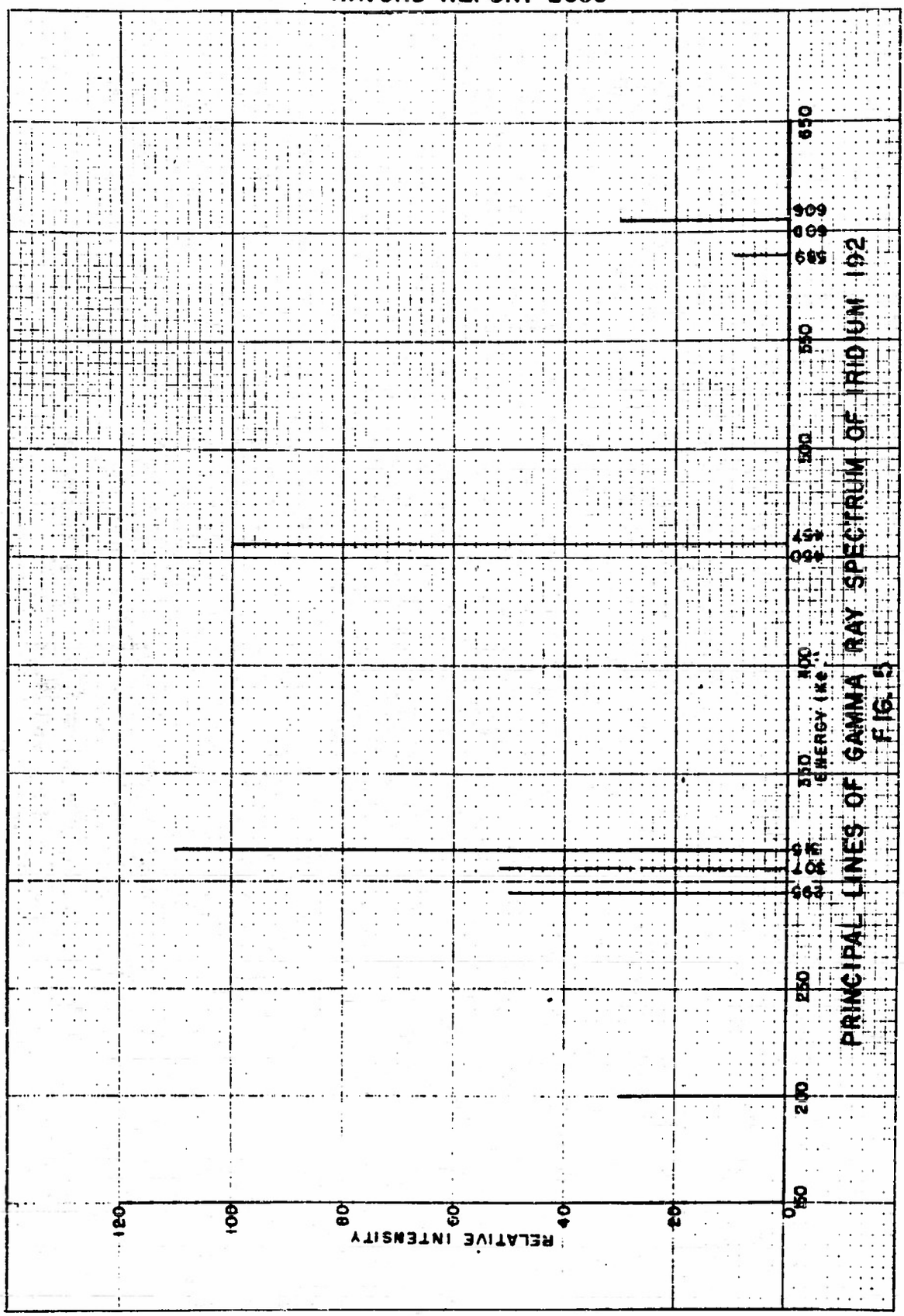
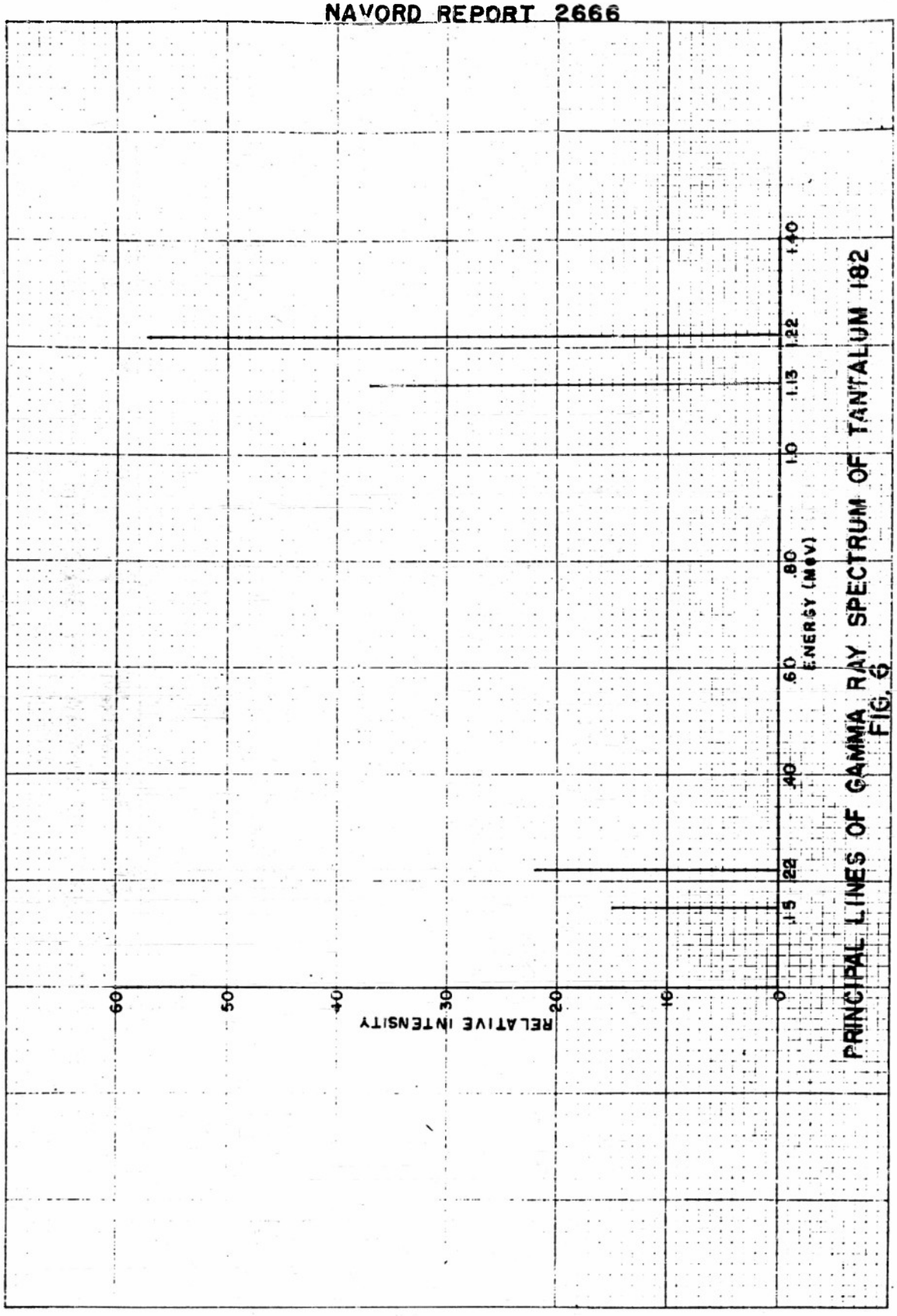


FIG. 4 DECAY CURVE OF IRIDIUM 192


PRINCIPAL LINES OF GAMMA RAY SPECTRUM OF IRIDIUM 192
FIG. 5
ENERGY (Kev)
RELATIVE INTENSITY
650
550
500
450
350
250
200
150
100
80
60
40
20
0

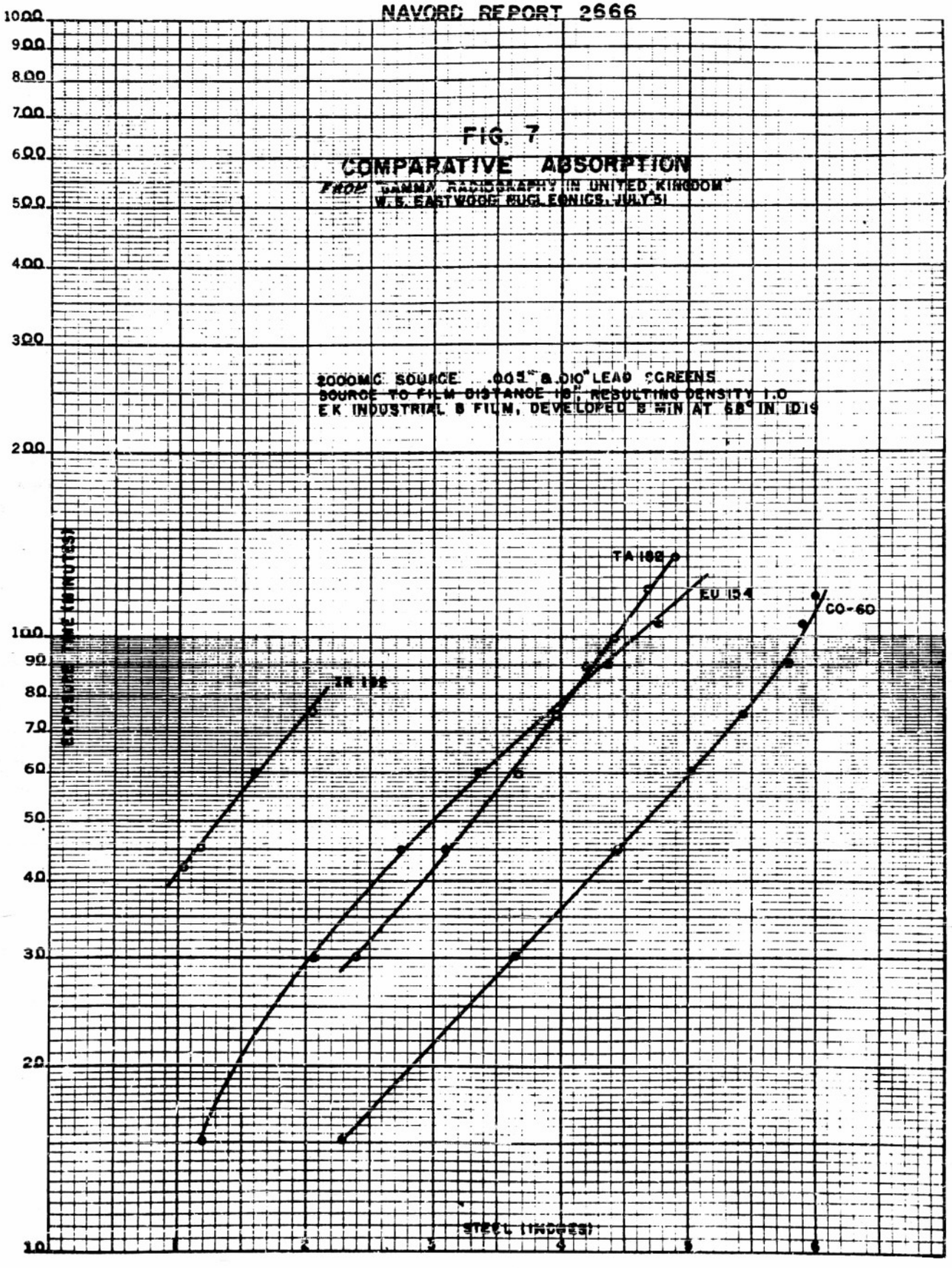


PRINCIPAL LINES OF GAMMA RAY SPECTRUM OF TANTALUM 182
FIG. 6

FIG. 7

COMPARATIVE ABSORPTION

FROM "GAMMA RADIOGRAPHY IN UNITED KINGDOM"
W. S. EASTWOOD NUCLEONICS, JULY 51



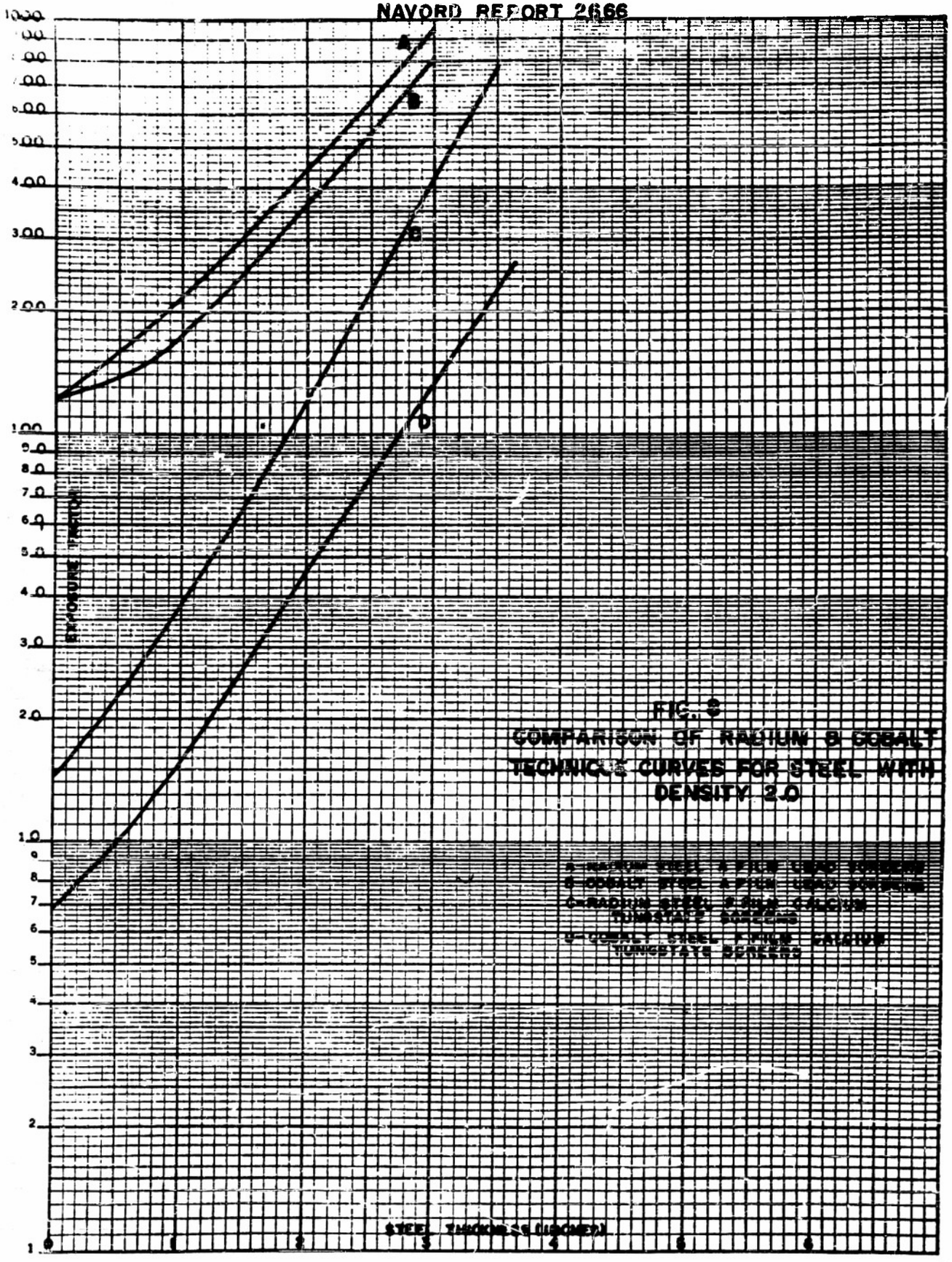


FIG. 8
COMPARISON OF RADIUM & COBALT TECHNIQUE CURVES FOR STEEL WITH DENSITY 2.0

A-RADIUM STEEL & FILM LEAD SCREENS
B-COBALT STEEL & FILM LEAD SCREENS
C-RADIUM STEEL & FILM CALCIUM TUNGSTATE SCREENS
D-COBALT STEEL & FILM CALCIUM TUNGSTATE SCREENS

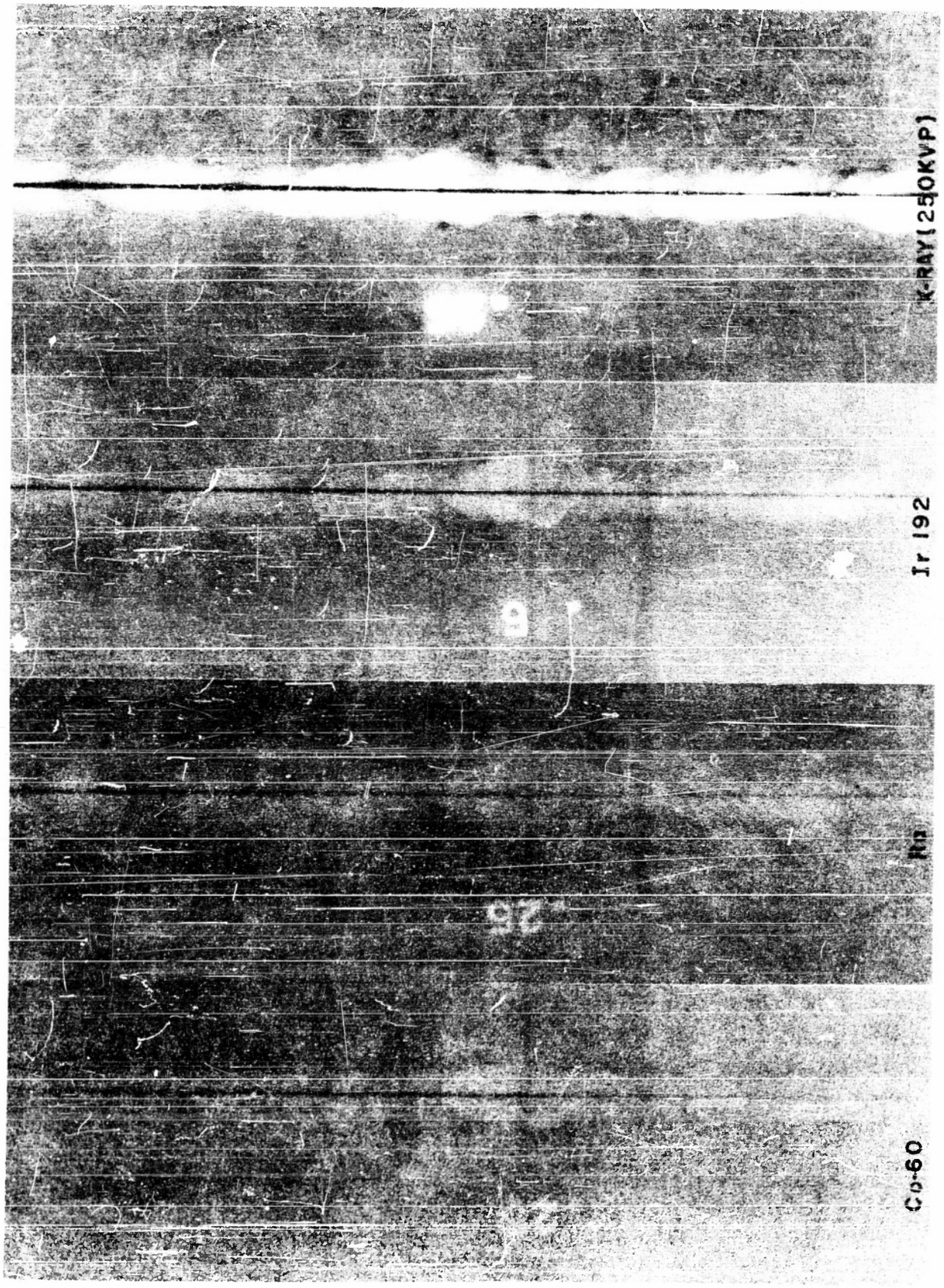


FIG. 9 COMPARATIVE RADIOGRAPHS OF 1/4" WELDED STEEL PLATE

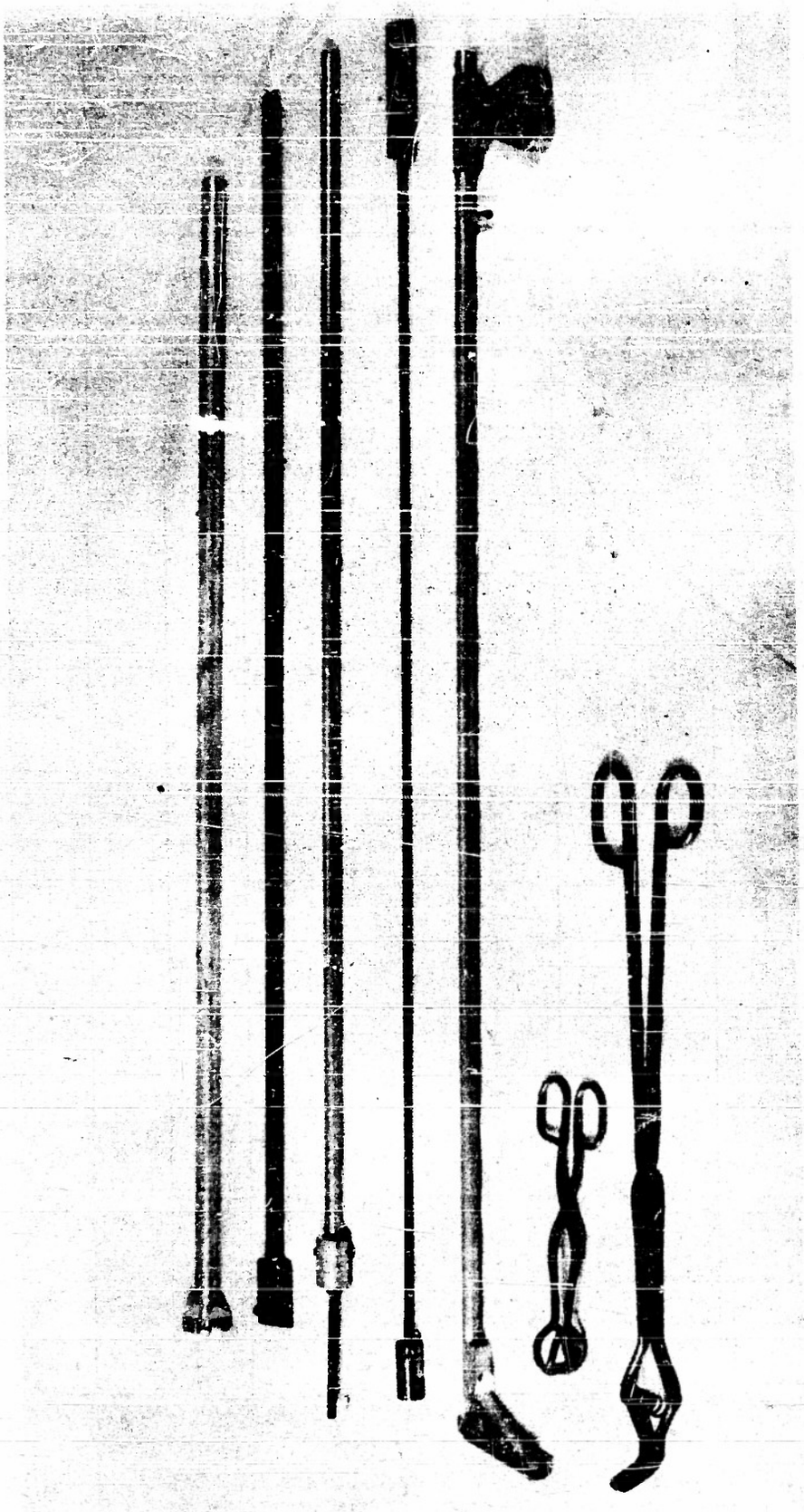


FIG. 10 SOME SOURCE HANDLING TOOLS

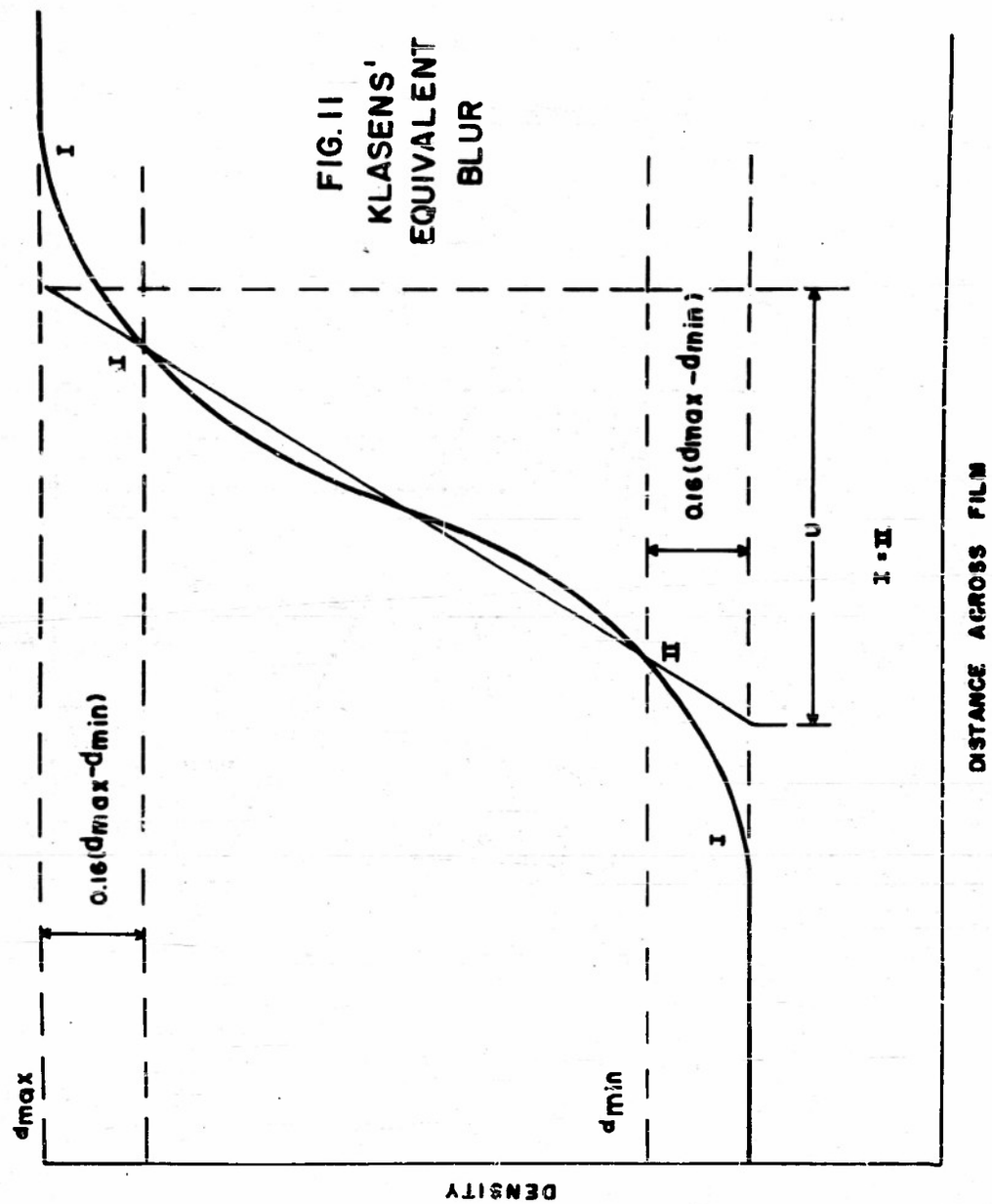


FIG. 11
KLASENS' EQUIVALENT BLUR

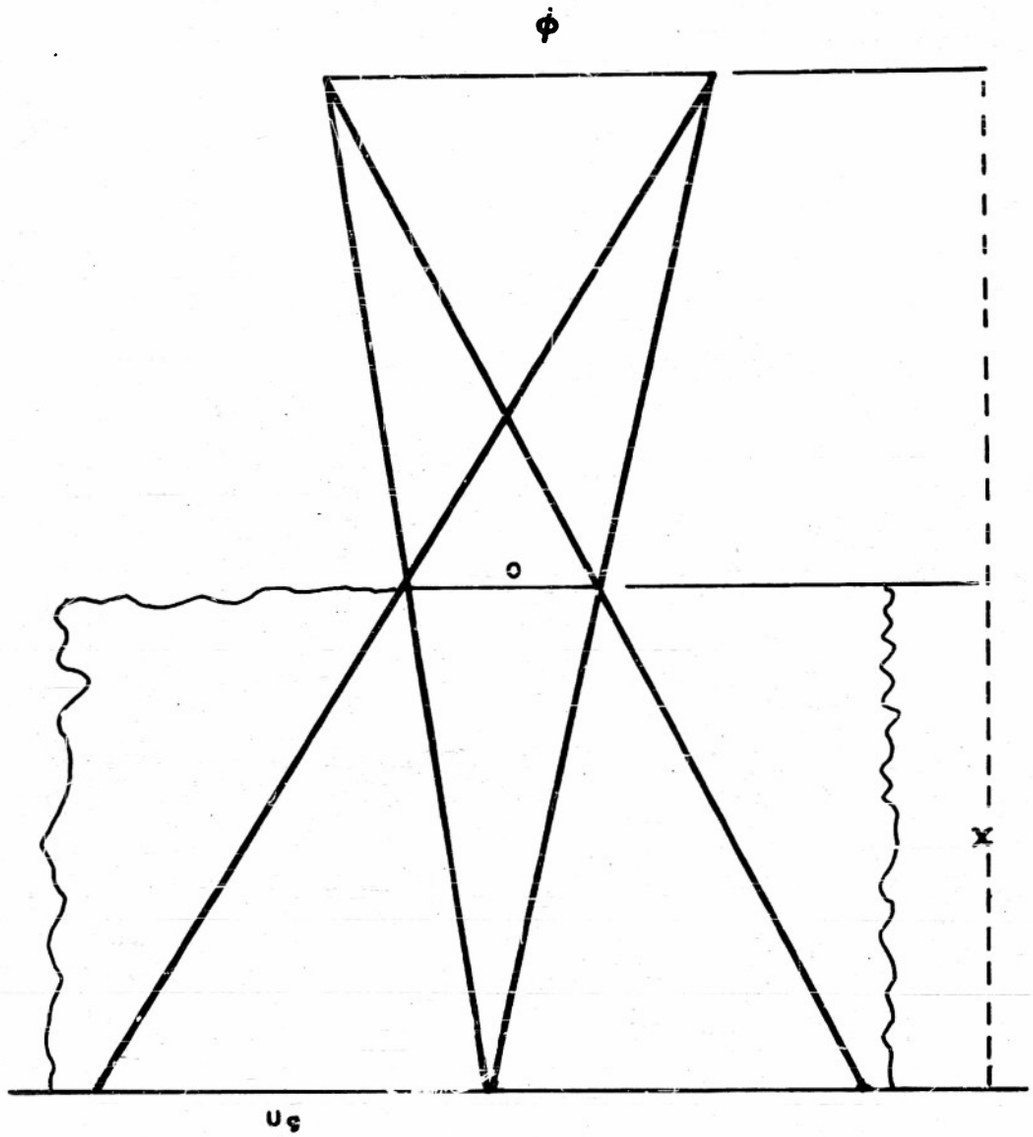


FIG.12 UMBRAL AND PENUMBRAL IMAGES

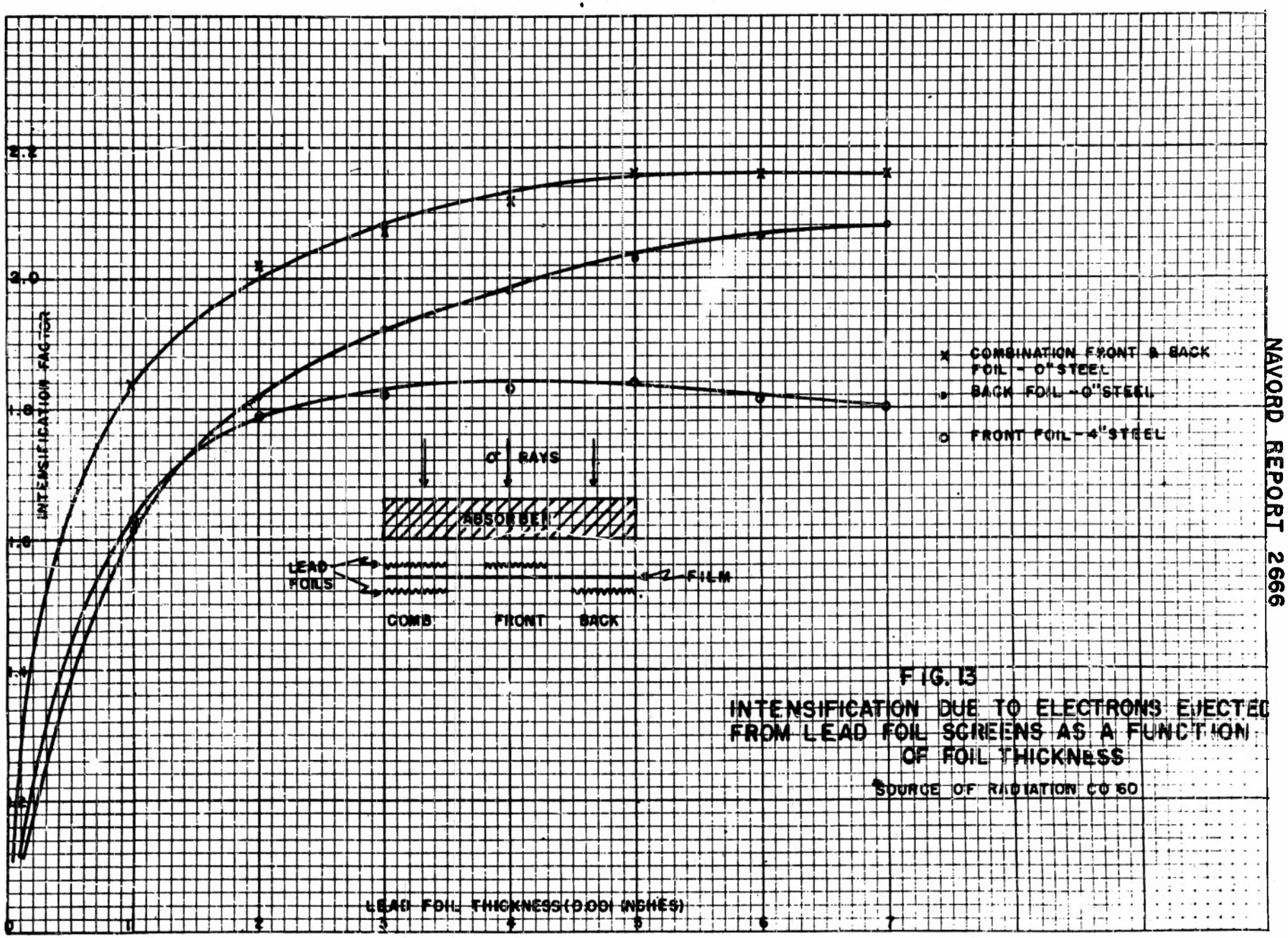


FIG. 13

INTENSIFICATION DUE TO ELECTRONS EJECTED FROM LEAD FOIL SCREENS AS A FUNCTION OF FOIL THICKNESS

SOURCE OF RADIATION CO 60

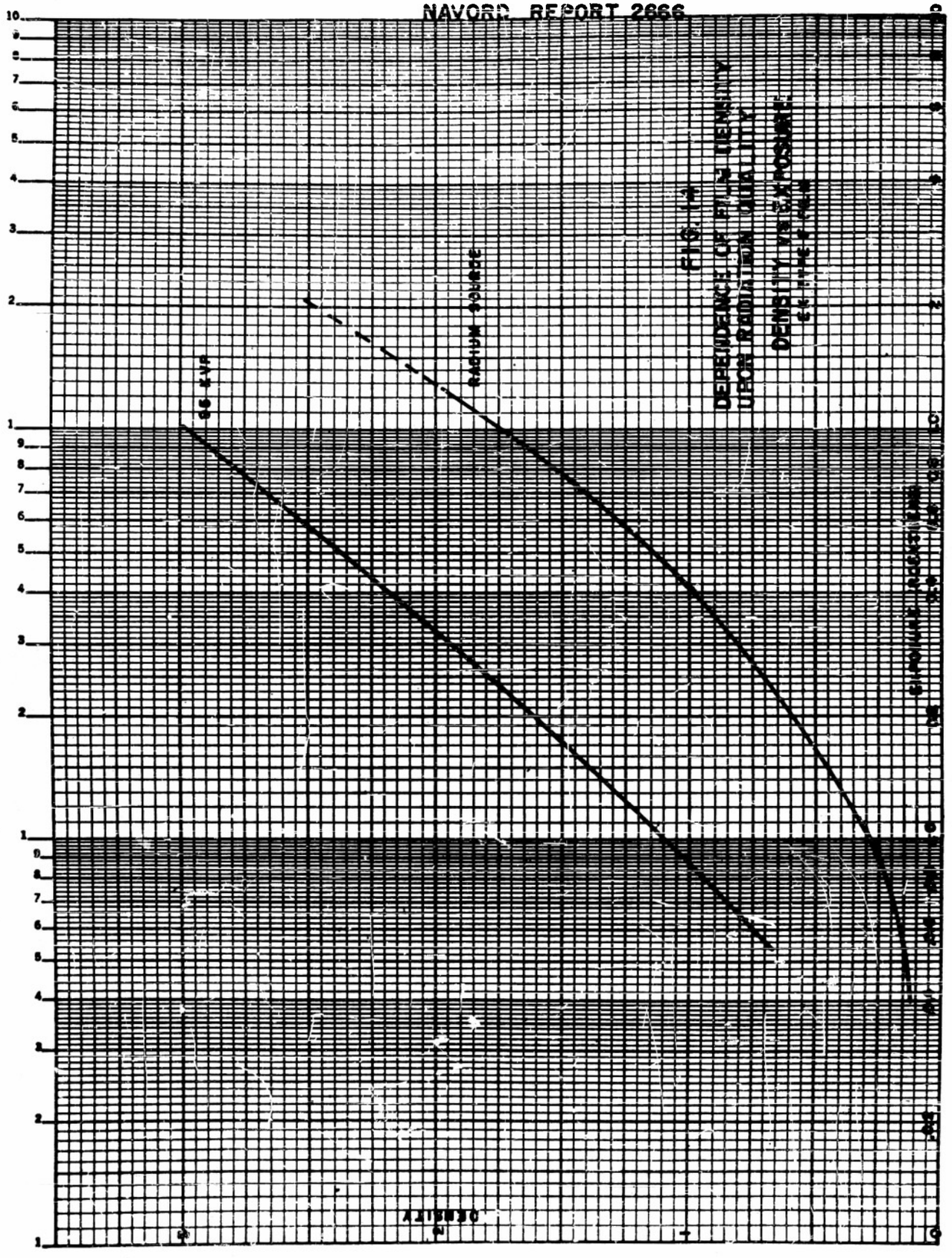
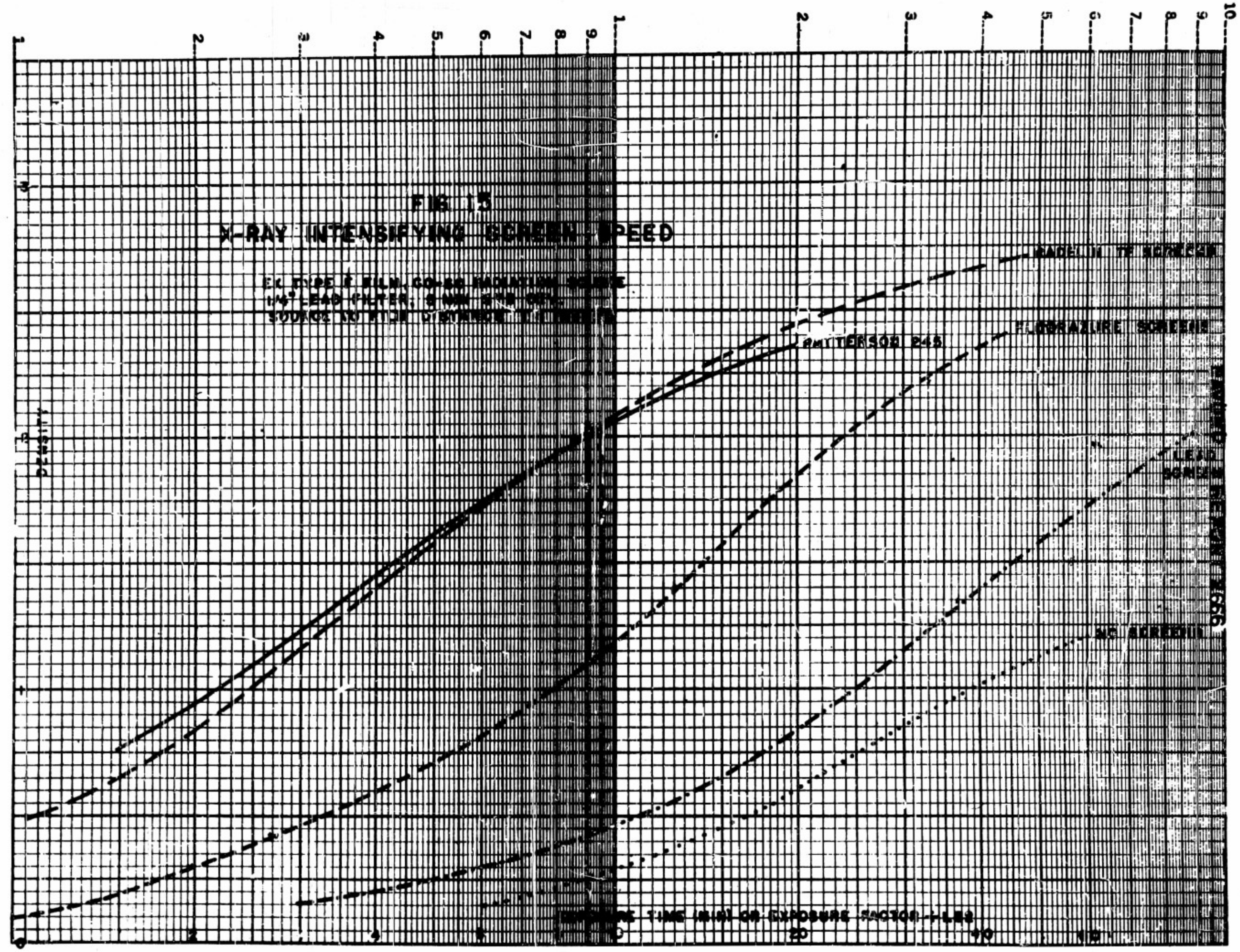
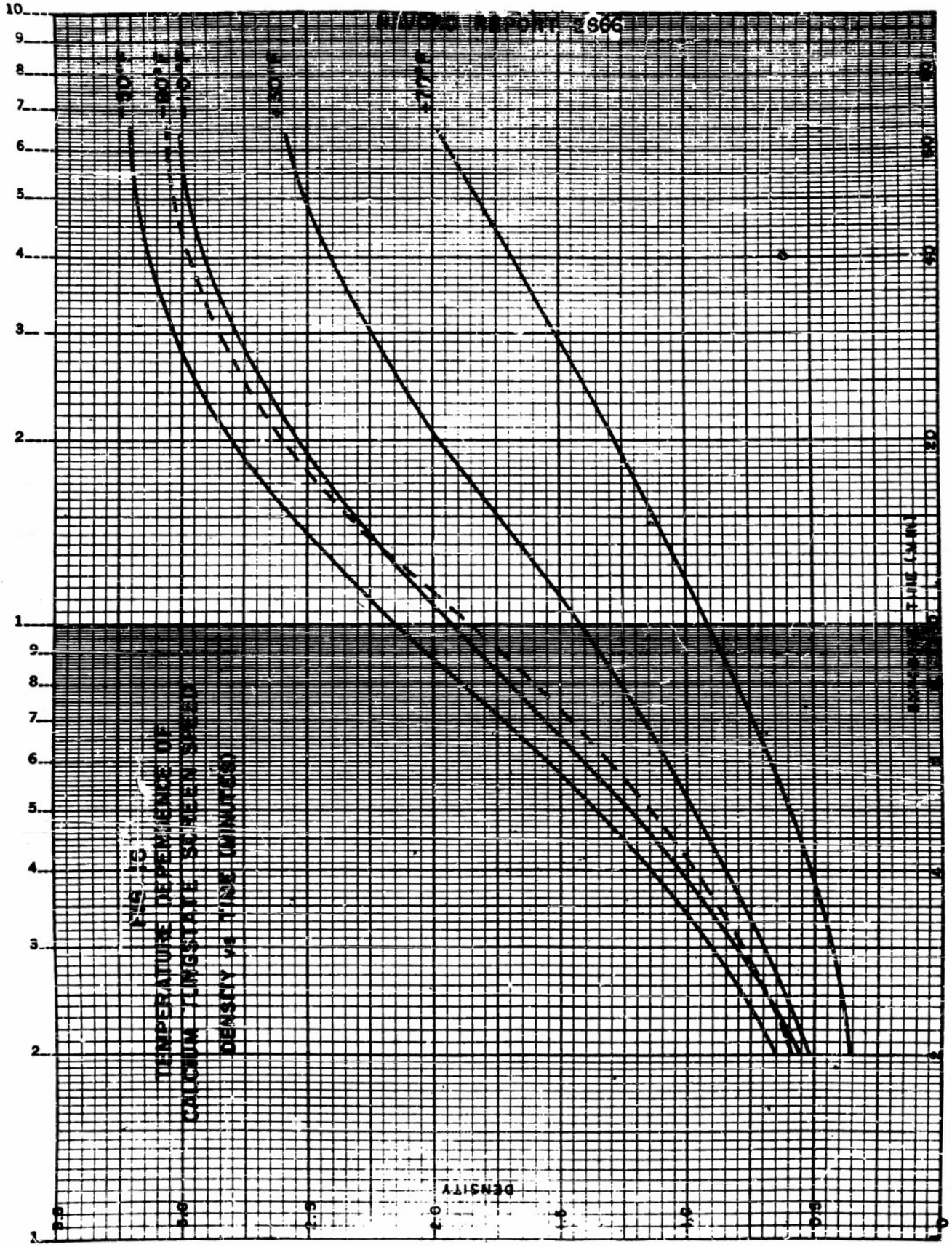
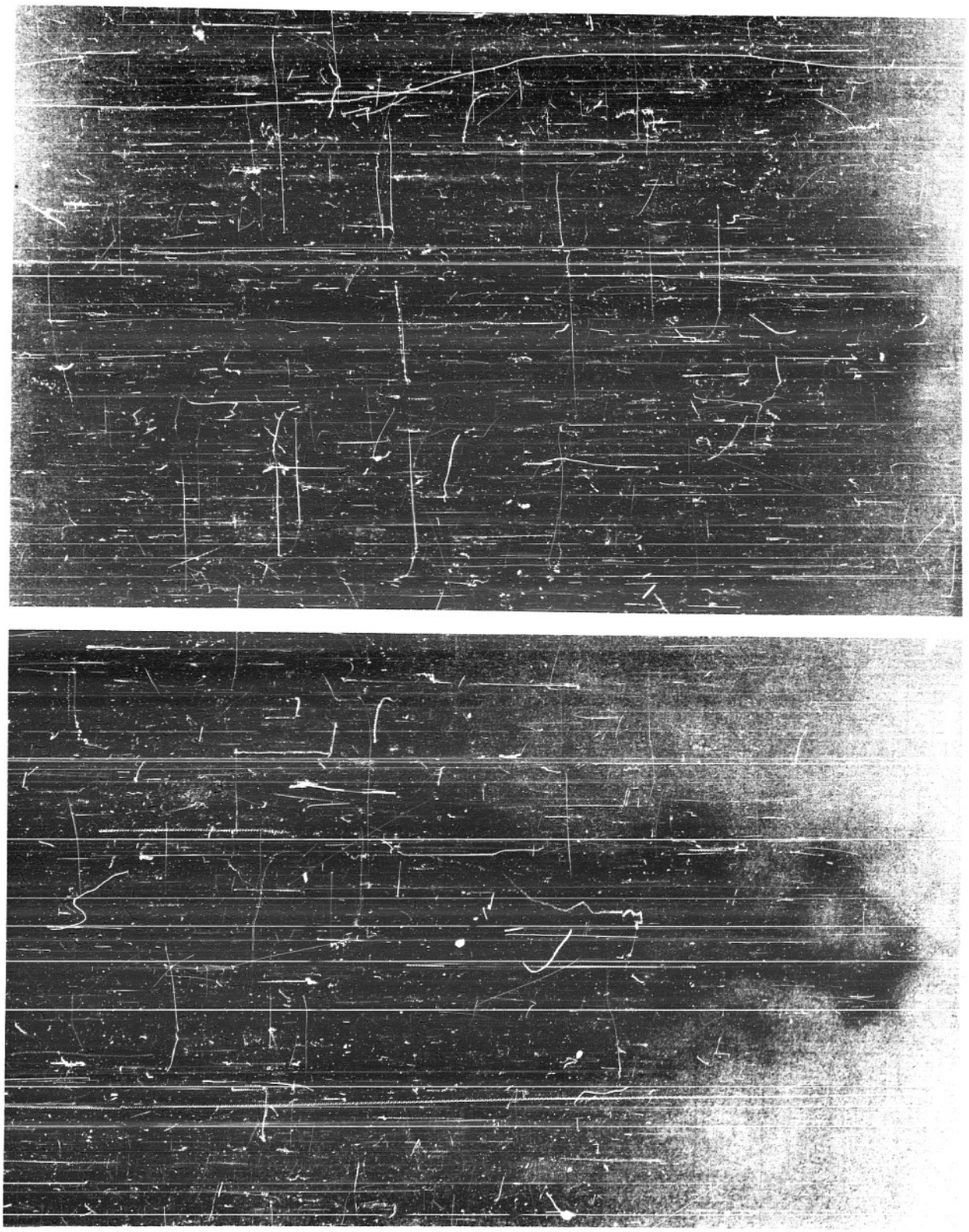

DEPENDENCE OF FILM DENSITY
UPON RADIATION QUALITY
DENSITY VS. KILOVOLTAGE
50 kvp
Radiographic Density
DENSITY

FIG. 1.3



NAVORD REPORT 2666
FIG. 15
X-RAY INTENSIFYING SCREEN SPEED
RADELIN TF SCREENS
FLUORAZURE SCREENS
PATTERSON 245
LEAD SCREENS
NO SCREENS
DENSITY
EXPOSURE TIME (MIN) OR EXPOSURE FACTOR


TEMPERATURE DEPENDENCE OF
CALCIUM TUNGSTATE SCREEN SPEED
DENSITY vs TIME (MINUTES)
DENSITY
TIME (MINUTES)



UNFILTERED

FILTERED

FIG. 17
EFFECT OF FILTERS ON RADIOGRAPHS

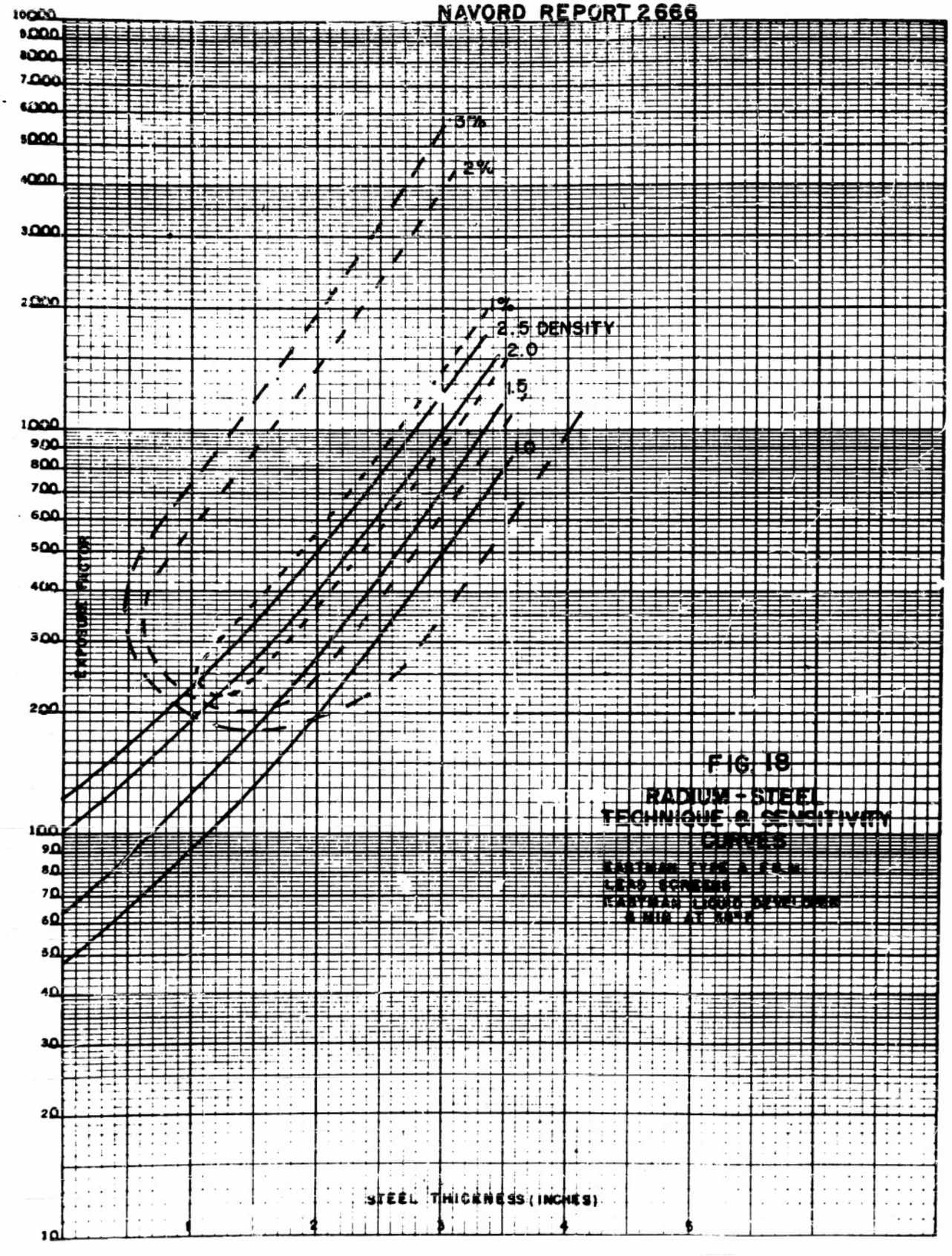


FIG. 18

RADIUM - STEEL
TECHNIQUE & SENSITIVITY
CURVES

EASTMAN TYPE A F & M
LEAD SCREENS
EASTMAN LIQUID DEVELOPER
8 MIN AT 68°F

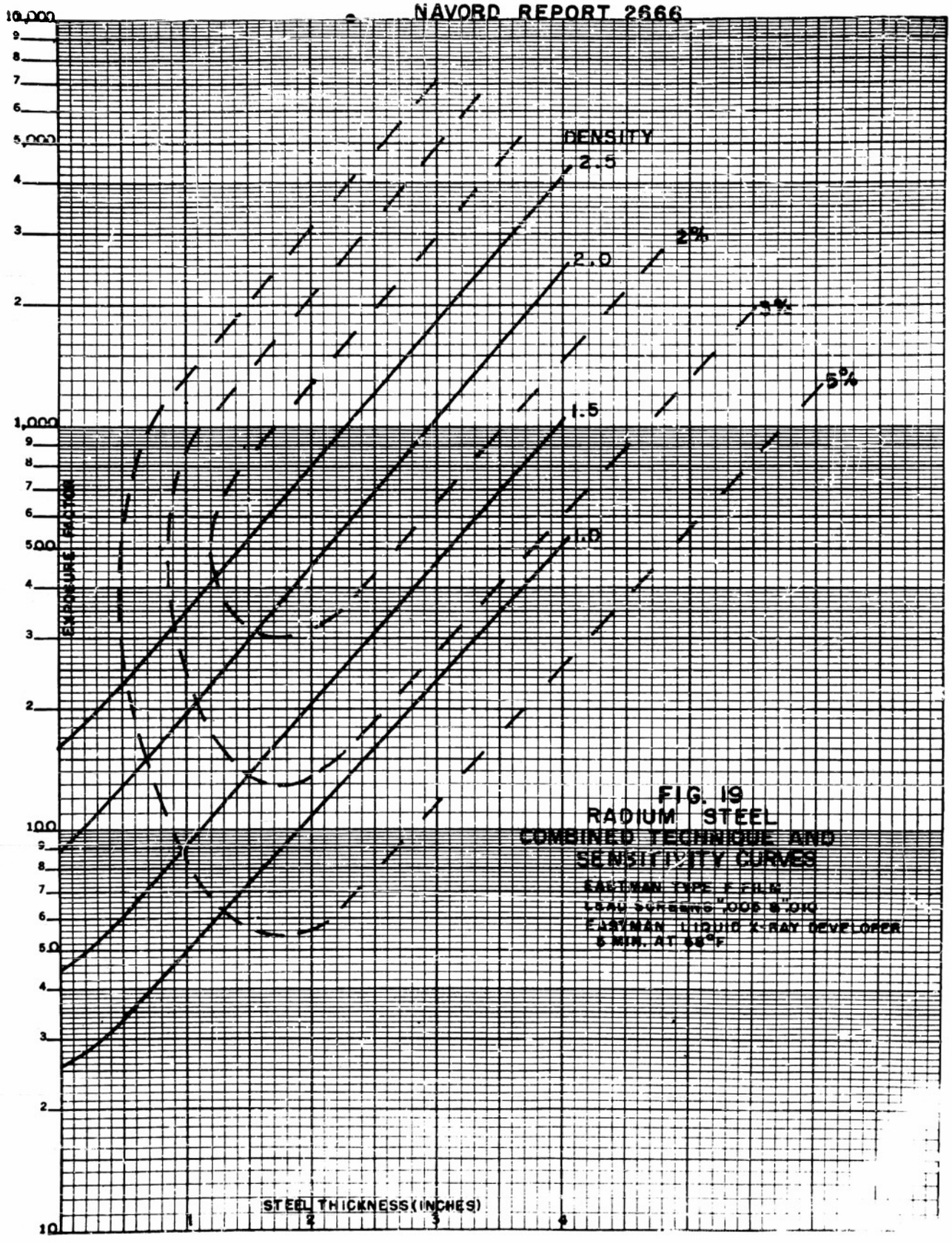


FIG. 19
RADIUM STEEL
COMBINED TECHNIQUE AND
SENSITIVITY CURVES
EASTMAN TYPE K FILM
LEAD SCREENS .005 & .010
EASTMAN LIQUID X-RAY DEVELOPER
5 MIN. AT 68°F

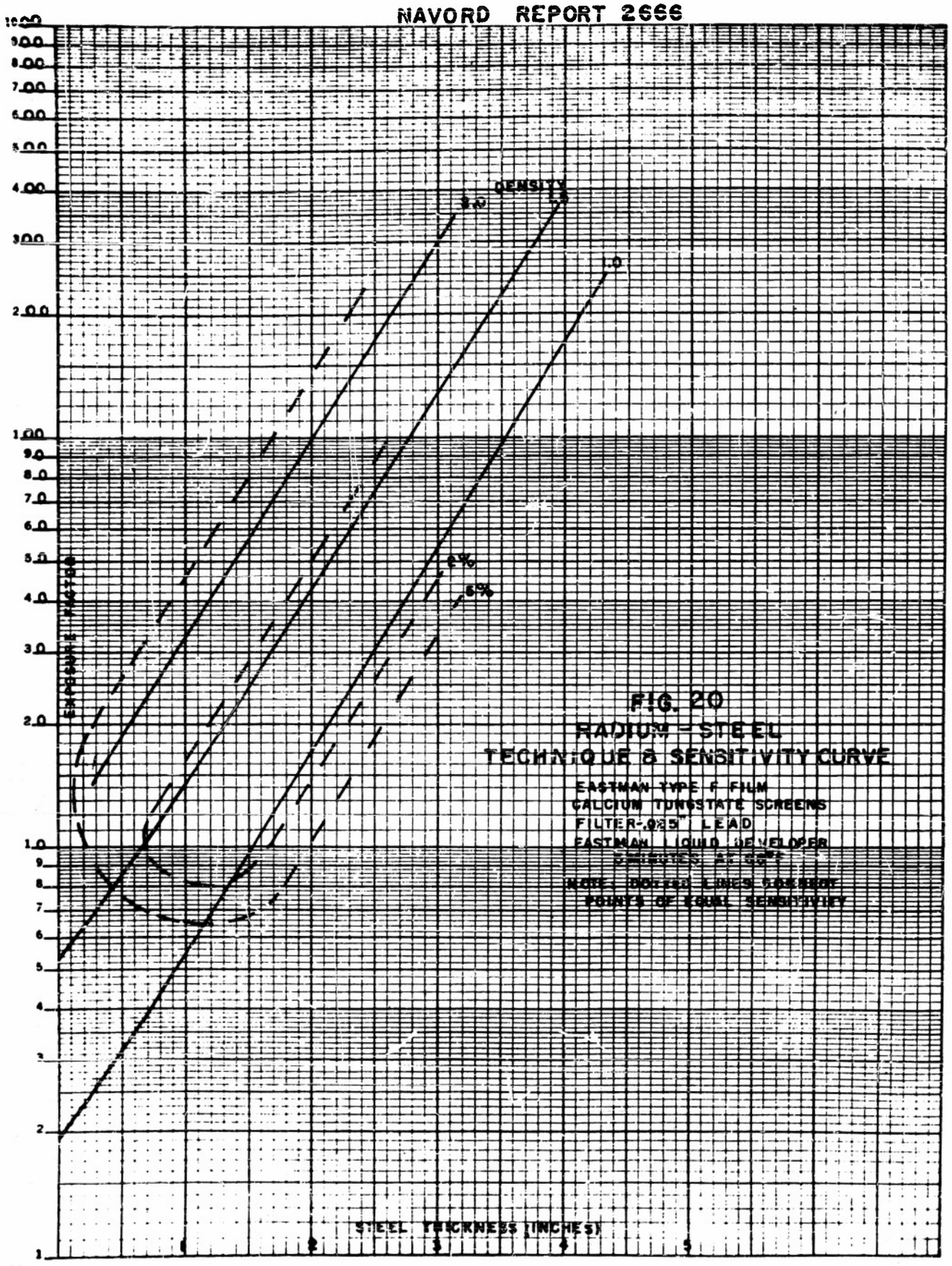


FIG. 20
RADIUM - STEEL
TECHNIQUE & SENSITIVITY CURVE
EASTMAN TYPE F FILM
CALCIUM TUNGSTATE SCREENS
FILTER-.025" LEAD
EASTMAN LIQUID DEVELOPER
DEVELOPED AT 68°F
NOTE: DOTTED LINES CONNECT
POINTS OF EQUAL SENSITIVITY

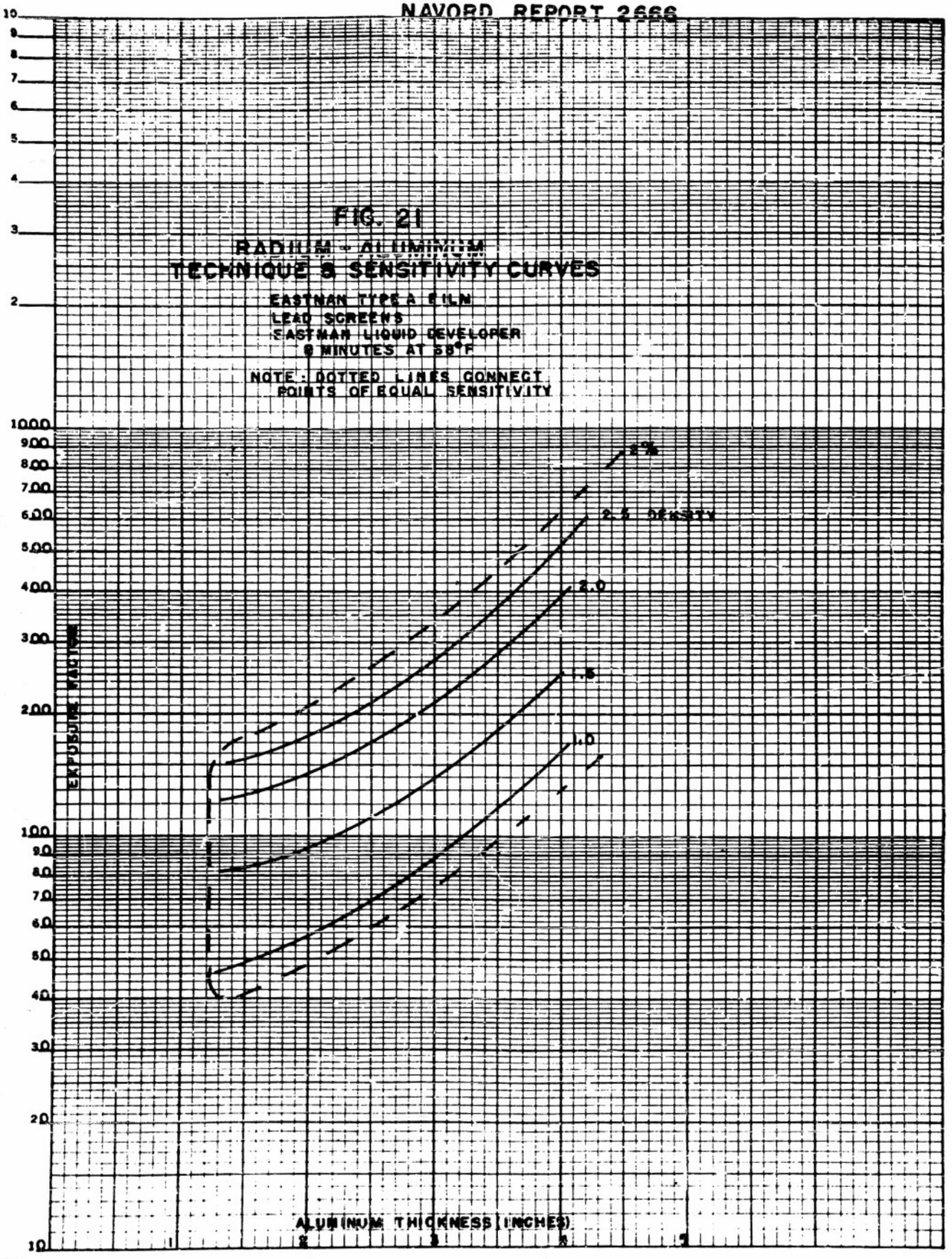


FIG. 21
RADIUM - ALUMINUM
TECHNIQUE 3 SENSITIVITY CURVES
EASTMAN TYPE A FILM
LEAD SCREENS
EASTMAN LIQUID DEVELOPER
8 MINUTES AT 68°F
NOTE: DOTTED LINES CONNECT POINTS OF EQUAL SENSITIVITY
EXPOSURE FACTOR
ALUMINUM THICKNESS (INCHES)
2.5 DENSITY
2.0
1.5
1.0

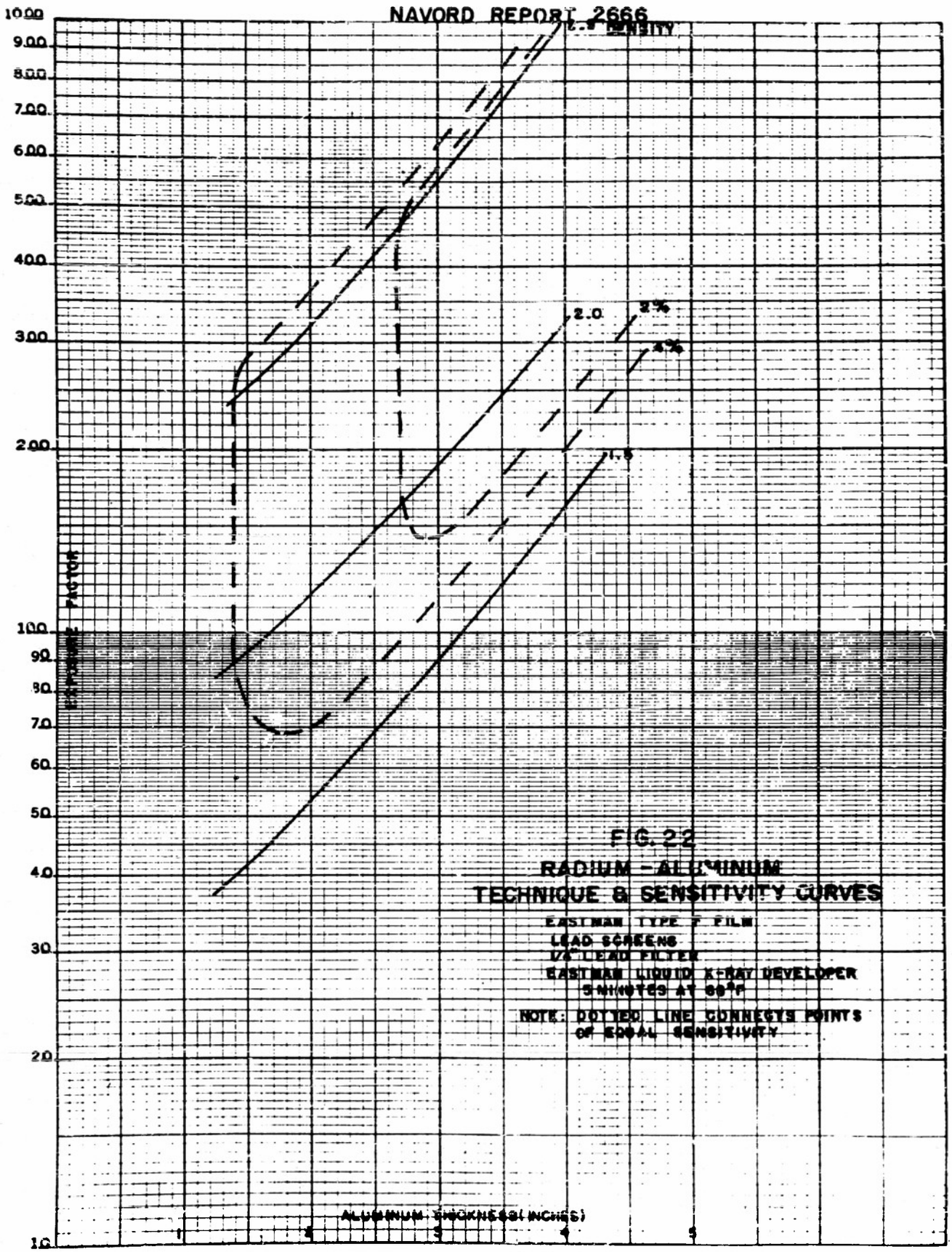


FIG. 22

RADIUM – ALUMINUM

TECHNIQUE & SENSITIVITY CURVES

EASTMAN TYPE F FILM
LEAD SCREENS
1/8 LEAD FILTER
EASTMAN LIQUID X-RAY DEVELOPER
5 MINUTES AT 68°F

NOTE: DOTTED LINE CONNECTS POINTS OF EQUAL SENSITIVITY

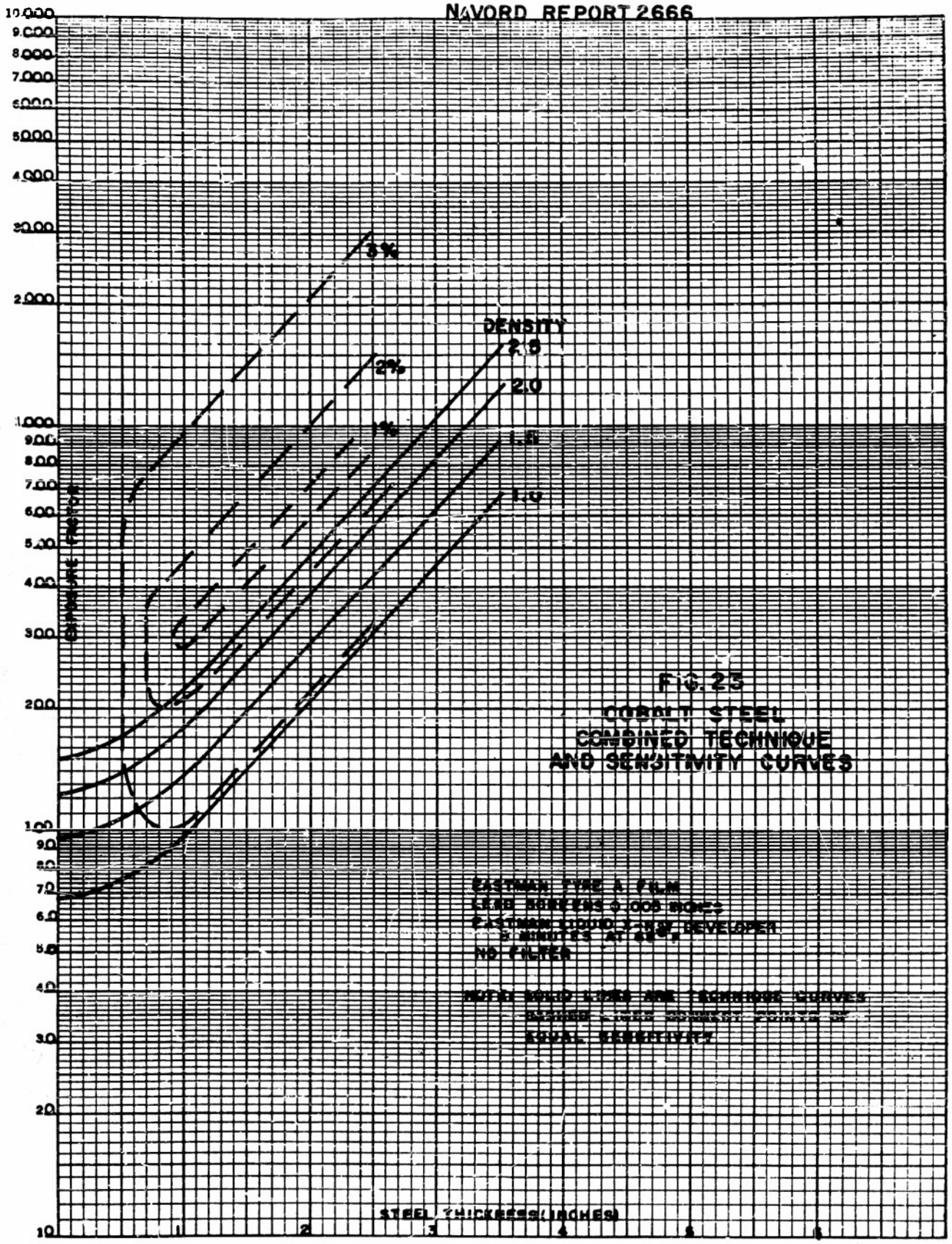


FIG. 23

COBALT STEEL
COMBINED TECHNIQUE
AND SENSITIVITY CURVES

EASTMAN TYPE A FILM
LEAD SCREENS 0.005 INCH
EASTMAN D19 X-RAY DEVELOPER
5 MINUTES AT 68°F
NO FILTER

HEAVY SOLID LINES ARE TECHNIQUE CURVES
DASHED LINES CONNECT POINTS OF
EQUAL SENSITIVITY

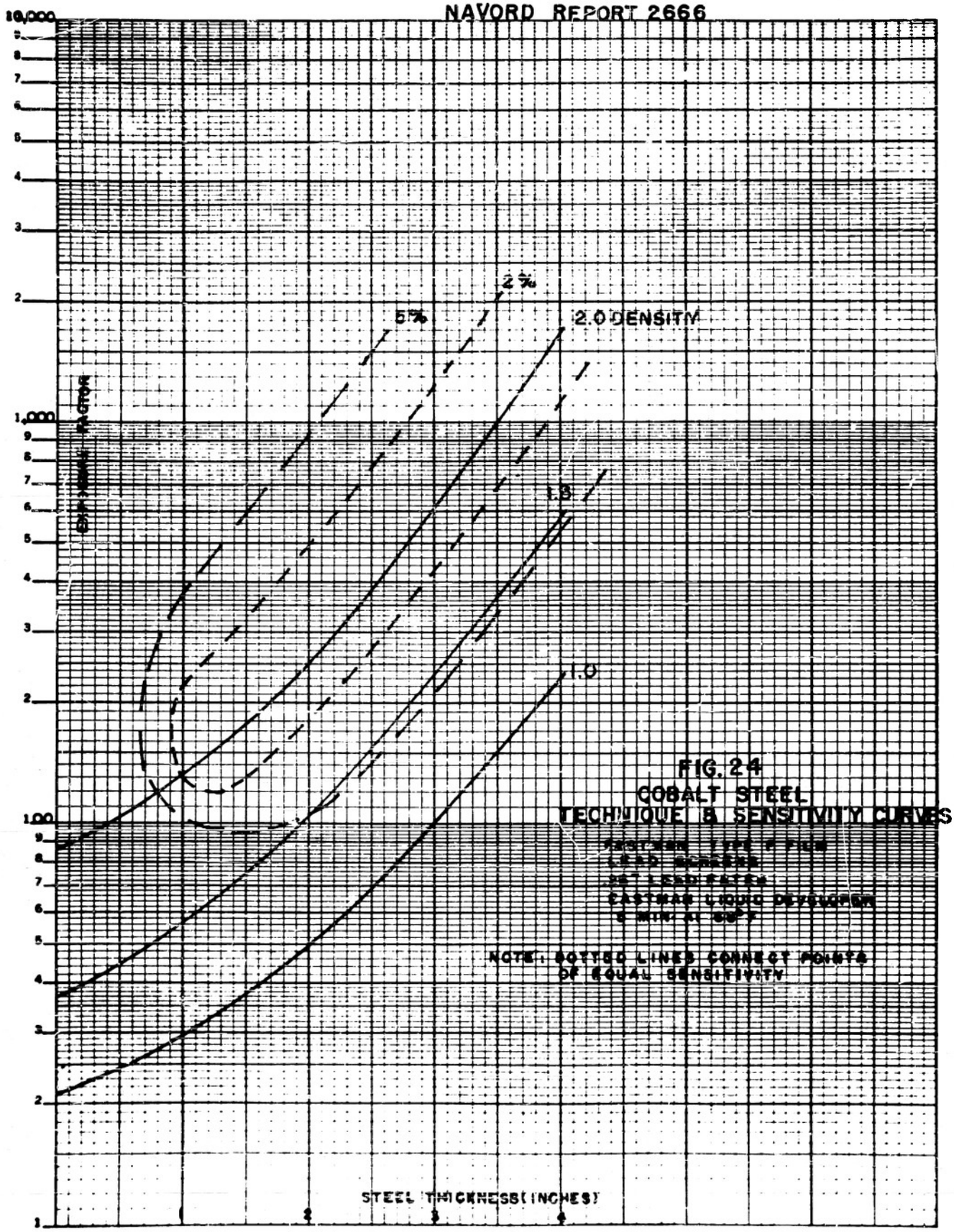


FIG. 24
COBALT STEEL
TECHNIQUE B SENSITIVITY CURVES

NOTE: DOTTED LINES CONNECT POINTS OF EQUAL SENSITIVITY

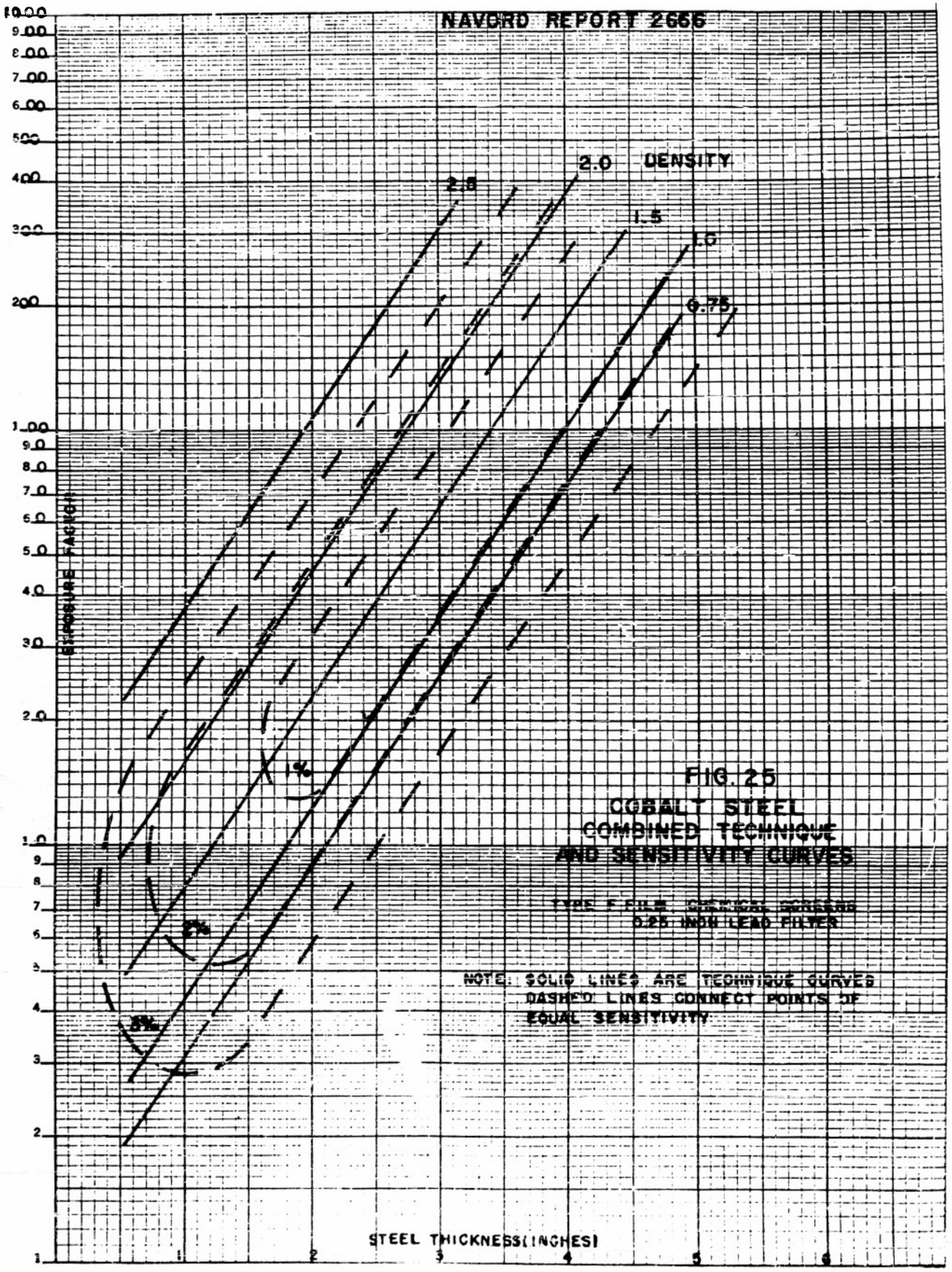


FIG. 25
COBALT STEEL
COMBINED TECHNIQUE
AND SENSITIVITY CURVES

TYPE F FILM, CHEMICAL PROCESS
0.25 INCH LEAD FILTER

NOTE: SOLID LINES ARE TECHNIQUE CURVES
DASHED LINES CONNECT POINTS OF
EQUAL SENSITIVITY

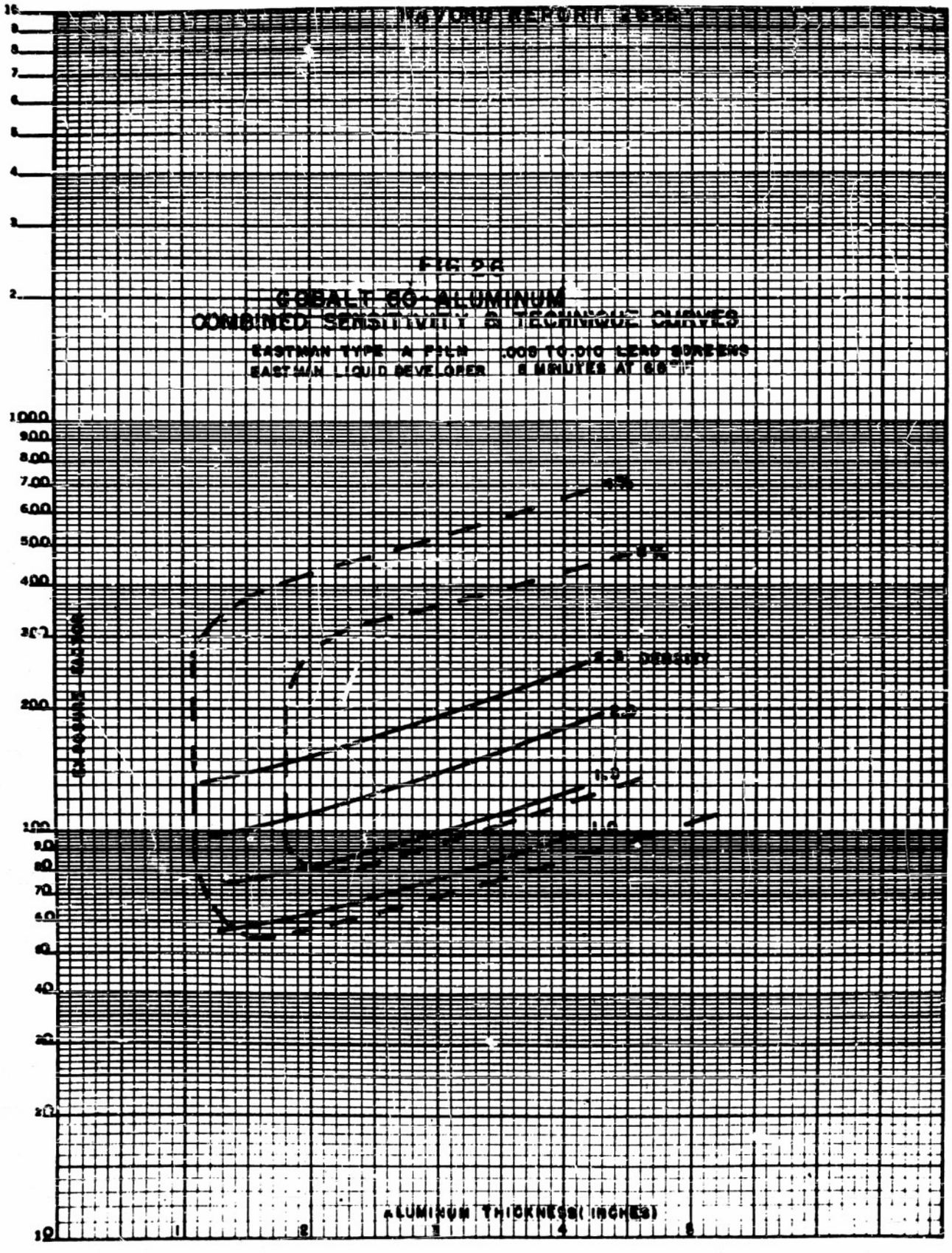


FIG. 24
COBALT 60 - ALUMINUM
COMBINED SENSITIVITY & TECHNIQUE CURVES
EASTMAN TYPE A FILM .005 TO .010 LEAD SCREENS
EASTMAN LIQUID DEVELOPER 8 MINUTES AT 68°F
KILOVOLTS (P-P)
ALUMINUM THICKNESS (INCHES)
1000
900
800
700
600
500
400
300
200
150
100
90
80
70
60
50
40
30
20
10
16
15
14
13
12
11
10
9
8
7
6
5
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12
13
14
15
16

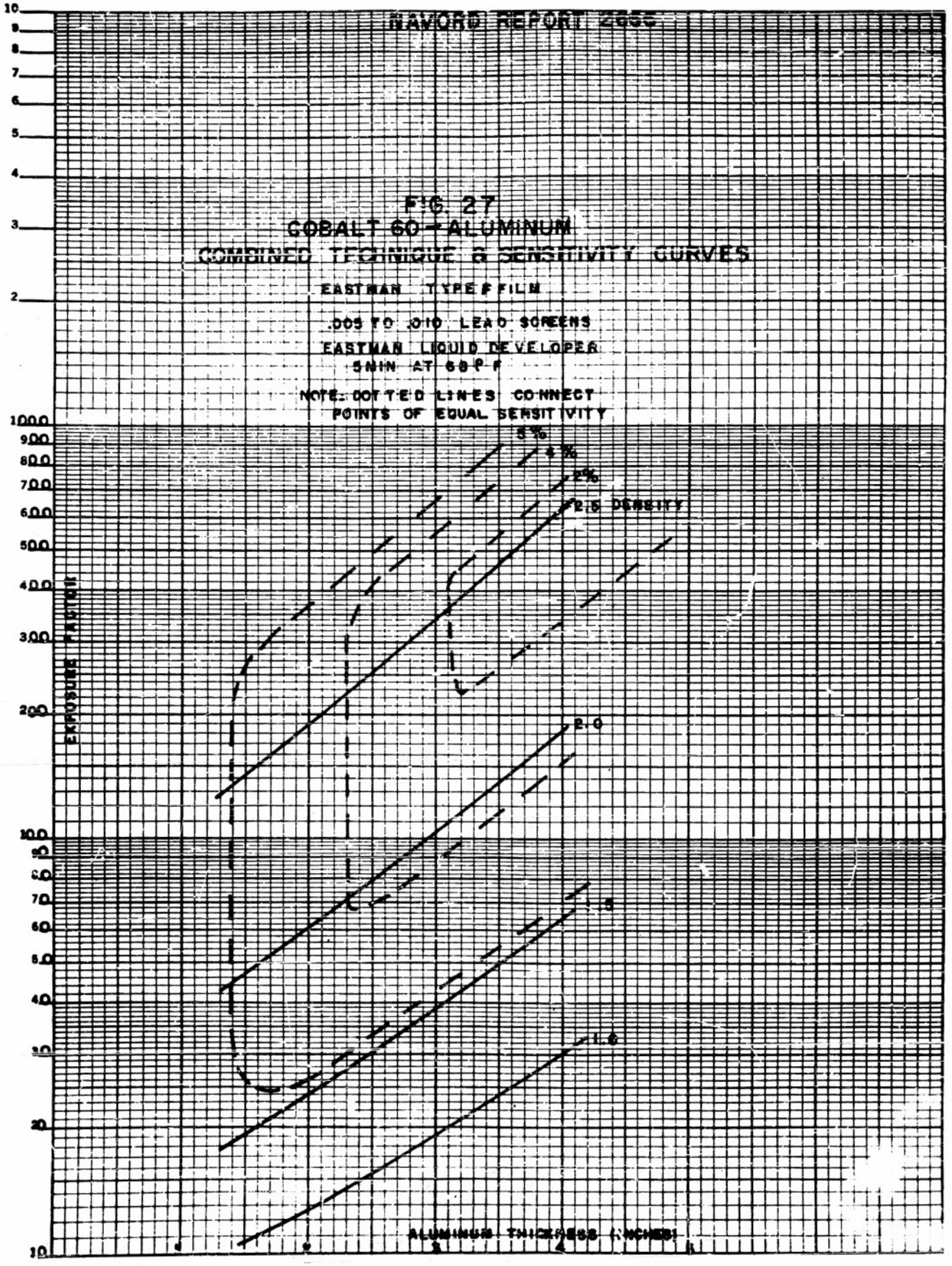


FIG. 27

COBALT 60 + ALUMINUM

COMBINED TECHNIQUE & SENSITIVITY CURVES

EASTMAN TYPE F FILM

.005 TO .010 LEAD SCREENS

EASTMAN LIQUID DEVELOPER

5 MIN AT 68° F

NOTE: DOTTED LINES CONNECT POINTS OF EQUAL SENSITIVITY

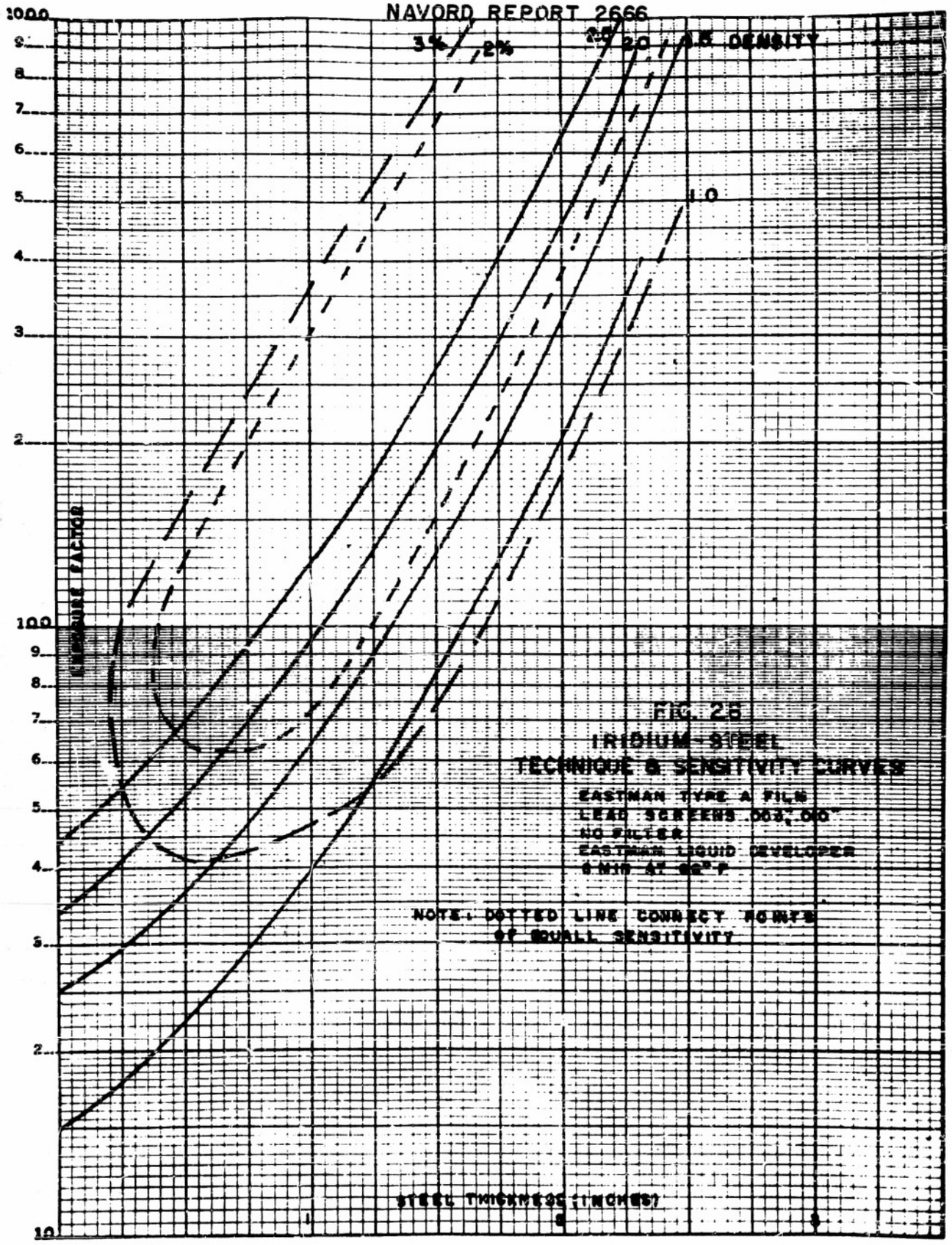


FIG. 25
IRIDIUM-STEEL
TECHNIQUE & SENSITIVITY CURVES

EASTMAN TYPE A FILM
LEAD SCREENS .003", .010"
NO FILTER
EASTMAN LIQUID DEVELOPER
6 MIN AT 68° F

NOTE: DOTTED LINE CONNECT POINTS OF EQUALL SENSITIVITY

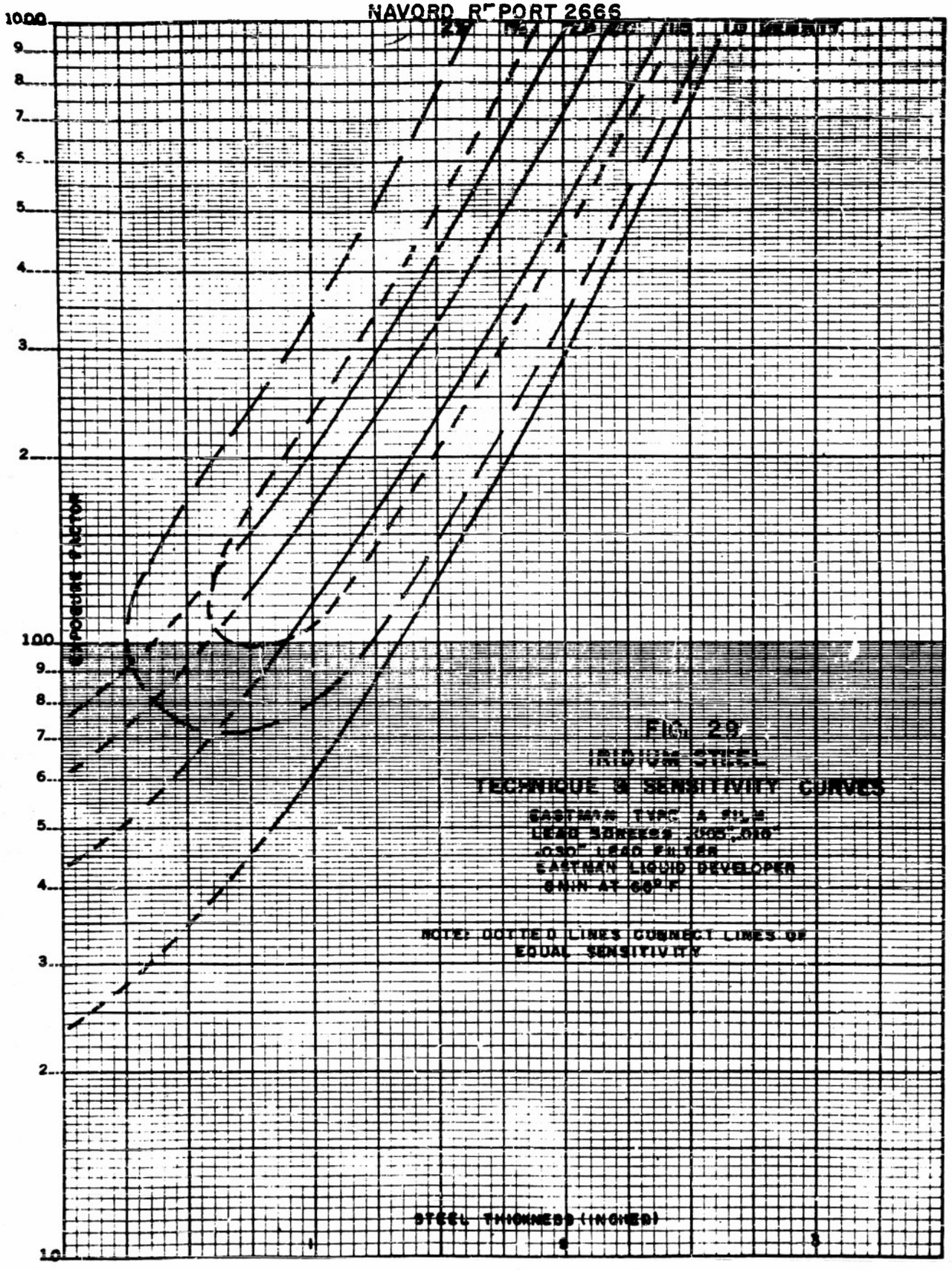


FIG. 29

INDIANA STEEL
INDIUM STEEL

TECHNIQUE & SENSITIVITY CURVES

EASTMAN TYPE A FILM
LEAD SCREENS .005", .010"
.030" LEAD FILTER
EASTMAN LIQUID DEVELOPER
6 MIN AT 68° F

NOTE: DOTTED LINES CONNECT LINES OF EQUAL SENSITIVITY

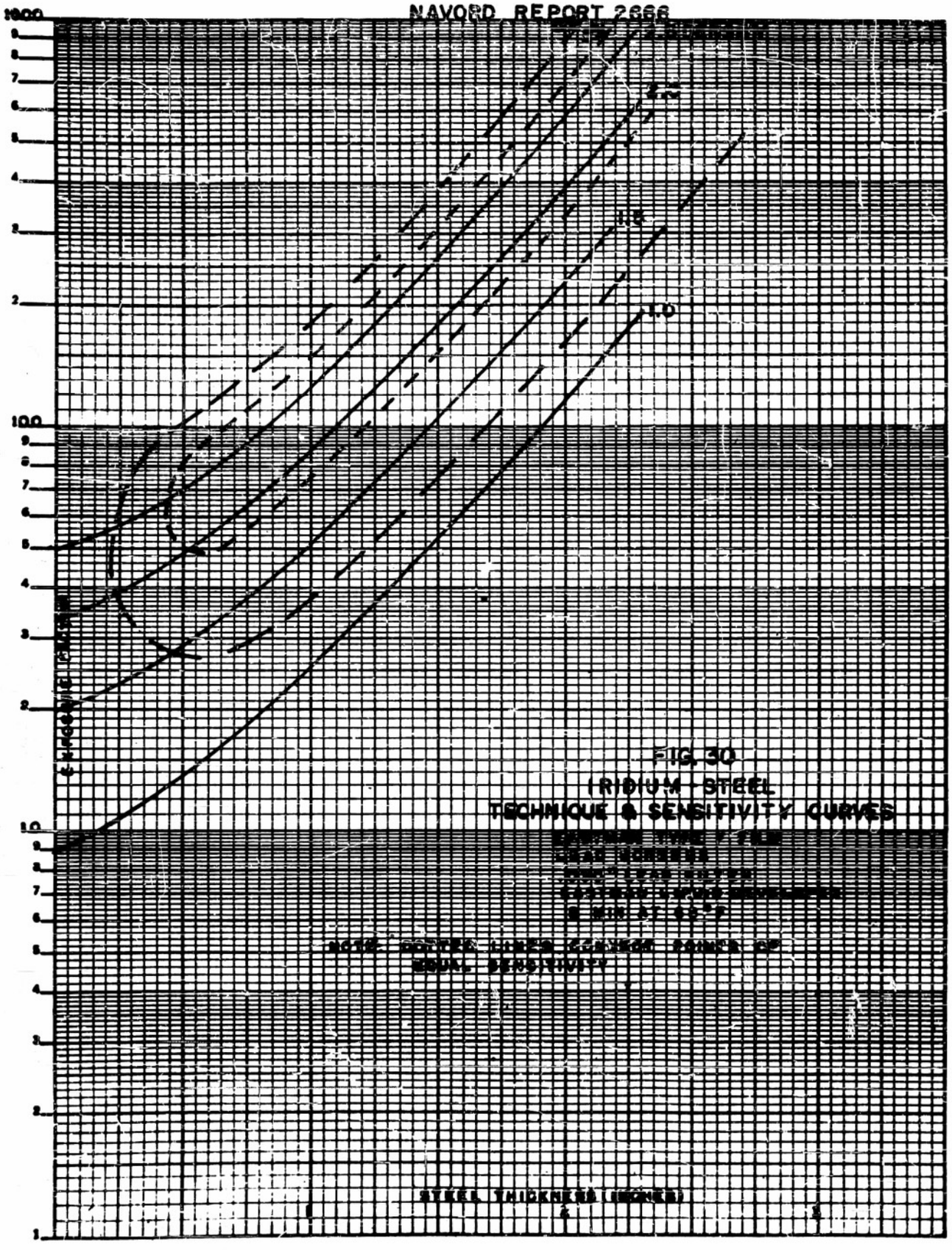


FIG. 30
IRIDIUM - STEEL
TECHNIQUE & SENSITIVITY CURVES

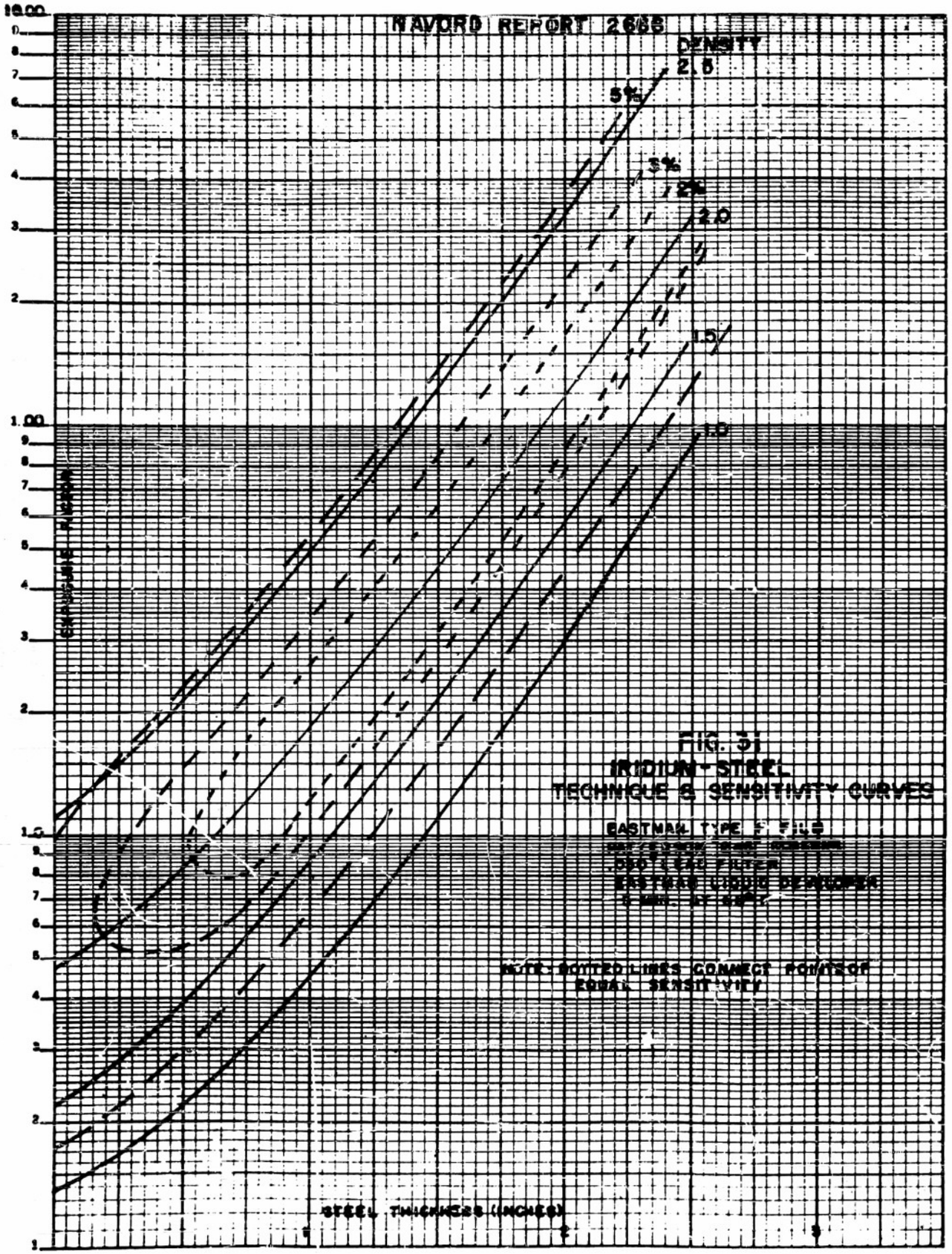


FIG. 31
IRIDIUM - STEEL
TECHNIQUE & SENSITIVITY CURVES

EASTMAN TYPE K FILM
.010 LEAD FILTER
EASTMAN LINDSAY DEVELOPER
6 MIN. AT 68°F.

NOTE: DOTTED LINES CONNECT POINTS OF EQUAL SENSITIVITY

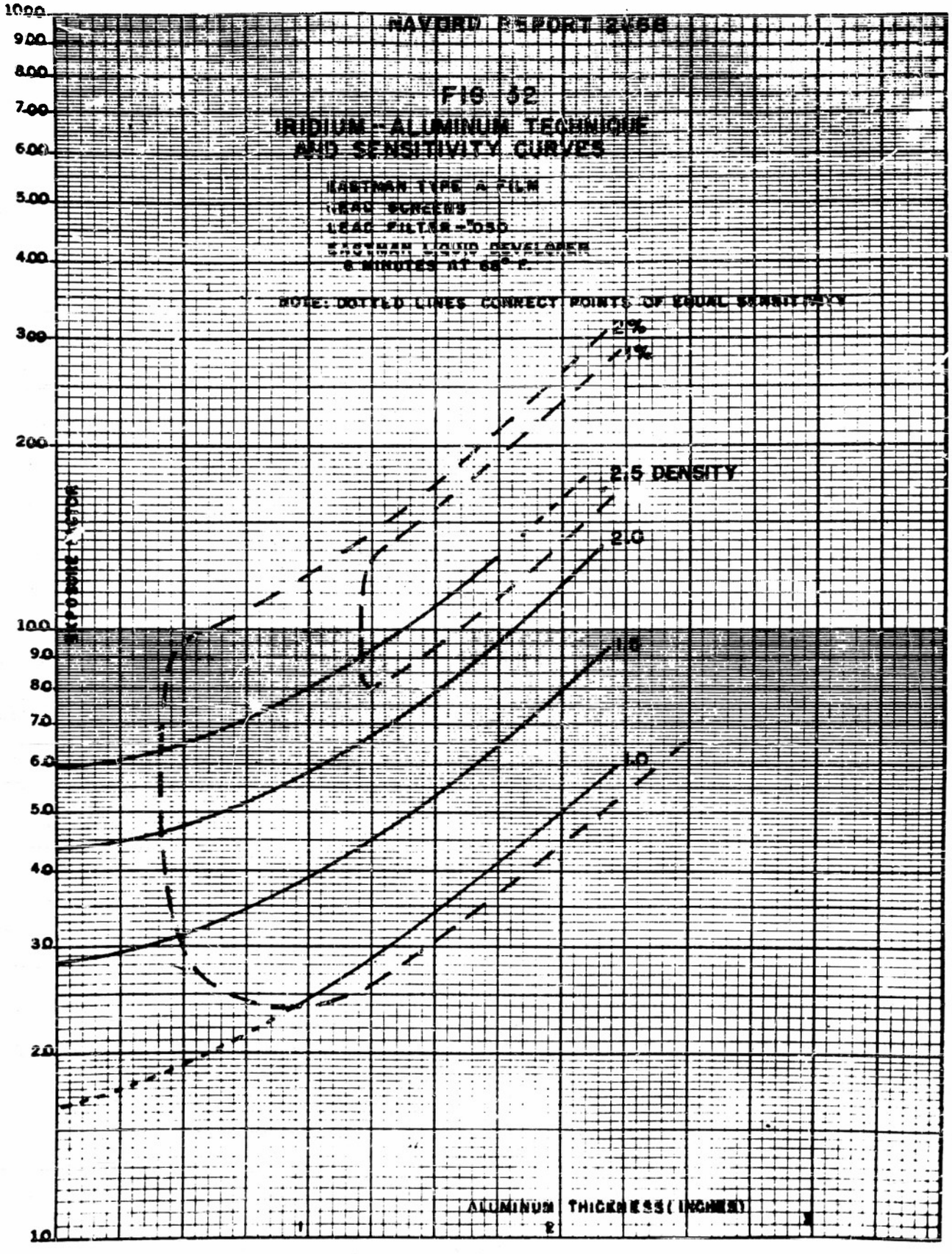
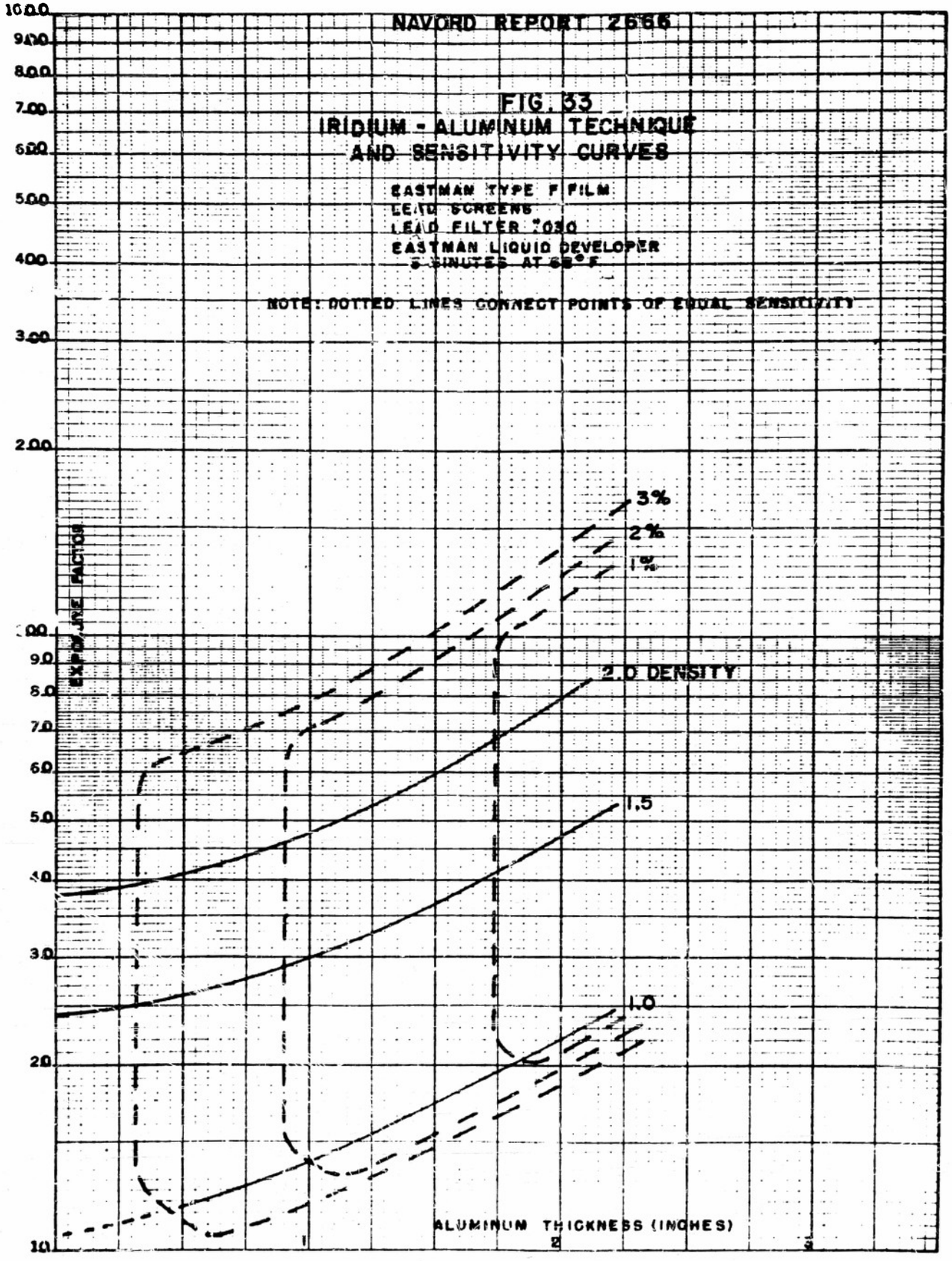

NAVORD REPORT 2458
FIG 32
IRIDIUM - ALUMINUM TECHNIQUE
AND SENSITIVITY CURVES
EASTMAN TYPE A FILM
LEAD SCREENS
LEAD FILTER - .050
EASTMAN LIQUID DEVELOPER
6 MINUTES AT 68° F.
NOTE: DOTTED LINES CONNECT POINTS OF EQUAL SENSITIVITY
2%
1%
2.5 DENSITY
2.0
1.5
1.0
EXPOSURE - ROENTGENS
ALUMINUM THICKNESS (INCHES)
1000
900
800
700
600
500
400
300
200
100
90
80
70
60
50
40
30
20
10
1
2

FIG. 33
IRIDIUM - ALUMINUM TECHNIQUE
AND SENSITIVITY CURVES

EASTMAN TYPE F FILM
LEAD SCREENS
LEAD FILTER .030
EASTMAN LIQUID DEVELOPER
5 MINUTES AT 68°F

NOTE: DOTTED LINES CONNECT POINTS OF EQUAL SENSITIVITY



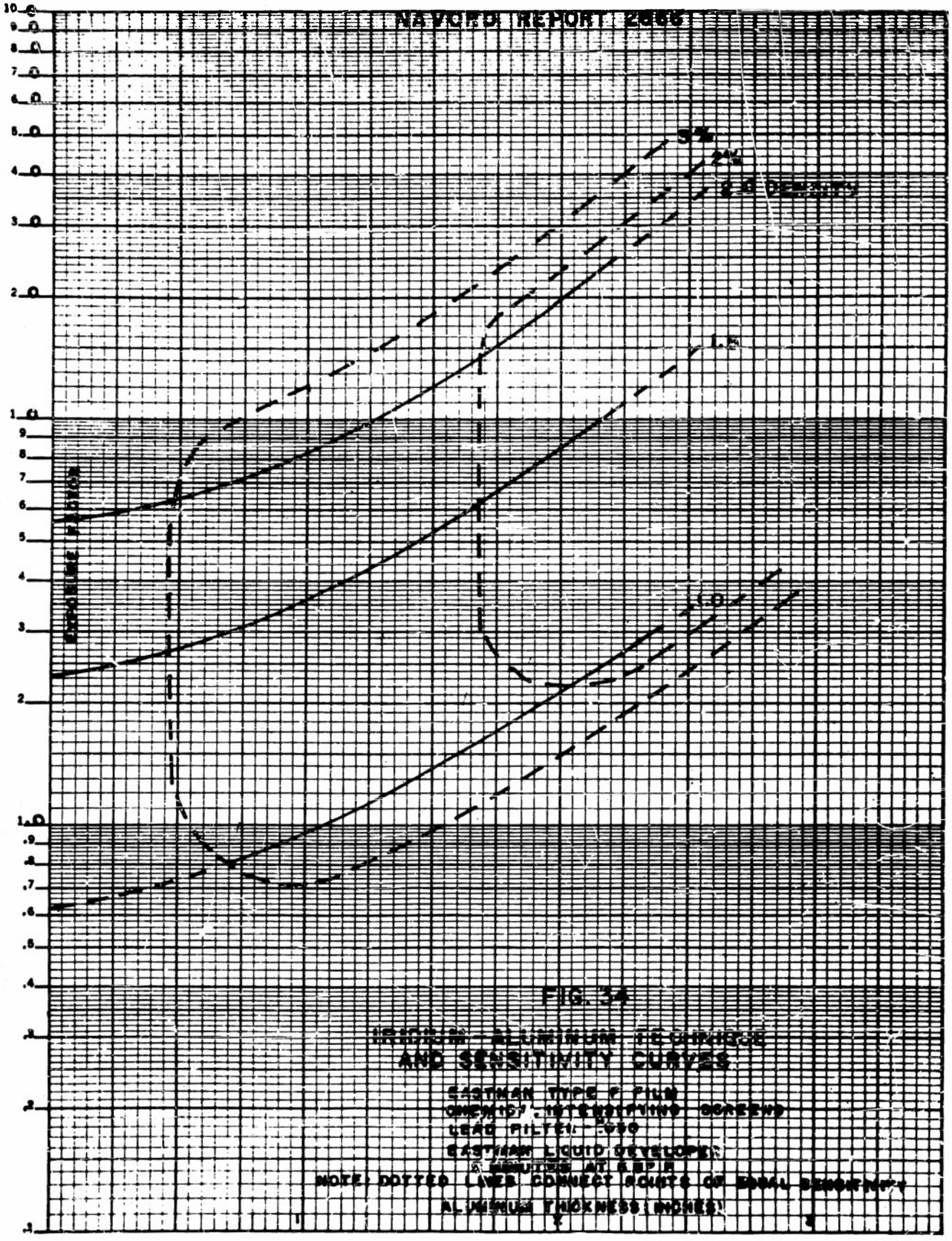


FIG. 34

IRIDIUM - ALUMINUM TC CURVES
AND SENSITIVITY CURVES

EASTMAN TYPE F FILM
DEVELOPED - NOTED IN TEXT
LEAD FILTER - 0.50
EASTMAN LIQUID DEVELOPER
8 MINUTES AT 68°F

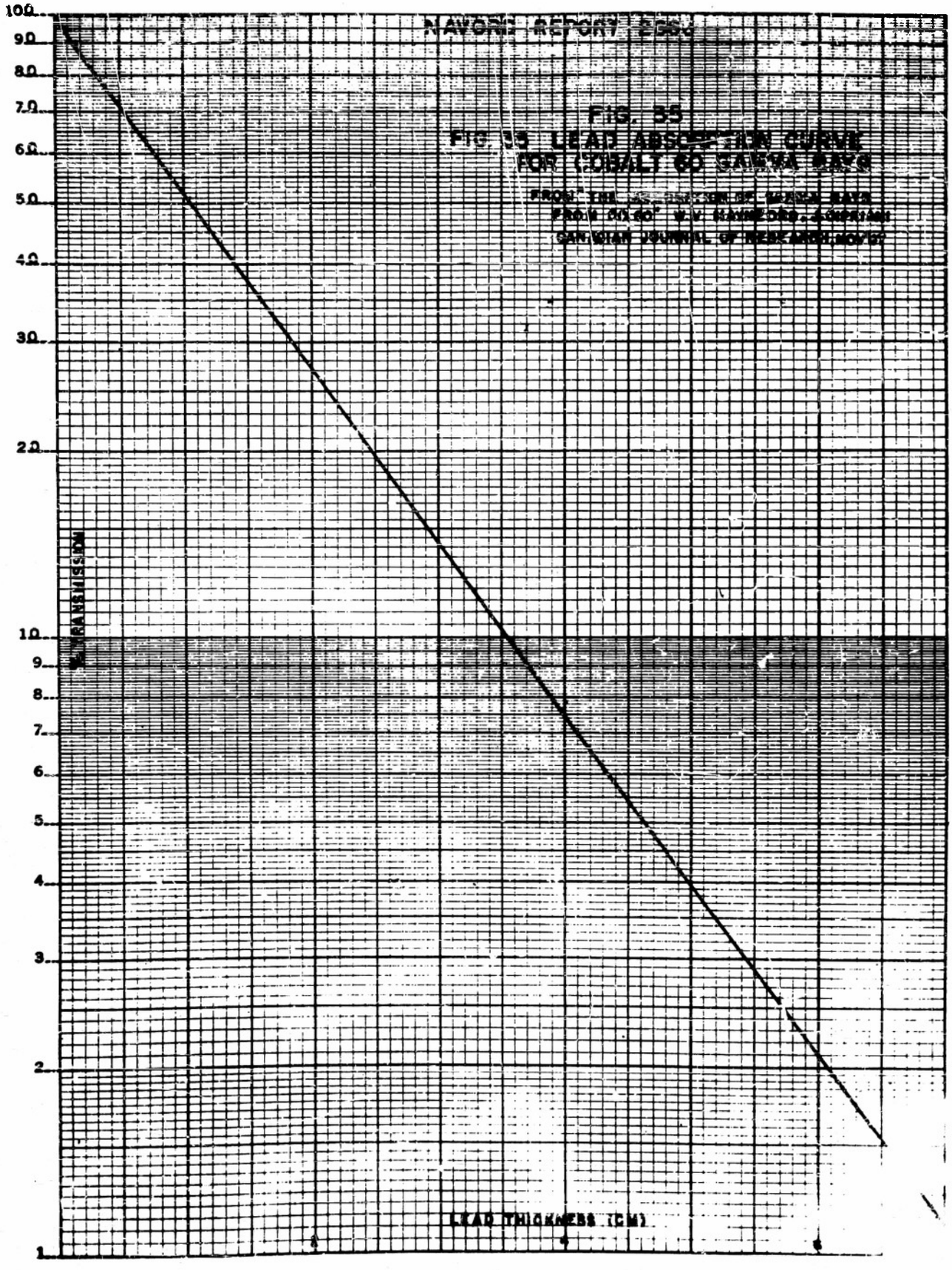
NOTE: DOTTED LINES CONNECT POINTS OF EQUAL SENSITIVITY

ALUMINUM THICKNESS (INCHES)

FIG. 35

FIG. 35 LEAD ABSORPTION CURVE FOR COBALT 60 GAMMA RAYS

FROM "THE ABSORPTION OF GAMMA RAYS FROM RADIUM" W.V. MAYNEORD, CANADIAN CANADIAN JOURNAL OF RESEARCH (1940)



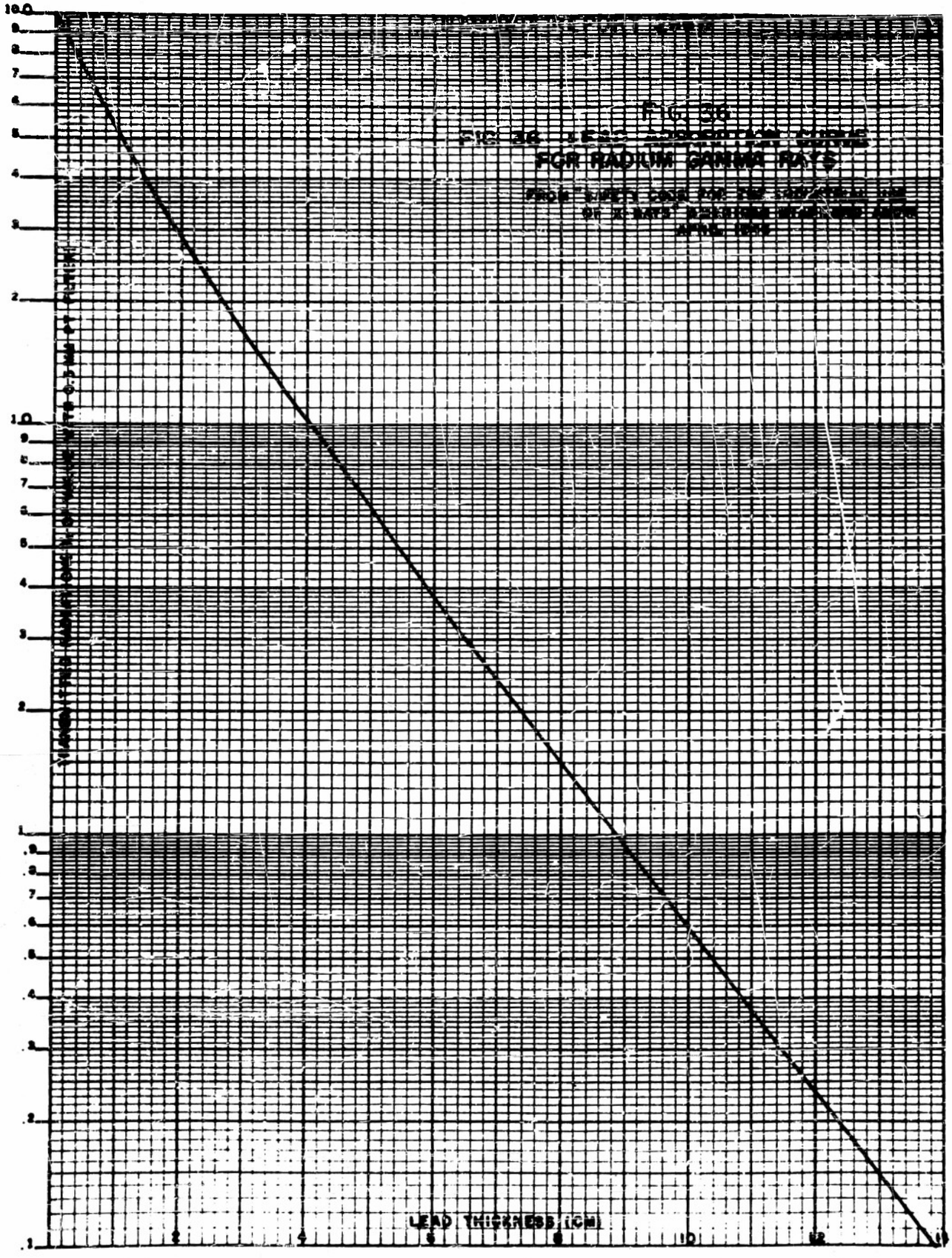
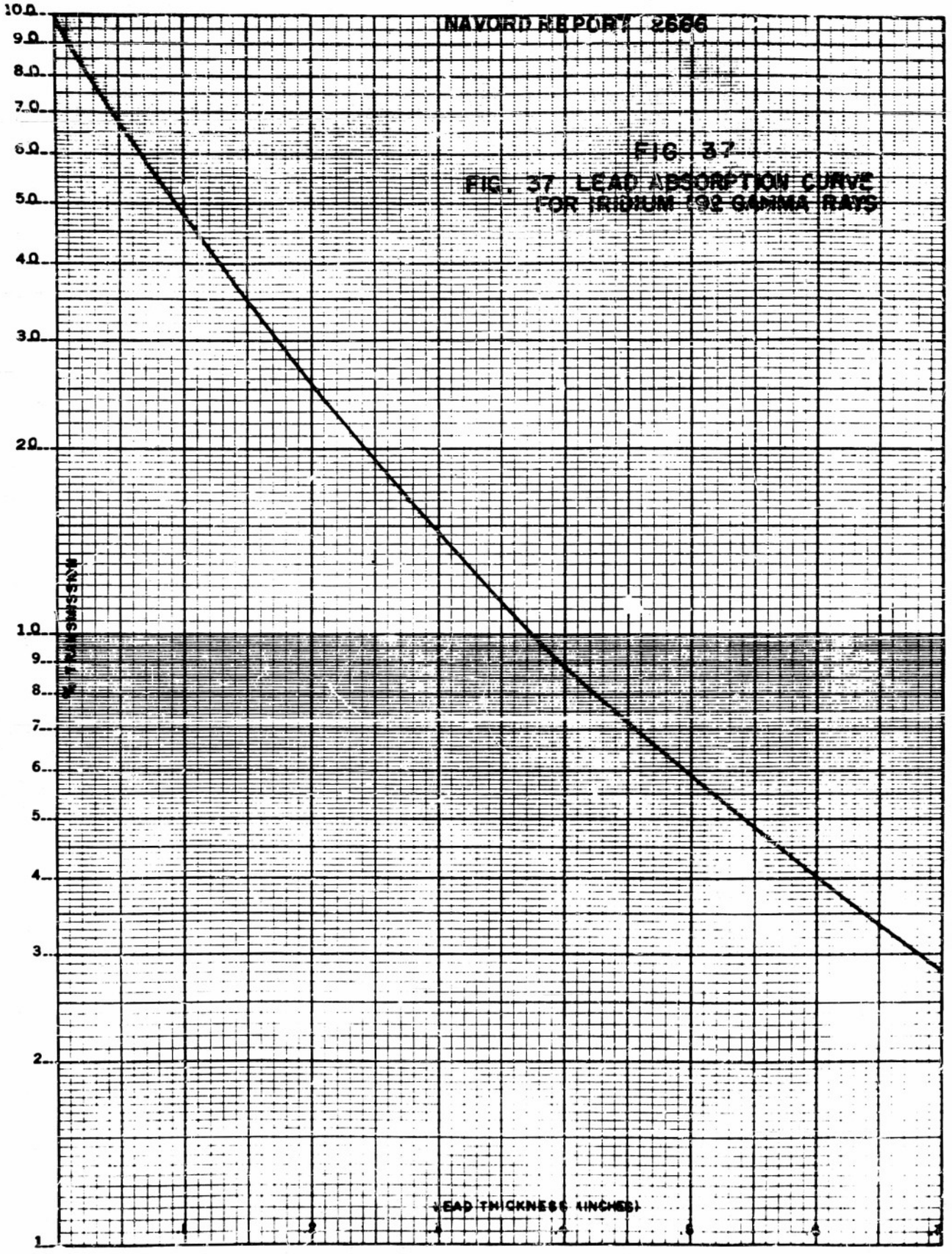


FIG 36
FOR RADIUM GAMMA RAYS
LEAD THICKNESS (CM)

FIG. 37

FIG. 37 LEAD ABSORPTION CURVE FOR IRIDIUM 192 GAMMA RAYS



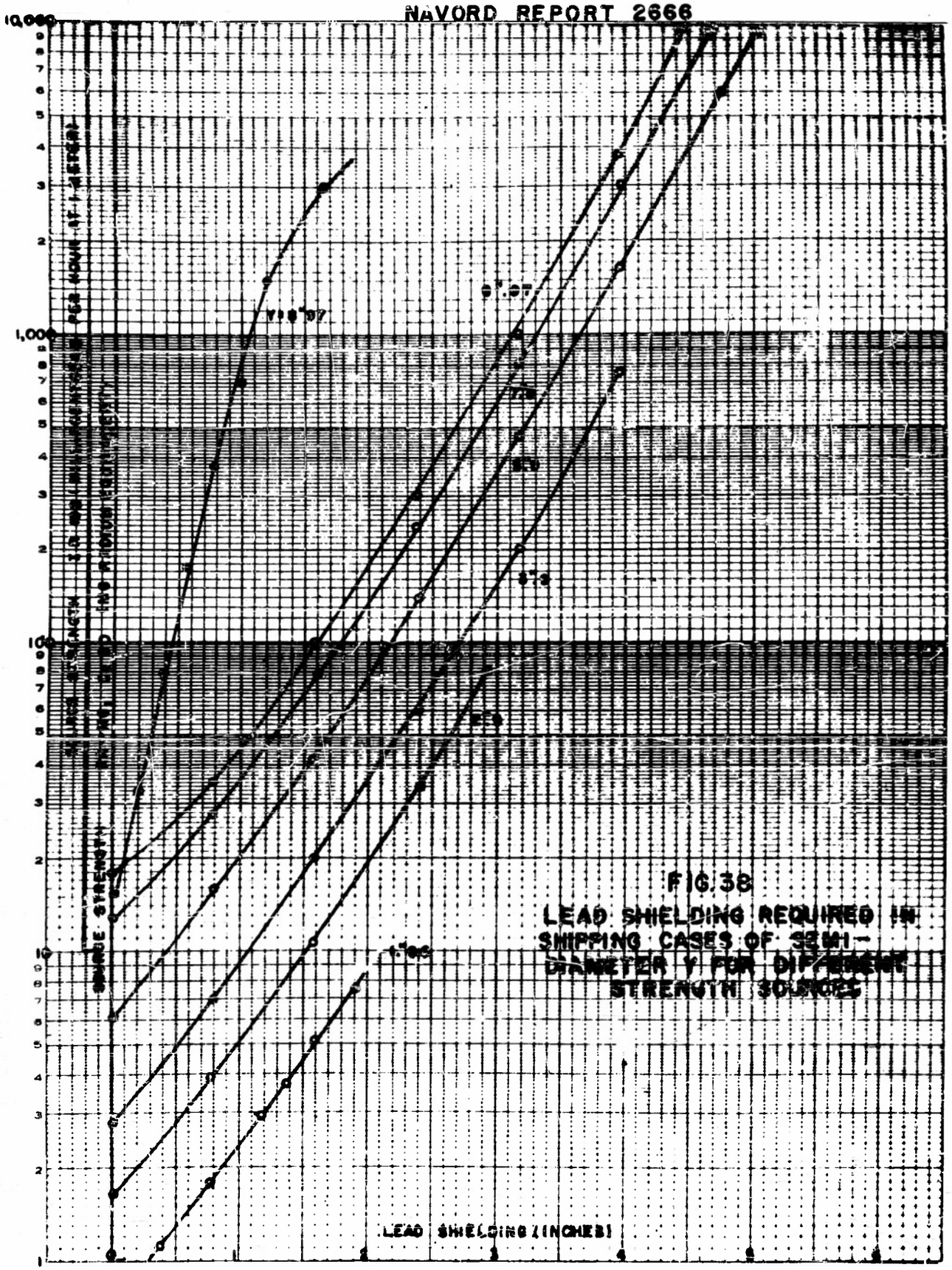


FIG. 38

LEAD SHIELDING REQUIRED IN SHIPPING CASES OF SEMI-DIAMETER Y FOR DIFFERENT STRENGTH SOURCES

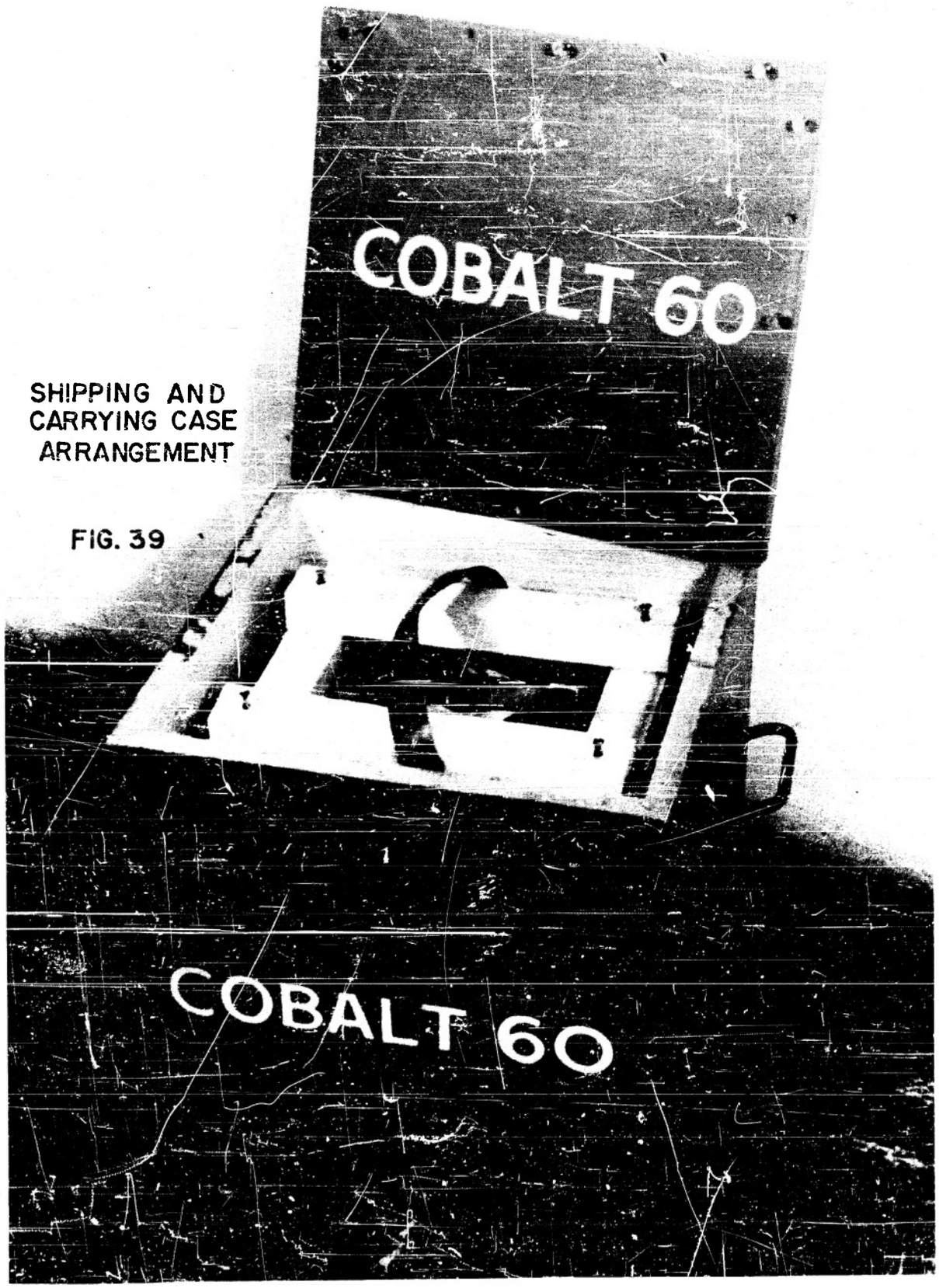


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FIG. 39

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