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FEASIBILITY STUDY FOR AN EARTH SIMULATING INFRARED SOURCE

by: Robert B. McIntosh
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Contract No. NAS 5-21049

December, 1969

Prepared by:

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For

The National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland 20771

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SECTION 1

ABSTRACT

A study was conducted to determine the feasibility of fabricating an infrared source for simulating earthshine radiation in a thermal-vacuum chamber. A circular array of sources is required to simulate both the spectral radiant emittance and the total energy exchanged between the earth and a test specimen.

A number of high temperature sources were investigated which use scatter filters to achieve spectral matching. This application of scatter filtering proved to be unfeasible when an attempt was made to incorporate a filter in a practical optical configuration.

Further study led to a more promising approach. A source is recommended which uses the emissive properties of heated, infrared-transmitting crystals and appears both technically feasible and economically practical. A source consisting of 70% Calcium Fluoride, 20% Magnesium Fluoride, and 10% Sapphire heated to 800°K will produce a source spectrum which lies within the tolerance band defined by the spectral radiances of black bodies operated at 250°K and 300°K in the wavelength region from 4 to 17 microns. In addition, the source's total radiant power output may be matched to the earth's over a range of earth temperatures between 250°K and 300°K by varying the number of sources in the simulator array.

SECTION 2

STUDY OBJECTIVE

The purpose of the study conducted by Barnes Engineering Company under Contract NAS5-21049 was to determine the feasibility of fabricating a special infrared source. The required source will be part of an array of sources to be placed in a 30 foot diameter thermal-vacuum chamber for simulating earthshine radiation on large test objects.

Three advantages of simulating earthshine by means of an array of sources are:

1. The radiation may be limited to the test specimen by field defining masks to avoid excessive radiative loading of the liquid nitrogen cooled thermal-vacuum chamber walls.

2. Changes in orbital altitude may be easily simulated by increasing or decreasing the number of sources on the circumference of the array.

3. Chamber wall area may be conserved for other purposes.

The sources are required to be operated at elevated temperatures and be spectrally filtered to produce a wavelength distribution of energy within the tolerance band defined by the spectral radiances of black bodies operated at 250°K and 350°K times a constant multiplying factor.

Because of the high absorption of spacecraft coatings and paints at long wavelengths, it is desirable that the source's radiant emittance be maintained specularly accurate as far out in the infrared as possible. A 50% spectral error in simulated earthshine at 15 microns might just be acceptable. Energy below 4 microns is undesirable.

The sources are also required to have a minimum field-of-view of 120°, a lambertian distribution, and accomodate interchangeable

field defining masks to limit radiated energy to only the test specimen.

The contract Statement of Work limits the active source area to 0.111 square feet and requires that each source emit 190 watts into 2π steradians before masking. To satisfy this requirement, a $250^{\circ}K$ source is required which has an apparent emissivity of 85.7. This specification has served as a design goal to the extent of both manufacturing and economic practicability.

An additional requirement not specified but implied is that the array of sources also simulate the total energy exchanged between the earth and a test object over all wavelengths.

SECTION 3
INTRODUCTION

The study consisted of two parts. The first part concerned itself with the investigation of the feasibility of using a low cost scatter filter to produce the required long wavelength filtering. This approach which was originally proposed, upon further investigation, did not prove practical due to its poor efficiency and contrast for wide field-of-view application.

The second part of the study was initiated when the scatter filter concept appeared unfeasible. A study was made of the spectral emissivity properties of common materials at elevated temperatures. It was recognized that the required source could be made by simply heating a material that had a low emissivity at short wavelengths and a high emissivity at wavelengths beyond 12 microns. A literature search was then made of the published spectral emissivity of metals, paints, and ceramics. During this search it was recognized that use could be made of a number of the infrared transmitting crystals. These crystals have low emissivities in the wavelength band where they transmit, and high emissivities at the long wavelengths where they absorb. It was further found that a very accurate spectral matching could be achieved by summing the spectral radiance emittance of several heated crystals each having slightly different long wavelength cutoffs and by varying the amount of exposed surface area of each crystal.

To produce an infrared source with a spectral distribution of a 250°K blackbody having a spectral radiant emittance greater than that of a 250°K blackbody, it is necessary to heat the source to a temperature higher than 250°K and then filter it to produce the required 250°K distribution. The apparent emissivity of such a source would be greater than unity.

A plot of the ratio of blackbody spectral radiance, for several blackbody temperatures, to the spectral radiance of a 250°K blackbody vs wavelength is found in Figure 1.

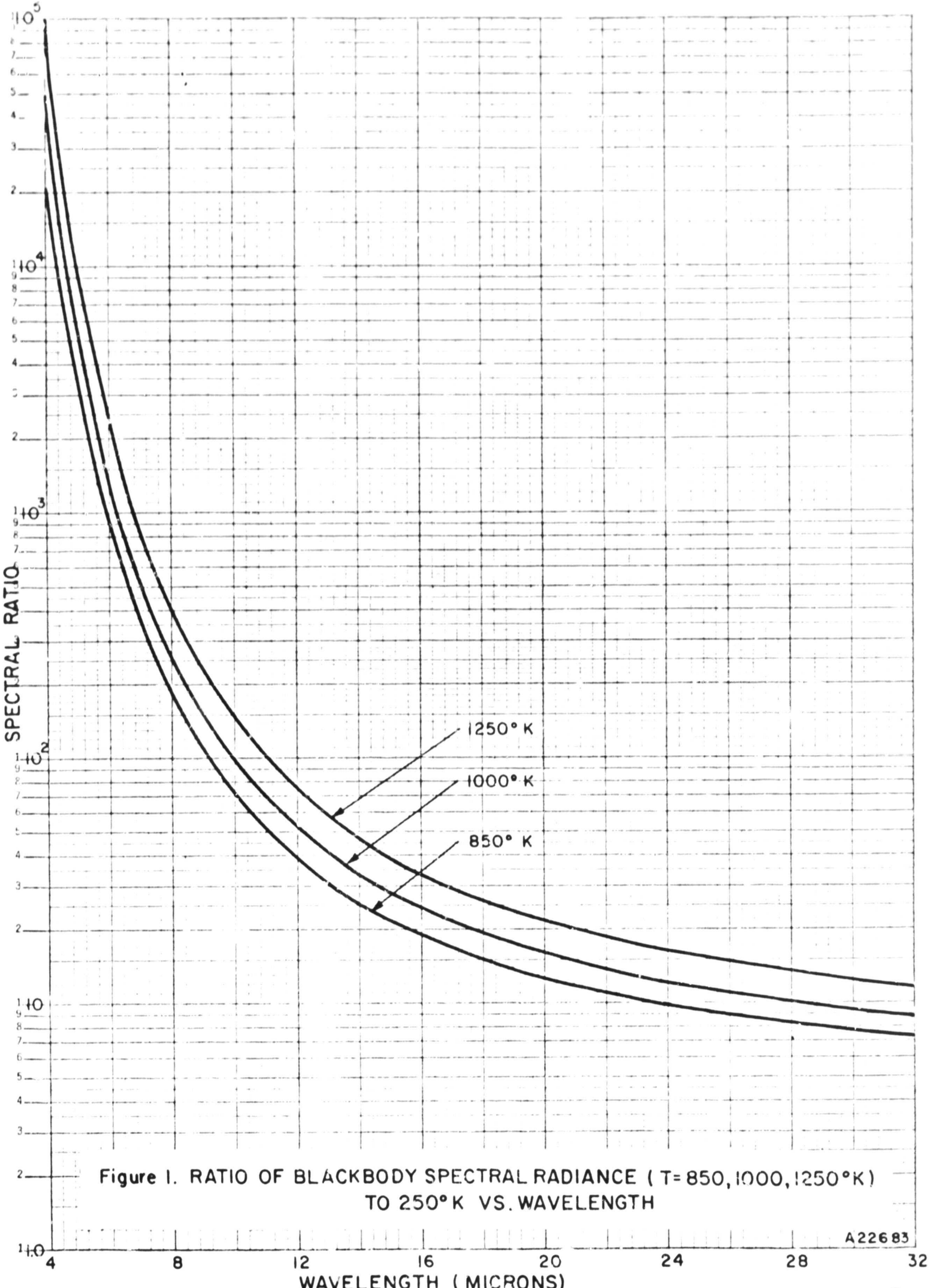

Figure 1. RATIO OF BLACKBODY SPECTRAL RADIANCE (T= 850, 1000, 1250°K) TO 250°K VS. WAVELENGTH

The ratios plotted represent the maximum effective spectral emissivity or radiance multiplier vs wavelength achievable for several source operating temperatures. Because blackbody spectral radiance at long wavelengths is proportional to temperature, the requirement of having a high effective emissivity source restricts spectral matching at long wavelengths for practical source temperatures.

Figure 2 is a plot of the error in projected specular radiance vs wavelength for a 1000°K source and for several chosen values of effective source emissivity. For example, if an effective emissivity of 48.6 is required from a 1000°K source, a 50% emissivity or specular radiance error will exist at 16 microns. Assuming ideal filtering, the source will have a spectral emissivity of exactly 48.6 at all wavelengths below 12.3 microns. The ideal filter in this example would have a high attenuation between 0 and 4 microns, and a steadily increasing output from 4 microns to 100% at 12.3 microns.

In addition to spectrally matching the array of high temperature blackbody sources, it is also necessary to simulate the total radiant power of the earth over all wavelengths. It should be noted that a flat disc at earth temperature may be used to simulate the radiation exchange between an orbiting vehicle and the earth in a thermal-vacuum chamber. For a given orbital altitude simulation, it is only required that the earth temperature disc subtend the same solid angle with the test object as that solid angle subtended by the earth when viewed from orbit.

When an array of sources are used to simulate earthshine, the total simulator radiant power output can be controlled by varying the density of sources or by their individual active areas.

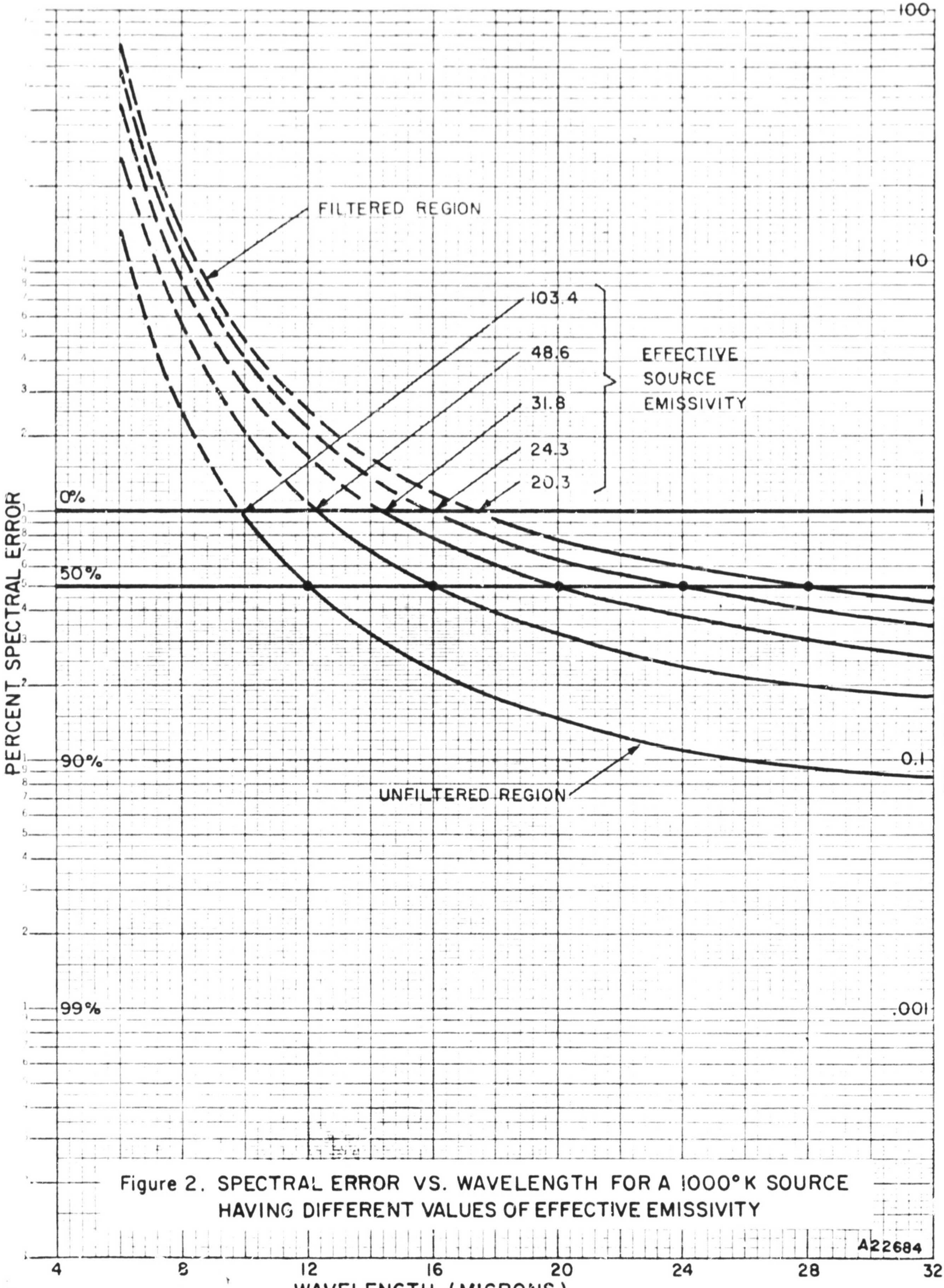

Figure 2. SPECTRAL ERROR VS. WAVELENGTH FOR A 1000° K SOURCE HAVING DIFFERENT VALUES OF EFFECTIVE EMISSIVITY

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To insure a proper energy balance, the integrated-filtered radiant output of the sources times the sum of their total active areas must equal the radiant output of an earth simulating disc times its area required for a given altitude simulation. This balance may be expressed as:

$$\pi A_S \int_0^\infty R(\lambda_1 T)\,\tau(\lambda)\,d\lambda = A_E \sigma T_E^4$$

where: A_S = sum of active source area

A_E = area of earth simulating disc

$R(\lambda_1 T)$ = spectral radiance of sources operated at temperature T

$\tau(\lambda)$ = filter transmission or output

σ = Boltzmann's constant

T_E = earth temperature

SECTION 4

SOURCES USING SCATTER FILTERS

The first part of the study concerned itself with the feasibility of producing a spectrally filtered high temperature source by means of scatter filters. A scatter filter is essentially a uniformly roughened reflective surface. The specular reflectance of rough surfaces has been found to be an increasing function of wavelength which closely approximates the required spectral filtering. The wavelength region at which the crossover from low to high specular reflectance occurs is a function of the surface roughness. The specular reflectance of rough surfaces has been described in detail by H. E. Bennet and J. O. Porter, Journal of the Optical Society of America, Volume 51 #2, February, 1961.

To determine the feasibility of shaping the spectral emission of a high temperature source, four areas were studied:

1. The actual performance of several practical rough surfaces to determine their feasibility as reflective infrared filters.

2. The ability to produce a large area, high emissivity source which could be operated at temperatures in excess of 1000°K.

3. The availability of a reflective optical system which could incorporate a scatter filter and project the filtered output of the large area source into a 120° cone.

4. The overall efficiency of the source.

Scatter Filters

The required reflective, scatter filter must have a uniform surface roughness which can accurately be reproduced and have the ability to be used as an optical element, such as a rough-surfaced elliptical mirror. Both these requirements can be met by producing rough-surfaced reflecting optical elements by electroforming. In this process, a mandrel is machined and uniformly

roughened to serve as a pattern upon which nickel is electrochemically deposited. Using this process, a large quantity of identical parts can be produced economically.

Garr Precision Products has been manufacturing for several years, a nickel electro-formed micro-finish comparator gauge. This gauge accurately reproduces surface finishes from 2 micro inches rms to 1000 micro inches rms. It was found that a surface roughness in the range of 16 to 32 micro inches is required to produce the desired filter function.

A micro-finish comparator gauge was purchased from Garr Precision for direct measurement of the specular reflection as a function of wavelength.

Figure 3 is a plot of the measured specular reflectance of 16, 24, and 32 micro inch rms nickel surfaces. A first surface aluminum mirror was also measured as a reference standard. These measurements show relatively poor contrast if the filter's contrast is defined as the ratio of long to short wavelength specular reflectance.

In an attempt to increase the filter's contrast, gold was evaporated on the three nickel surfaces. The specular reflectance of the surfaces was again measured and the results are shown in Figure 4. The evaporated gold was found to increase the specular reflectance at all wavelengths between 2 and 15 microns while only slightly increasing the filter's contrast.

Another attempt was then made to improve filter contrast. The surface irregularities of ground glass have a greater rms slope than ground metal surfaces. The greater rms slope was found by H. E. Bennet to yield lower reflectance at short wavelengths and therefore greater contrast.

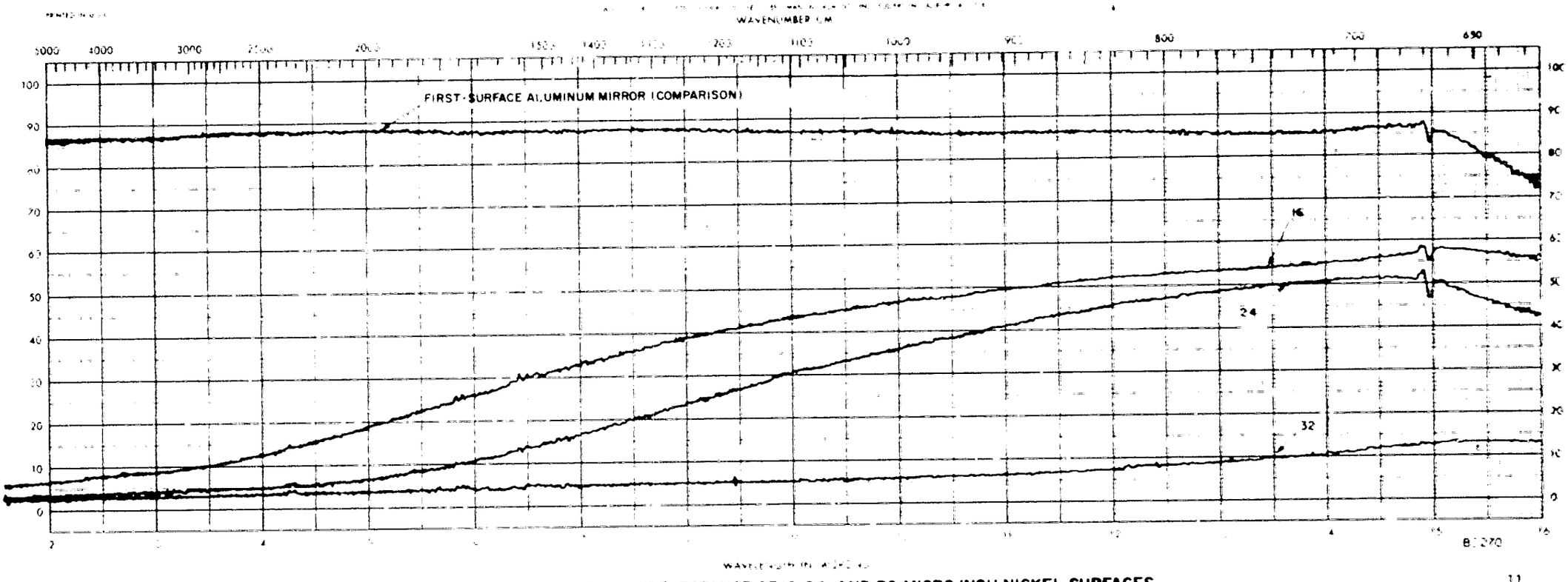

Figure 3. SPECULAR REFLECTANCE OF 16, 24, AND 32 MICRO INCH NICKEL SURFACES

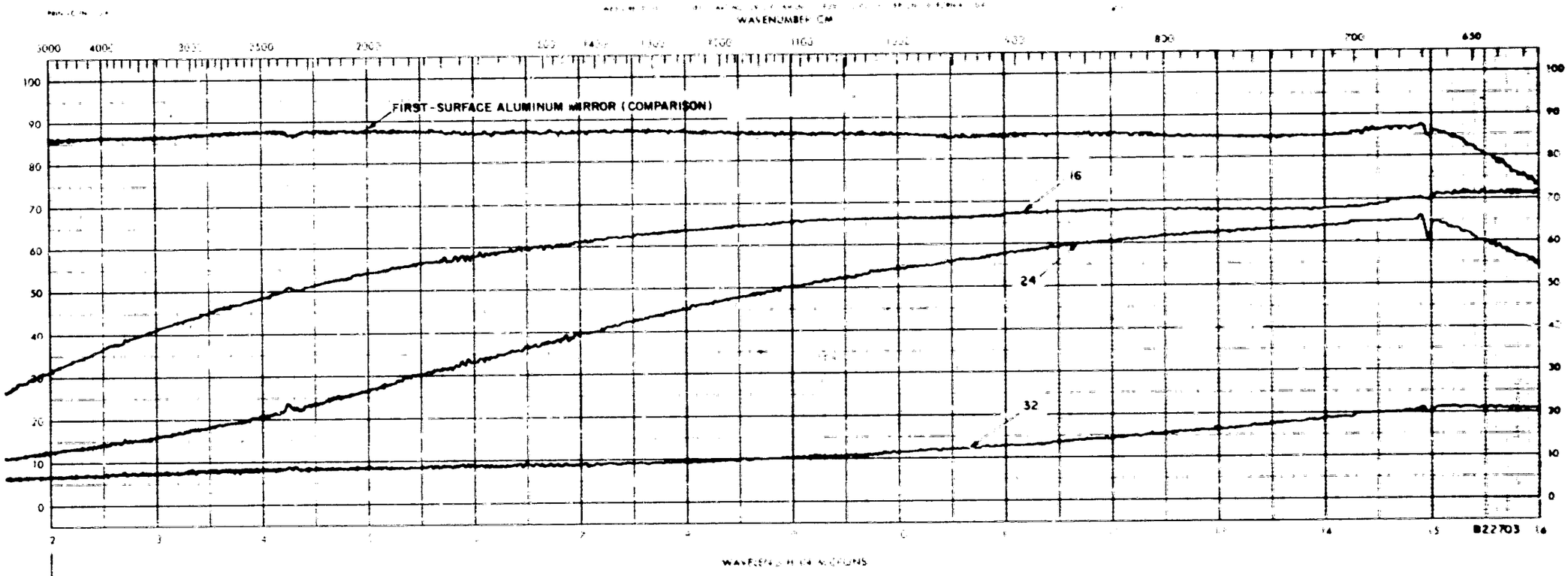

Figure 4. SPECULAR REFLECTANCE OF 16, 24, AND 32 MICRON INCH-GOLD-PLATED NICKEL SURFACES

Five graded samples of ground glass surfaces were prepared using different polishing grits. It was observed that very uniform surface roughness could be prepared using any particular grade of grit. Gold was then evaporated onto the ground glass surfaces. Figure 5 and 6 shows the results of specular reflectance measurements of a number of the prepared surfaces. The long to short wavelength reflectance contrast has been improved with the short wavelength reflectance reduced to less than 5%. The contrast between short and long wavelength reflection for evaporated gold on ground glass is believed to be about the best obtainable for simple scatter filters.

The extension of this filtering principle to ruled reflection or transmission diffraction gratings was not considered practical either on the basis of cost, or ease in incorporation in an optical system.

High Temperature Radiators

In order to build a source having a high effective emissivity using a scatter filter, it is necessary to heat a large-area, high-emissivity, radiator to temperatures on the order of 1000°K. Two materials were studied for their possible application as heater elements - carbon and silicon carbide. Carbon was chosen as the preferable material because of its ease of machining and because it has previously been successfully used by Barnes in the manufacture of high temperature blackbodies. The carbon heating element recommended would consist of a 2 to 4 inch disc with a spiral pattern machined into it. The spiral pattern increases the resistance of the element, improves its uniformity, and aids in electrode attachment.

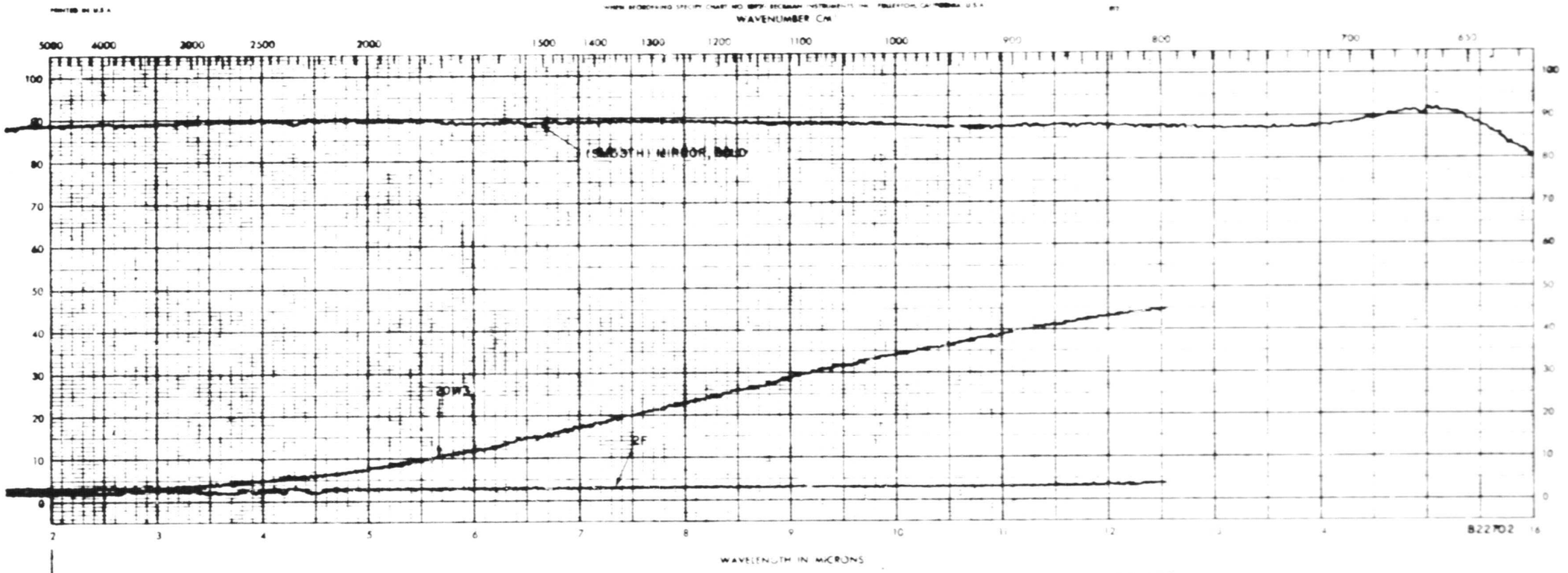

Figure 5. SPECULAR REFLECTANCE OF EVAPORATED GOLD ON TWO GROUND GLASS SURFACES PRODUCED BY 20W3 AND 2F OPTICAL POLISHING GRITS

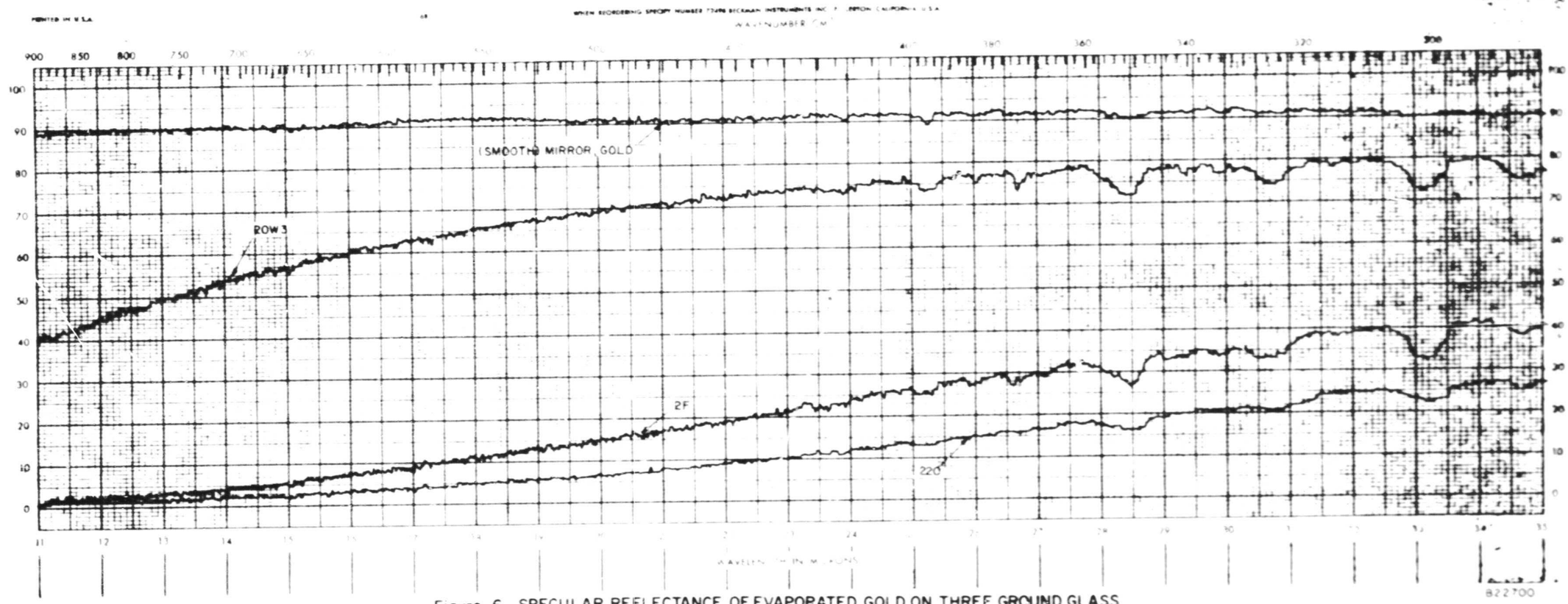

Figure 6. SPECULAR REFLECTANCE OF EVAPORATED GOLD ON THREE GROUND GLASS SURFACES PRODUCED BY 20W3, 2F, AND 220 OPTICAL POLISHING GRITS

Optical Configurations

The scatter filter operates by reflection. It must be used as a reflective optical element. A number of optical configurations were studied in an attempt to find a method to project the filtered radiation into a 120° cone.

The first configuration studied was an ellipsoidal mirror which reimaged the carbon heating element at a field stop. This configuration is shown in Figure 7.

In the ellipsoid, rays emerging from the heater placed at one focus F_1 are reflected toward the second focus F_2 without spherical aberration. The ellipsoid when used as a scatter filter has the desirable property that rays reflected off the roughened surface, that pass through the field stop, strike the mirror at angles close to normal. This property prevents the loss of filter contrast and shifts in long wavelength reflection at large angles of incidence. Maximum filter contrast will be maintained, if the angle of incidence is held within $\pm 15^{\circ}$ of normal.

It is essential that the image and field stop have the smallest possible size. This requirement arises from the fact that for a large field stop, large quantities of unwanted scattered radiation will be projected from the source. In Figure 6, the axial ray A strikes the rough surface of the ellipsoidal mirror at p. The mirror at point p scatters short wavelength radiation over wide angles while reflecting the long wavelength radiation along A'.

It should be noted that the field stop diameter is determined by the magnification of the system. A minimum magnification of

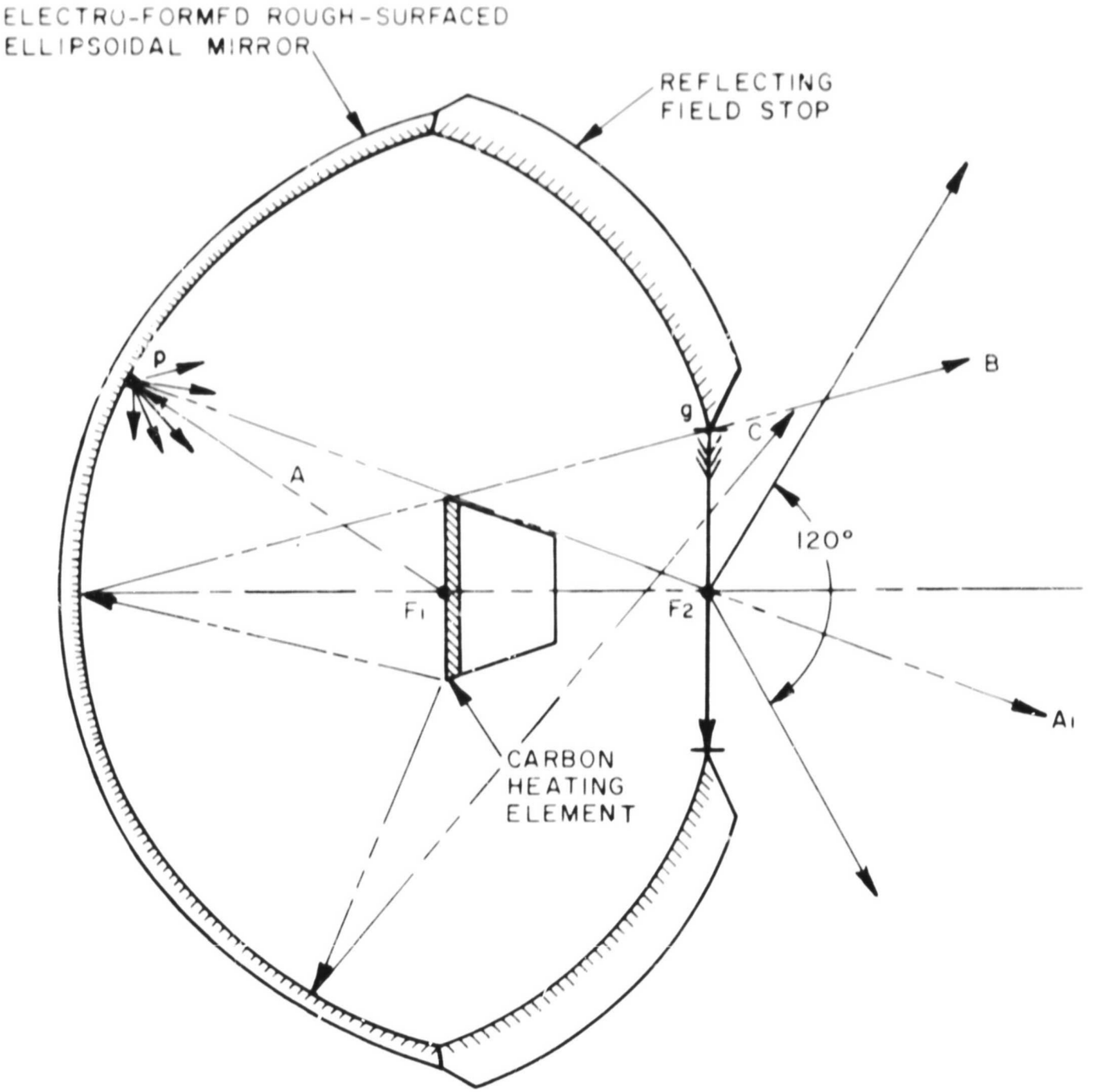

Figure 7. 120° FOV INFRARED SOURCE USING ROUGH SURFACED ELLIPSOIDAL MIRROR

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unity for this configuration would require that the ellipsoid become a sphere with the field stop at the same location as the heater. This would, unfortunately, produce 100% obscuration of the desired energy. The optical magnification must be chosen to both minimize obscuration and the projection of scattered radiation. The ellipsoid constructed in Figure 7 has a magnification of 1.7 and is the ellipsoid having the maximum eccentricity which just accommodates a 120° projection field-of-view. The chief ray B in Figure 7, which passes through the focal plane at point g, determines the image size and stop diameter. Ray C which does not pass through point g demonstrates the large coma associated with ellipsoidal mirror resulting from extended objects. However, this aberration has the characteristic that all rays pass within the field stop. The principle effect of coma is, therefore, to produce a non-uniform image which is brightest in its center. This in itself will not prevent the system from being lambertian.

The large obscuration and acceptance angle for scattered radiation, however, do present a severe limitation to the distribution and specular matching of the earth by this source configuration.

A number of other optical configurations were studied for possible application with scatter filters. These included a conical reflector surrounded by a cylindrical heater, a cylindrical rod heater mounted inside a hollow cone, and a spherical mirror with an off axis heater element. All these alternate optical configurations either project more scattered radiation or had greater obscuration that the ellipsoidal system previously described.

In addition to the above mentioned problems, all sources using a scatter filter have very poor efficiencies because of the large amounts of scattered short wavelength energy. A portion of this energy may be recollected by the heater saving heater power but a sufficient portion will be lost by mirror and field stop absorption.

At this point in the study it was recognized that alternate approaches for fabricating a source should be explored. Attention was turned to the possibility of directly utilizing the emissivity of known materials to achieve the required spectral matching.

SECTION 5

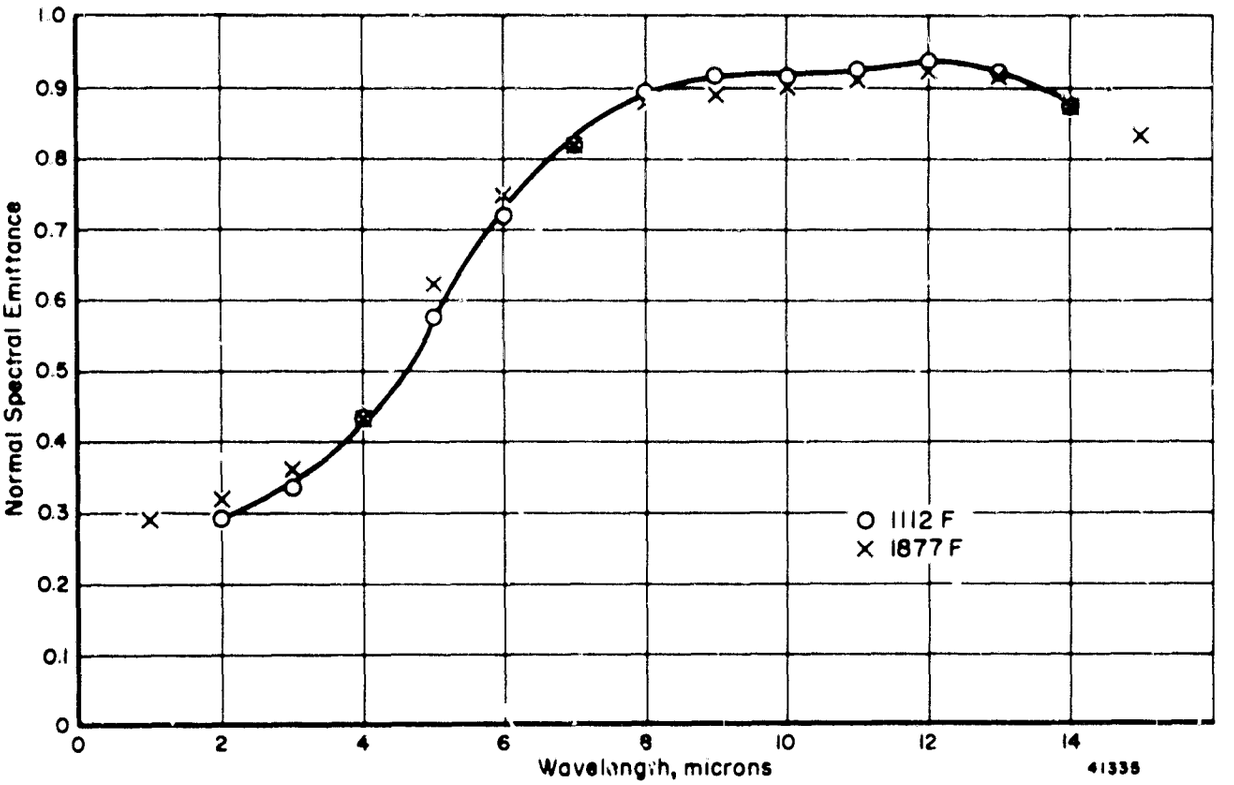
DIRECTLY HEATED SOURCES

As the problems associated with the scatter filter method of shaping spectral distribution of a high temperature heating element became apparent, a search was made for alternate approaches to solving the problem. One alternate approach was to use a heated disc of material having the proper spectral emissivity, to directly produce the required spectral matching.

Published data is available showing the emissivity variation with wavelength of a great number of materials. In general terms, the ideal material would have a low emissivity at wavelengths shorter than 4μ, an increasing emissivity from 4 - 12 microns, and a peak at 12μ and beyond.

The first group of materials examined were opaque materials which are reflective at short wavelengths and emissive at longer wavelengths. Included in this group of materials are special paints, ceramics and flame sprayed ceramic coatings. Curves of the specular emissivity of several materials whose emissivity increases with wavelength are shown in Figures 8, 9 and 10.

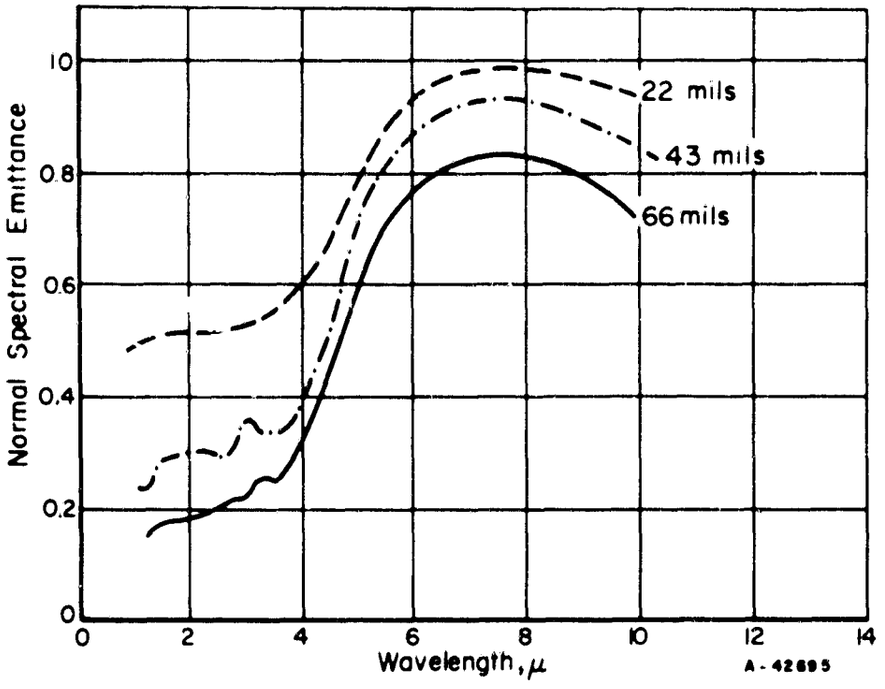
To evaluate materials for directly heated sources, two short computer programs were generated. The first program calculated the ratio of $W_\lambda(250^\circ K)/W_\lambda(T)$, the spectral radiant emittance of a $250^\circ K$ blackbody divided by the spectral radiant emittance from a blackbody at temperature T, for a given value of T over a given range of λ. For a specific source temperature, this program allowed the calculation of the required spectral emissivity as a function of wavelength for proper spectral matching.



NORMAL SPECTRAL EMITTANCE OF ZIRCONIUM OXIDE

Reference	Investigator	Symbol	Composition and Surface Condition	Test Method	Remarks
3	Blau, Marsh, Martin, Jasperse, and Chaffee		Zirconia (ZrO_2) Norton RZ 5601 Purity: 92% ZrO_2, 4.5% CaO Surface condition not given	Normal spectral emittance. Specimen mounted in wall of cylindrical Globar (SiC) heater. Comparison blackbody hole in heater wall. Monochromator and thermocouple detector. Temperatures measured with thermocouples.	Measured in air. Data taken from curves. (Curves drawn through 1112 F points only.)
		O	Measured at 1112 F		
		×	Measured at 1877 F		

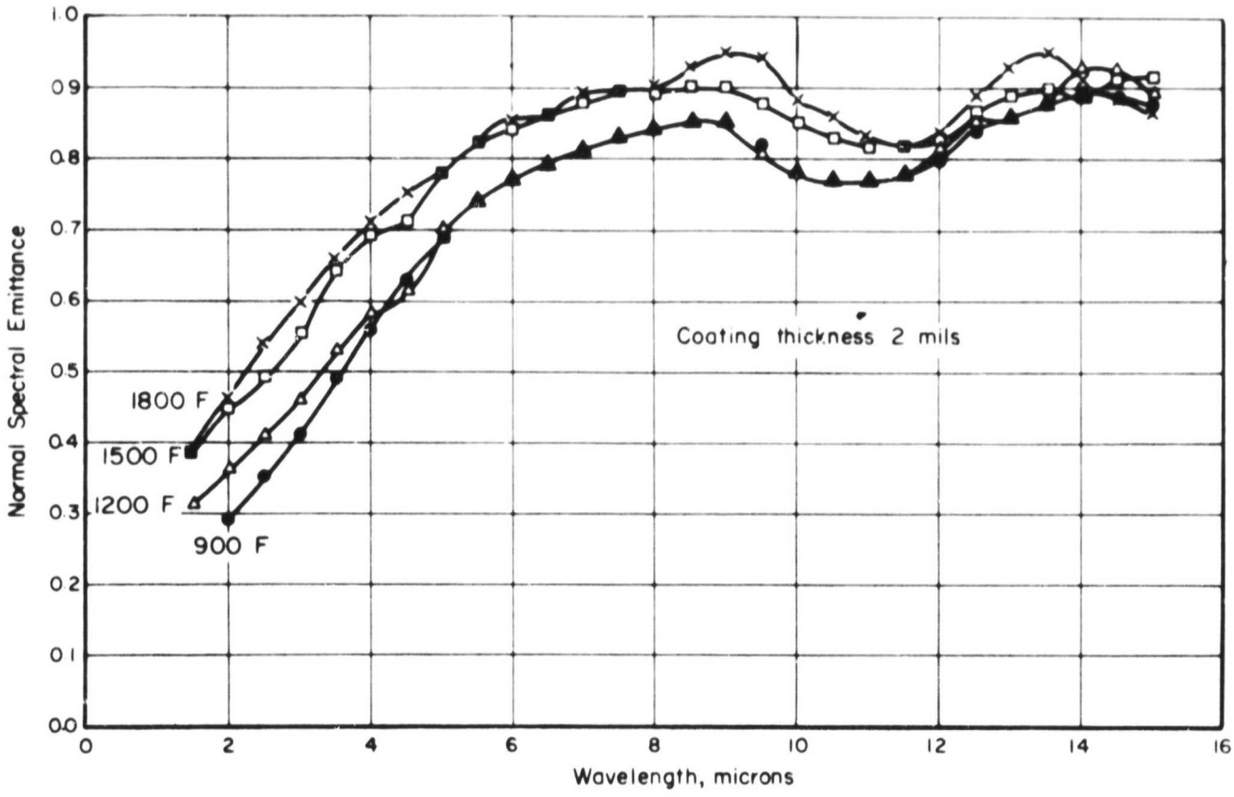
Figure 8



NORMAL SPECTRAL EMITTANCE OF ROKIDE A ON INCONEL X AT 1600° F

Reference	Investigator	Symbol	Composition and Surface Condition	Test Method	Remarks
13	Gravina and Katz		Norton Rokide A, white 93.5 per cent alumina. Melting point about 3600 F. Porosity about 4 to 8 per cent. Flame sprayed on degreased, grit-blasted surface coated with 12-mil-thick Nichrome V undercoat. Coating thickness: 66 mils 43 mils 22 mils	Normal total emittance. Resistance-heated strip specimen. Thermistor-bolometer detector. Reference blackbody. Temperatures measured with thermocouples.	Measured in air. Data taken from curves.

Figure 9



NORMAL SPECTRAL EMITTANCE OF A-418 ENAMEL ON TYPE 321 STAINLESS STEEL

eference	Investigator	Symbol	Composition and Surface Condition	Test Method	Remarks
2	Richmond and Stewart		A-418 consists of alkali-free barium beryllium silicate frit with addition of chromic oxide. Coating thickness 2 mils. Coated on Inconel. Runs made at the following temperatures:	Normal spectral emittance. Double-beam infrared spectrometer with sodium chloride prism. Secondary standard [silicon carbide (Globar)] calibrated against laboratory blackbody. Temperatures measured with thermocouples.	Measured in air. Data taken from table.
		●	900 F		
		△	1200 F		
		□	1500 F		
		×	1800 F		

Figure 10

The results of a typical calculation are shown in Figure 11, a plot of the spectral emissivity of 1000°K blackbody required to match the spectrum of a 250°K source. This curve has been normalized to 20 microns. An attempt to improve spectral match at long wavelengths very rapidly reduces the effective source emissivity (radiance multiplier) and total power output.

The second program, when given emissivity values as a function of wavelength and of temperature of a particular material, calculated both the spectral radiant emittance and the total integrated radiant emittance over all wavelengths. After a material or a group of materials was chosen, the calculated radiant emittance versus wavelength was plotted.

At this point it should be noted that a 250°K blackbody emits less than 0.04% of its total power at wavelengths shorter than 4 microns. This power can be considered negligible for the purposes of simulation, therefore, accurate spectral matching below 4 microns is not necessary. The significant requirement is that the total radiant power in this region be negligible when compared to the total simulator output. As an example, the spectral radiant emittance was calculated for a typical member of the ceramic group, zerconium oxide, at 1000°K using the emissivity data in Figure 8. The results of this calculation shows that about 40% of the radiant output is emitted in the spectral region from 1 to 4 microns.

Examination of the results of this and similar calculations, indicated that at source temperatures necessary to produce a reasonably high effective emissivity, the attenuation necessary in the short wavelength region was much greater than that achievable by the low emissivities of materials examined up to this point.

It was found that a 1000°K source is required to have an emissivity of 1 percent in the 1 to 4 micron region in order to

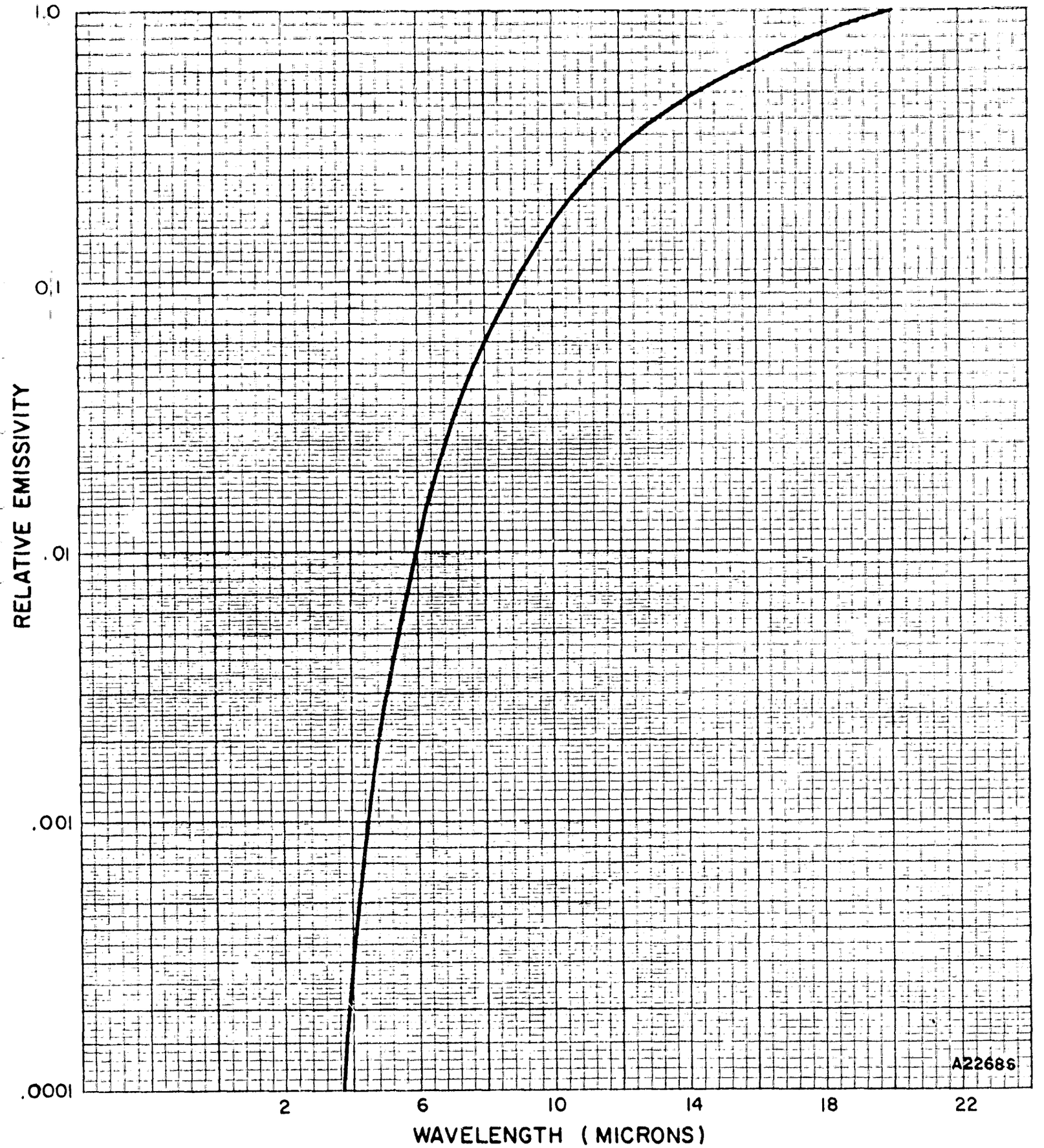


Figure 11. THE SPECTRAL EMISSIVITY OF A 1000°K SOURCE REQUIRED TO MATCH A 250°K BLACKBODY

limit the radiant emission in this region to 5 percent of the total spectrally matched radiant output. A 1400°K source having an emissivity of 1 percent in the 1 - 4 micron region will emit approximately 15 percent in this region. These examples demonstrate the very rapid increase in short wavelength radiated power with temperature.

In addition to excessive energy in the 1 to 4 micron, all the members of the ceramic group change from low to high emissivity at too short a wavelength to provide good simulation of a 250° to 350°K earth.

For opaque materials, only metals exhibit low emissivities (less than .05) in the 1 to 4 micron region. This is a result of their high reflectivity in this region. Unfortunately, most metals become more highly reflective at longer wavelengths.

The results of the above considerations led to the rejection of directly heated opaque materials or coatings for accurate earthshine simulation. A more promising possibility was uncovered upon examination of a number of infrared transmitting materials.

Sources Using Heated Infrared Transmitting Materials

The next step taken in the search for directly heated material which could be used for sources was to consider infrared transmitting materials.

For infrared transmitting materials, the relation between their reflectivity, absorption and transmission is:

$$\rho(\lambda) + \alpha(\lambda) + \tau(\lambda) = 1$$

where: $\rho(\lambda)$ = specular reflectivity

$\alpha(\lambda)$ = specular absorption

$\tau(\lambda)$ = specular transmission

Since the absorption of a material is equivalent to the materials emissivity $\epsilon(\lambda) = 1 - \rho(\lambda) - \tau(\lambda)$

The above equations show that in the region where a material transmits, absorption is low and transmission is limited only by reflection losses. For this condition the material's emissivity will be low. It also follows that in an infrared transmitting material's region of transmission cutoff the emissivity will approach unity.

Examination of infrared transmitting crystals indicated that a number of crystals exhibited the emissivity properties required. The material which appeared to have the best combination of desired physical and optical properties was Calcium Fluoride. Figure 12 is a plot of the spectral radiant emittance of a 2mm thick piece of Calcium Fluoride heated to 1400°K. Also plotted for comparison is the spectral radiant emittance of a 250°K blackbody. Both curves are normalized to their peak amplitude. 1400°K was chosen as the upper limit to which it would be possible to heat Calcium Fluoride. It will be noticed that both curves peak at about the same wavelength, but Calcium Fluoride falls off more rapidly at both longer and shorter wavelengths.

The long-wavelength mismatch cannot be improved since beyond 13 microns Calcium Fluoride is completely opaque and has an emissivity close to unity. At short wavelengths it is possible to make improvements by utilizing the property that Calcium Fluoride's long-wavelength absorption cutoff is a function of its thickness (see Figure 13). If in addition to the 2mm element of Calcium Fluoride a thicker piece is heated, an additional contribution will be made to the short-wavelength radiated power. Figure 14 shows the spectral radiant emittance of a 1400°K source consisting of an element of 2mm thick Calcium Fluoride making up 80% of the source's surface area and a 50mm thick element making up the remaining 20% of the surface area. As can be seen, the match has been greatly improved in the region between 8 and 11

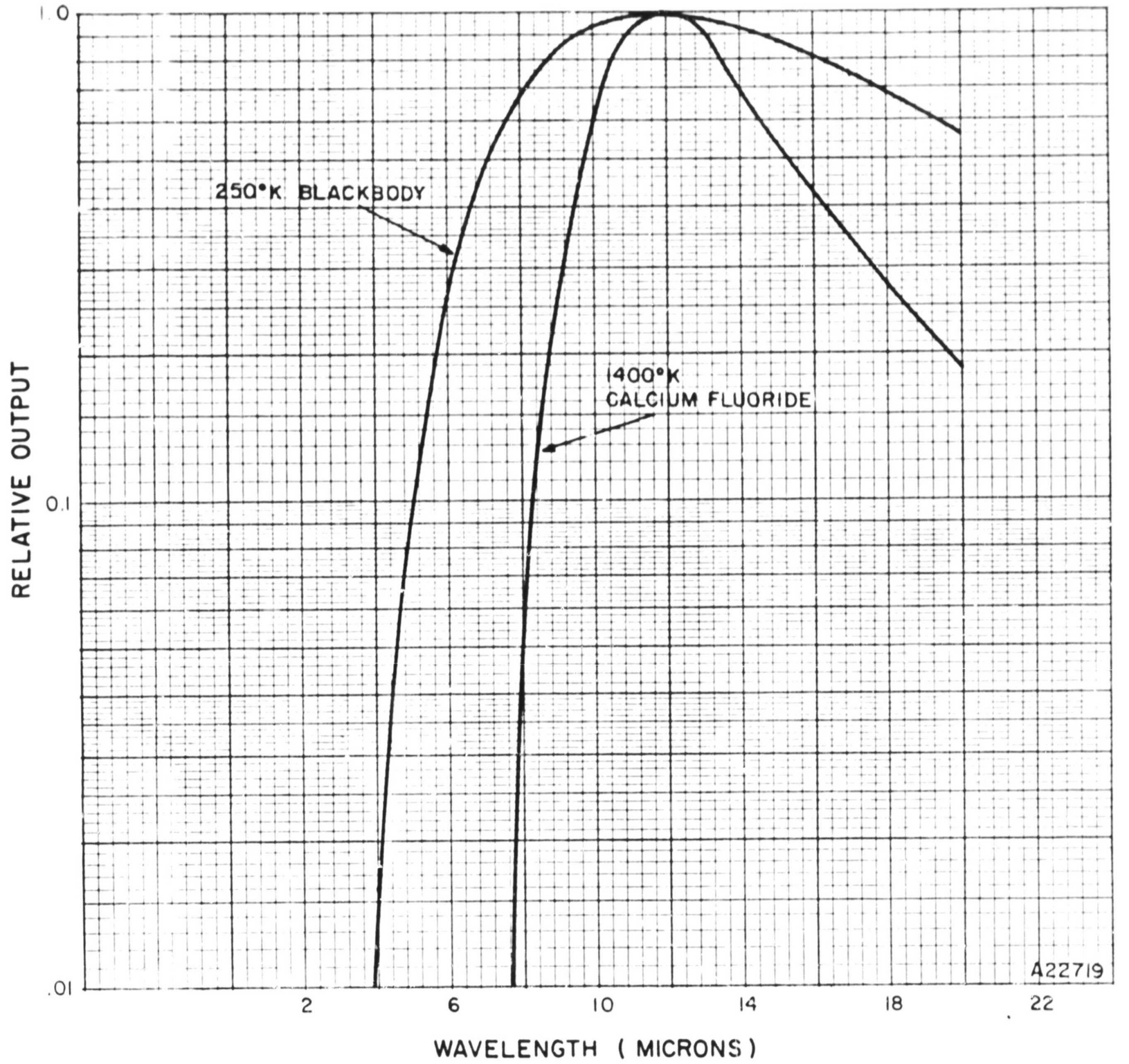
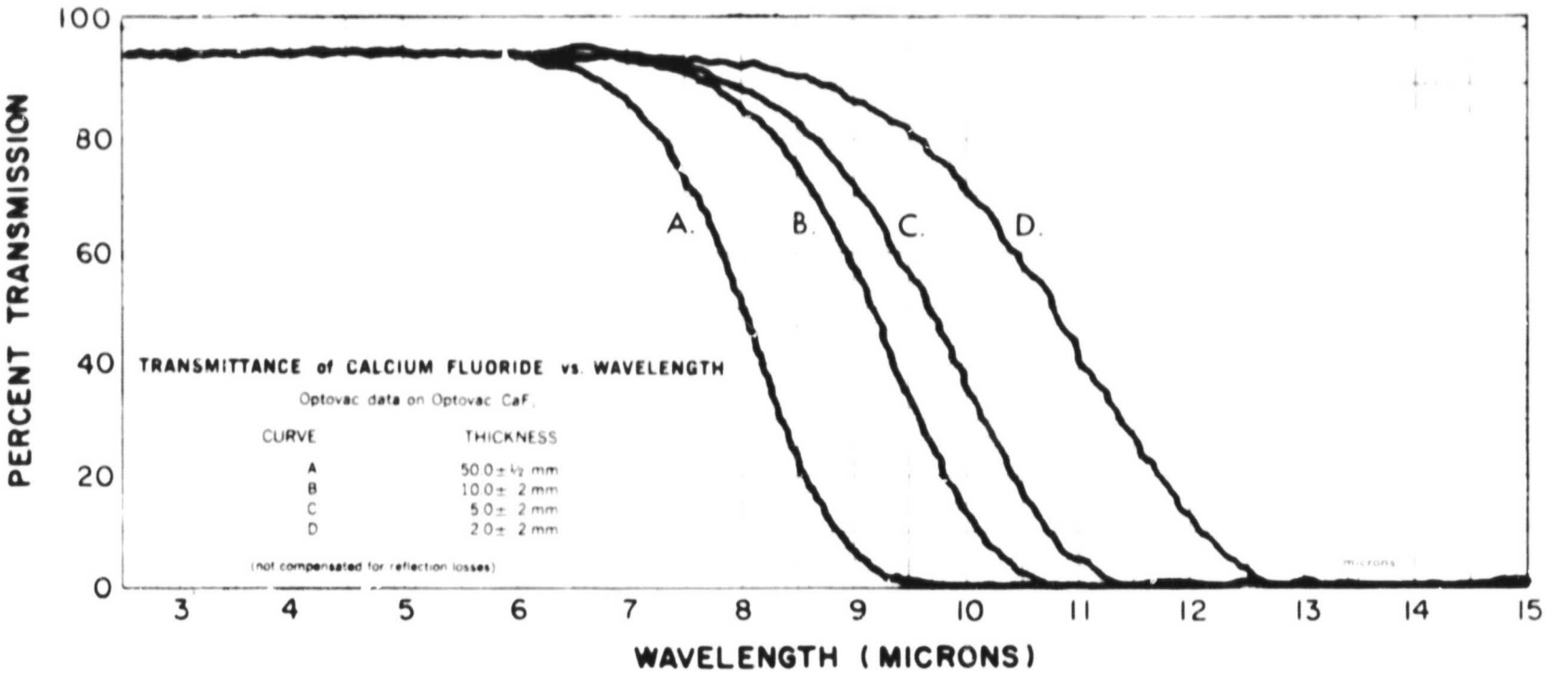


Figure 12. THE SPECTRAL RADIANT EMITTANCE OF A 1400°K CALCIUM FLUORIDE (2 MM THICK) SOURCE AND A 250°K BLACKBODY



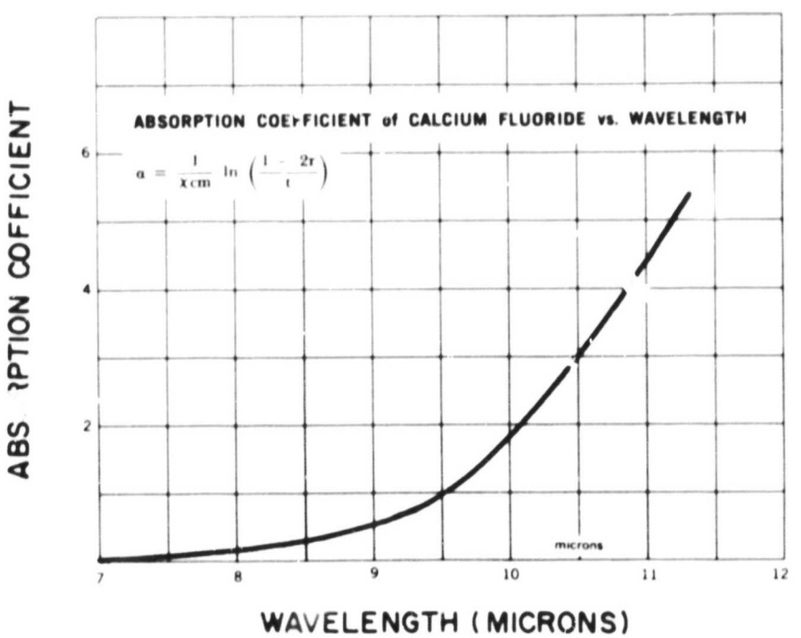


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Figure 13. OPTICAL PROPERTIES CALCIUM FLUORIDE

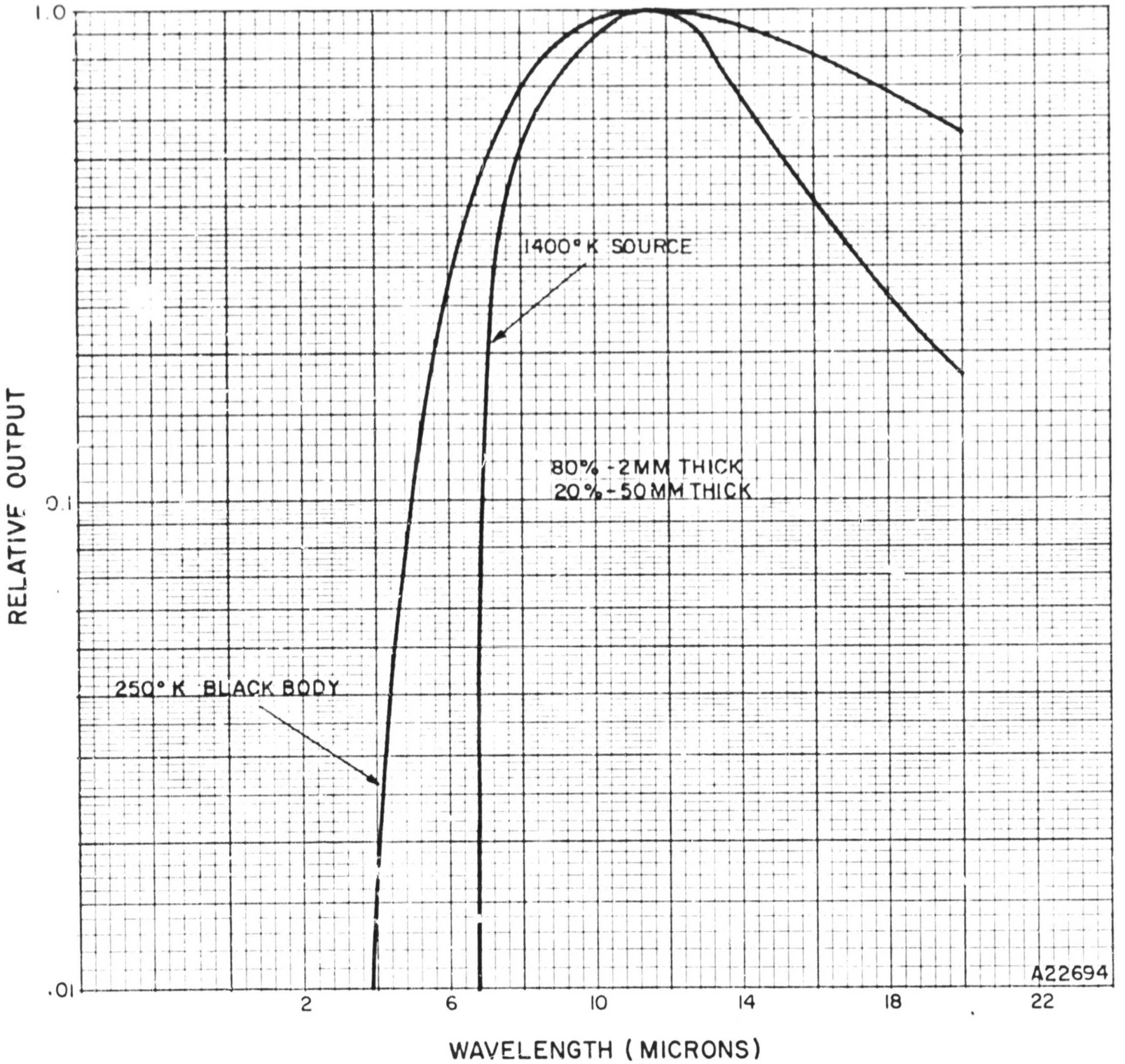

Figure 14. THE SPECTRAL RADIANT EMITTANCE OF A TWO-ELEMENT, 1400°K CALCIUM FLUORIDE SOURCE AND A 250°K BLACK BODY

microns, but is still poor between 4 and 7 microns. The fact that there is virtually no energy between 4 and 6 microns is due to the high transmission of the Calcium Fluoride in this region.

It is possible to further improve the spectral match between 4 and 7 microns if a third element is employed, made from a material having a lower long-wavelength cutoff such as Sapphire.

Figure 15 is a plot of the spectral radiant emittance of a 1400°K source whose surface area consists of 75% of 2mm thick Calcium Fluoride, 20% of 50mm thick Calcium Fluoride, and 5% of 1.5mm thick Sapphire. This three-element source makes a good spectral match at short wavelengths to a 250°K blackbody. This same output is plotted in a slightly different manner in Figure 16.

In Figure 16 the spectral radiant emittance of this 1400°K source is compared to that of 250°K and a 350°K blackbody. The sources output from 4 to 20 microns falls between the 250°K and 350°K blackbody curves. In this region the total radiant emittance of this source is 55 times greater than that of a 250°K blackbody of equal area.

While the source operating temperature in the above example appears to be optimistically high, this technique of producing an earth simulating source is far more promising than any of the alternate approaches studied. By choosing the proper material and a practical operating temperature, it should be possible to produce a source which approximates the output of the earth between the limits of 250° and 350°K with total radiant power output substantially greater than a source at earth temperature.

This type of source has a major advantage over methods using filters and a uniform high emissivity emitter to produce a similar output. The efficiency of a uniform source which is filtered to produce the required spectral content is very low. For example,

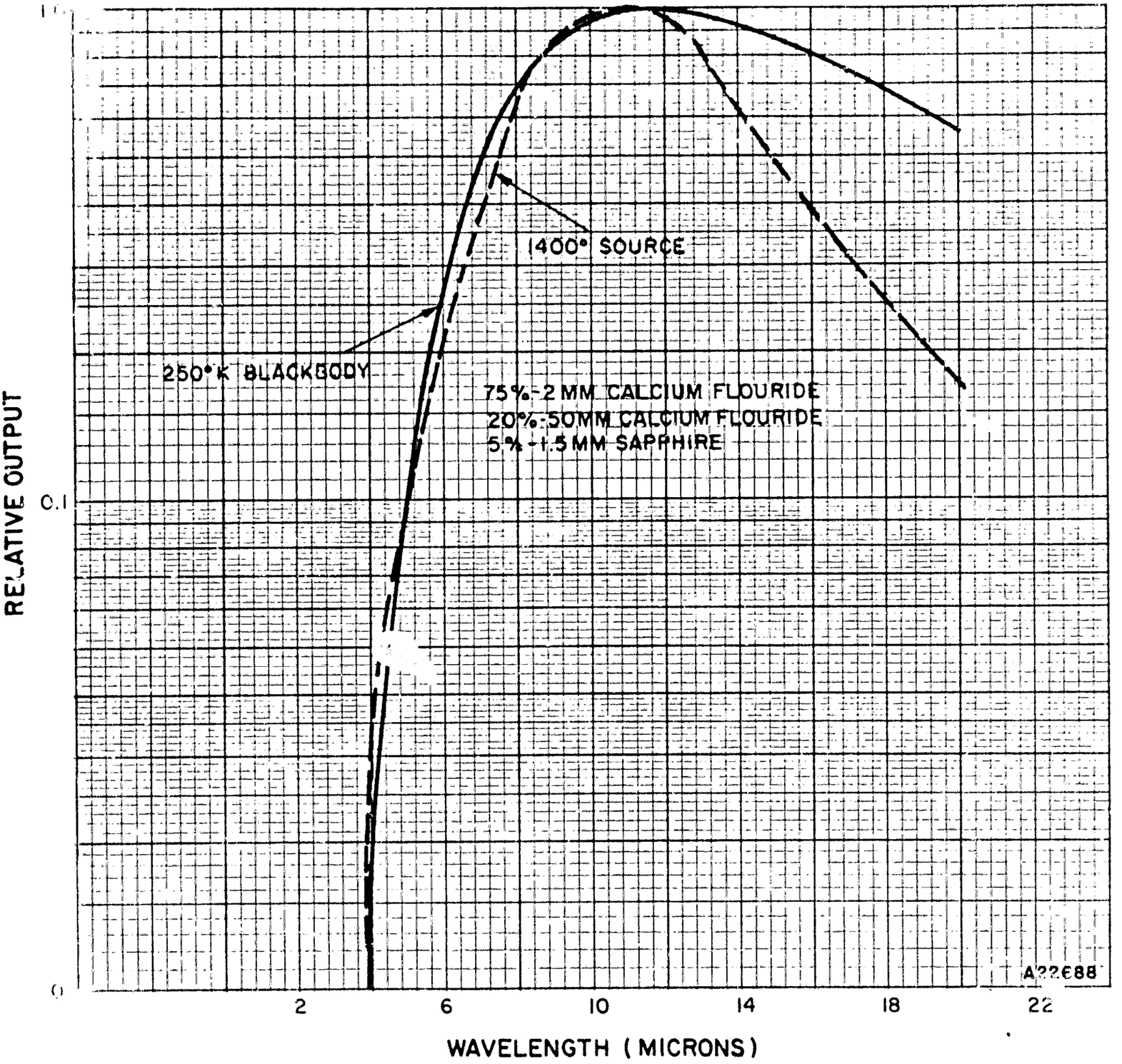

Figure 15. THE SPECTRAL RADIANT EMITTANCE OF A THREE-ELEMENT, 1400° K SOURCE AND A 250° K BLACK BODY

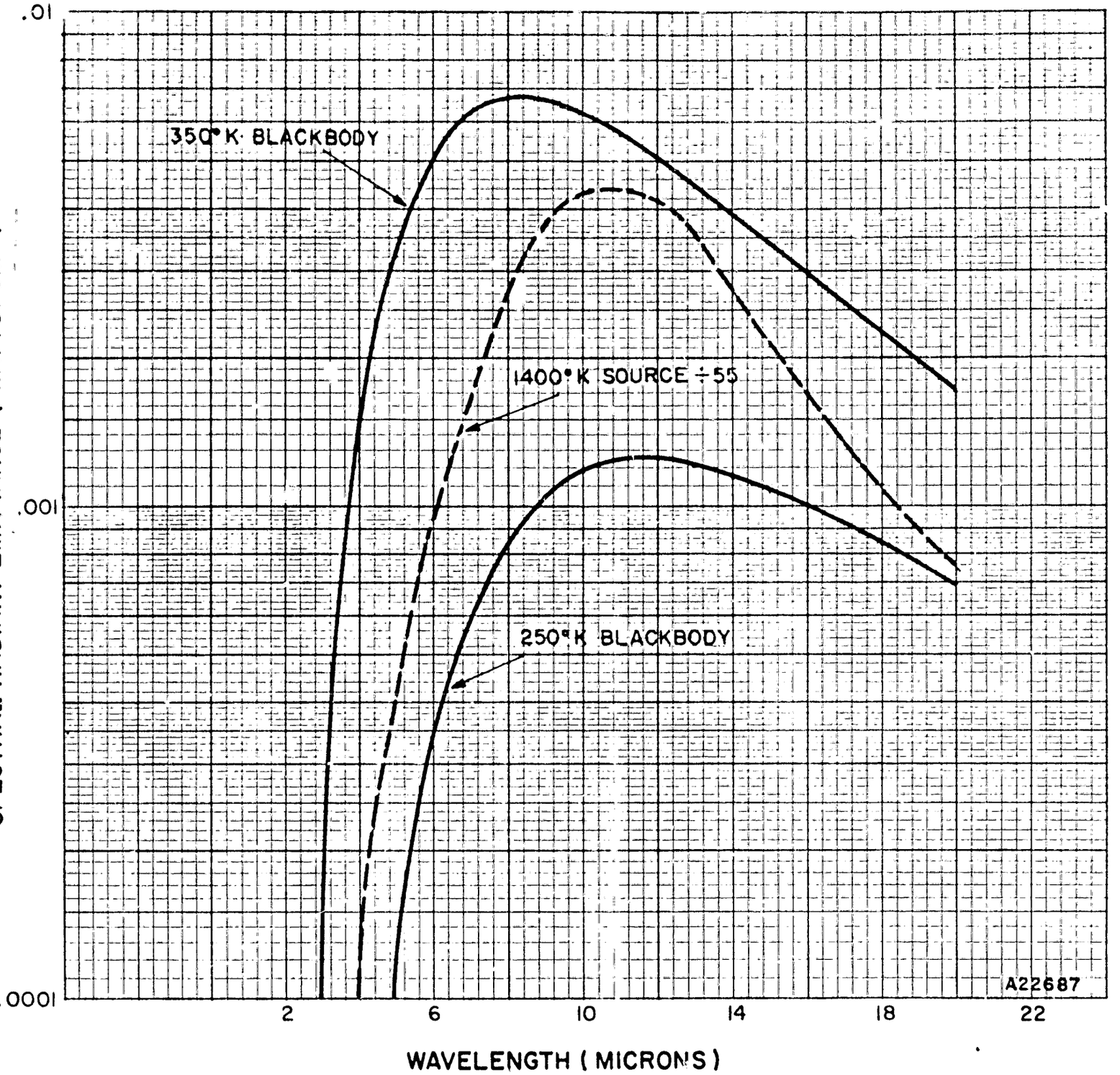

Figure 16. THE SPECTRAL RADIANT EMITTANCE OF A THREE-ELEMENT, 1400°K SOURCE COMPARED TO A 350°K AND A 250°K BLACKBODY

a 1400°K source spectrally shaped (using filters or a scatter plate) to match a 250°K spectral distribution, has an efficiency less than 4%. This means for every 100 watts of projected radiant power, 2400 watts of short-wavelength radiation must be either absorbed or blocked. The efficiency of a "Calcium Fluoride" source on the other hand is estimated to be greater than 50%. The major losses arise primarily from inefficiencies in heating the Calcium Fluoride.

If a more practical source operating temperature of 800°K is chosen, an option is available as to whether a 2 or 3 element source is used. Figure 17 is a plot of the spectral radiant emittance of three Calcium Fluoride sources each having a second 10% element of 1.5mm Sapphire. The thickness of the Calcium Fluoride element was varied from 2 to 50 millimeters. As expected, the long-wavelength peak shifts to shorter wavelengths with increasing Calcium Fluoride thickness. All three sources have some mismatch at wavelengths just below the source's peak response. While the responses of a two-element source shown in Figure 17 are considered typical, they are not necessarily the most optimum two-element combination.

A more perfect match may easily be achieved from a three-element 800°K source. Figure 18 is a plot of the spectral emittance radiant of a source whose surface area contains 70% of 2mm thick Calcium Fluoride, 20% of 2mm thick Magnesium Fluoride and 10% of 15mm Sapphire. This 800°K three-element system will have a total radiant emittance of .334 watts per cm^2. This output is 15 times total radiant emittance of a 250°K blackbody.

If in addition to having the proper spectral match, it is desired that an array of sources simulate the total power exchanged between the earth and a test object, only 1/15 of the radiating area of an earth temperature disc is required.

Figure 19 is a plot of the specular radiant emittance of an 800°K three-element source compared to the radiant outputs of a

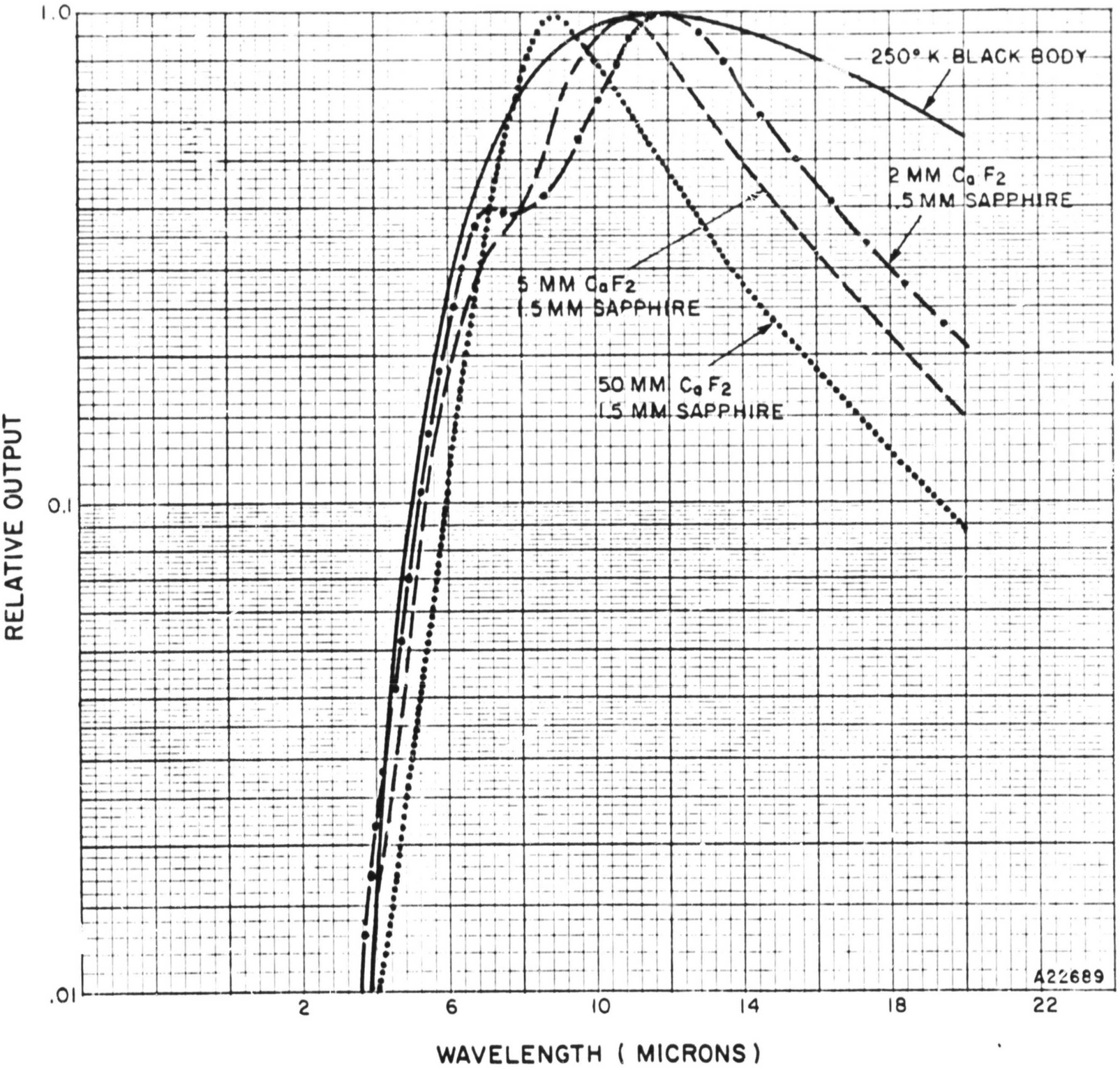

Figure 17. THE SPECTRAL RADIANT OUTPUTS OF SEVERAL TWO-ELEMENT, 800° K SOURCES (90% CALCIUM FLUORIDE, 10% SAPPHIRE) AND A 250°K BLACK BODY

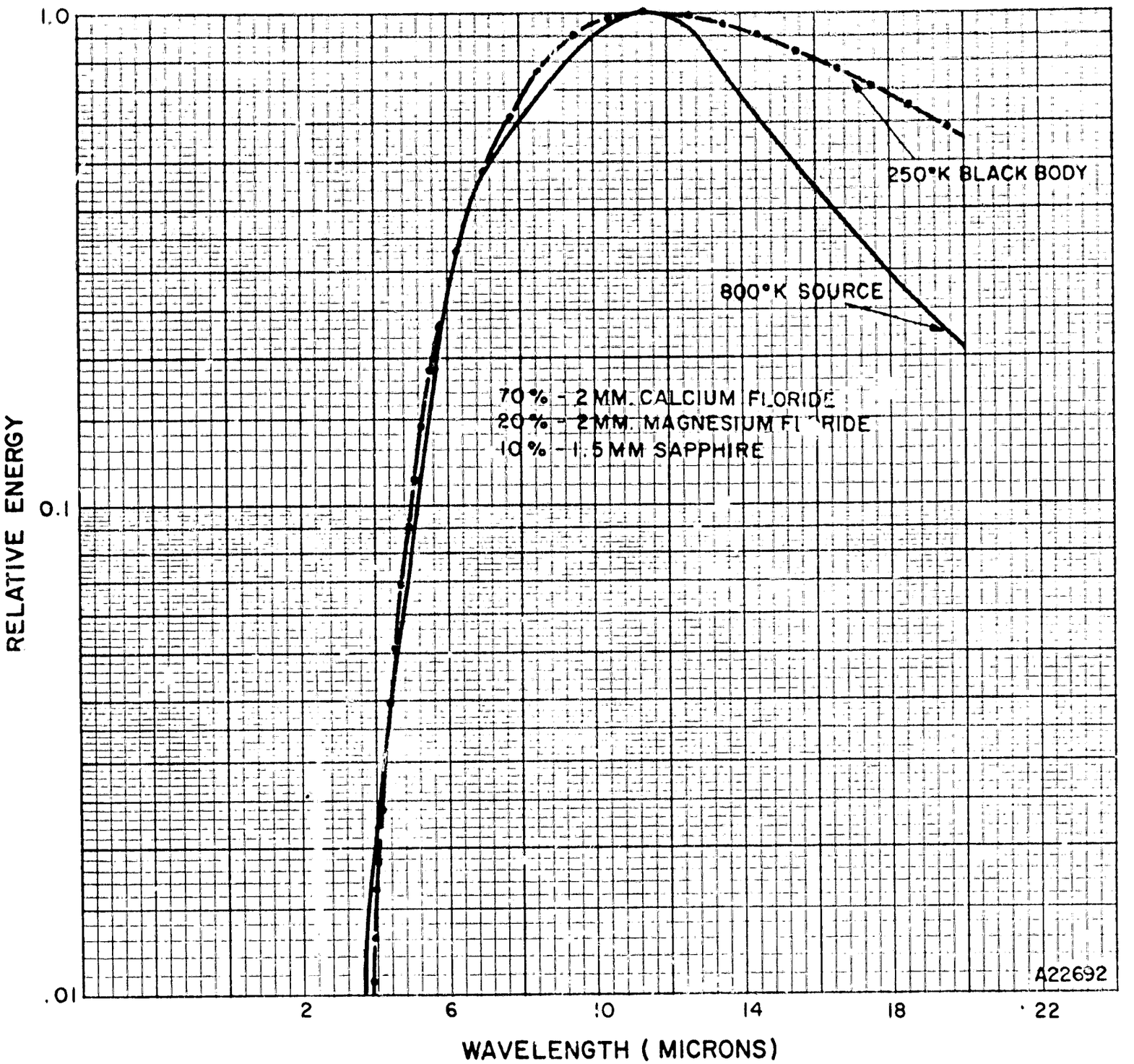

Figure 18. THE SPECTRAL RADIANT EMITTANCE OF A THREE-ELEMENT, 800°K SOURCE AND A 250°K BLACK BODY

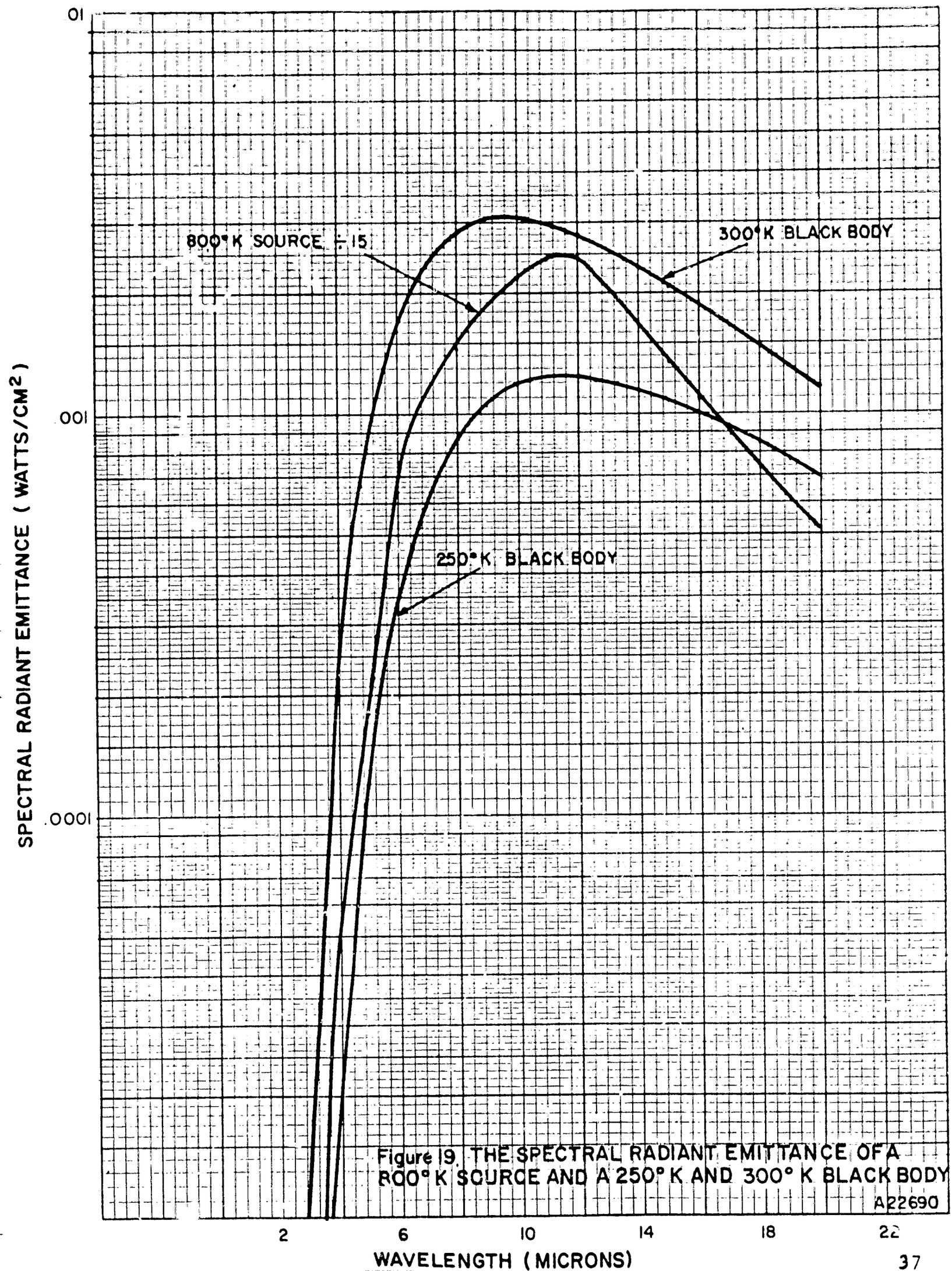

Figure 19. THE SPECTRAL RADIANT EMITTANCE OF A 800° K SOURCE AND A 250° K AND 300° K BLACK BODY

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250°K and 300°K blackbody. This source allows the 350°K upper tolerance limit to be reduced to 300°K. The narrower limits of 300°K and 250°K more closely bind the effective blackbody temperature of the earth over all wavelengths. In this illustration the amplitude of the 800°K source was chosen so that the integral of the source's spectral radiant emittance is exactly 1/15 of that for a 250°K blackbody over all wavelengths. This results in an effective source emissivity or radiance multiplier of 15. Under these conditions, the curve of the simulator's radiant emittance output lies between the curves plotted for a 250°K and 300°K blackbody out to 17 microns. The simulator output plotted in Figure 19 also represents the output of an array of simulators if the simulator density is arranged so that the total power out is exactly equal to a 250°K earth in a thermal-vacuum chamber.

Methods of Heating Transmitting Materials

Having established a method of which earth radiation may be simulated, it is now necessary to determine whether the proposed method is both practical and economically feasible. The first question to be answered is how to heat the infrared transmitting crystalline materials.

The method of placing the required materials directly in contact with a heated surface has several drawbacks. First, in a vacuum environment it is very difficult to obtain a good thermal contact mechanically. The second problem results from the fact that the heater will be visible through the infrared transmitting material. Therefore, the heater itself will contribute to radiated energy. It is possible to reduce the amount of energy radiated by the heated surface by making the surface highly reflective (reducing its emissivity). If the surface is both polished and

gold plated, the emissivity could be reduced to approximately 3%, providing the surface is kept smooth, clean and scratch free. The results of including the emission from a gold-surfaced contact heater in the output of an 800°K three-element simulator is shown in Figure 20 Shown for comparison is an ideal simulator's output without a visible heating surface. The gold surface adds a large amount of radiation in the 1 to 4 micron region due to its non-perfect reflectivity. To reduce the amount of unwanted radiation it is necessary to reduce the area of the metallic heating surface. One practical way of doing this is to pass current through a metallic pattern vacuum-deposited on the element. A typical pattern, shown in Figure 21, can be constructed to cover less than 10% of the area being heated.

It is desirable that the emissivity of the electrode material be low, but its thin film resistance be reasonably high. A material which has these properties is rhodium. Using the heater pattern shown in Figure 21 with a deposition thickness of .5 microns and a trace width of 1 mm, the estimated resistance of the element will be 50 ohms at room temperature. This resistance will increase to over 100 ohms at 800°K. These resistance values are high enough to allow the construction of power supplies of practical size and efficiency.

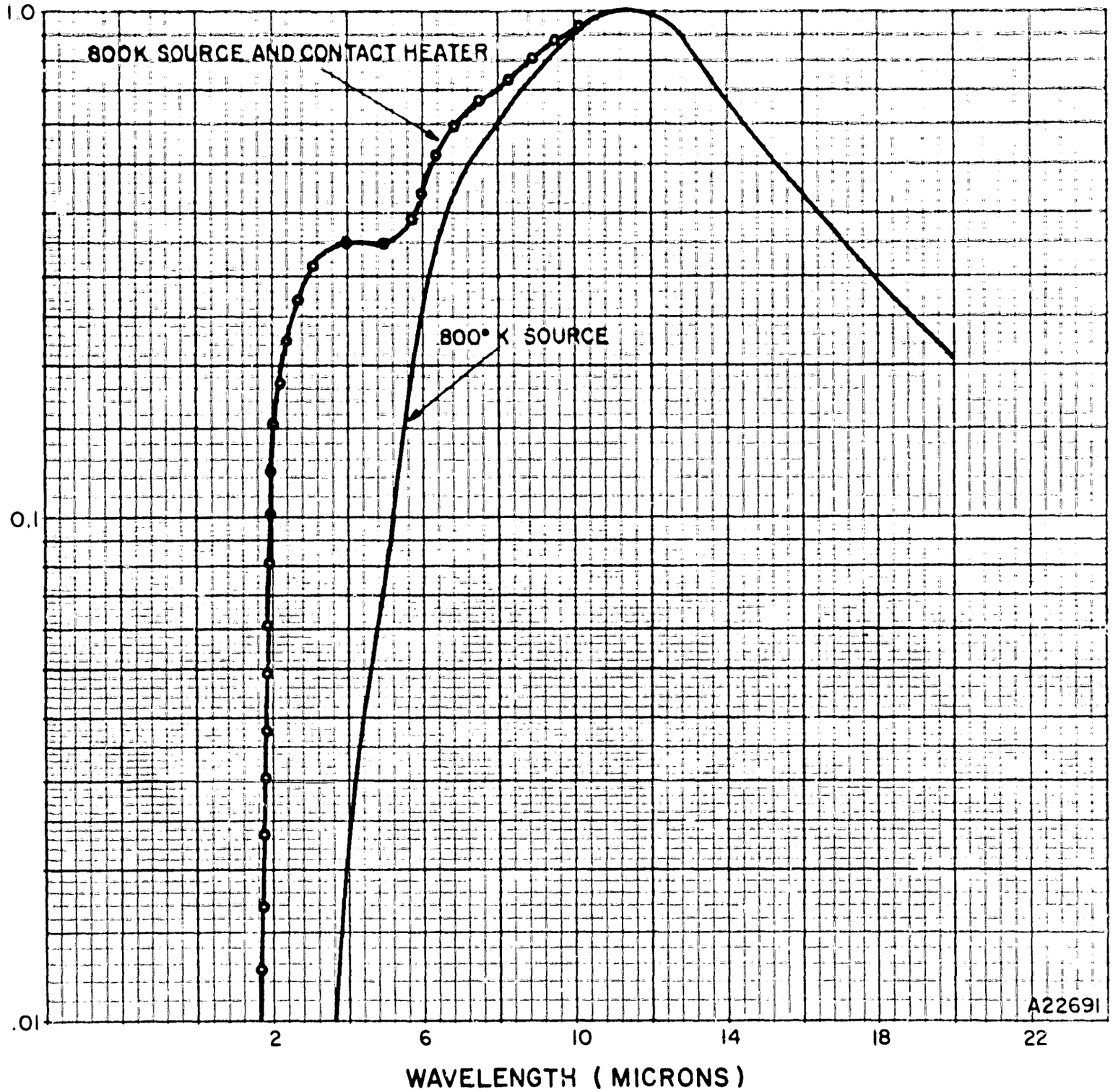

Figure 20 THE EFFECT OF A SOLID GOLD-SURFACED CONTACT HEATER ON AN 800°K SOURCE OUTPUT

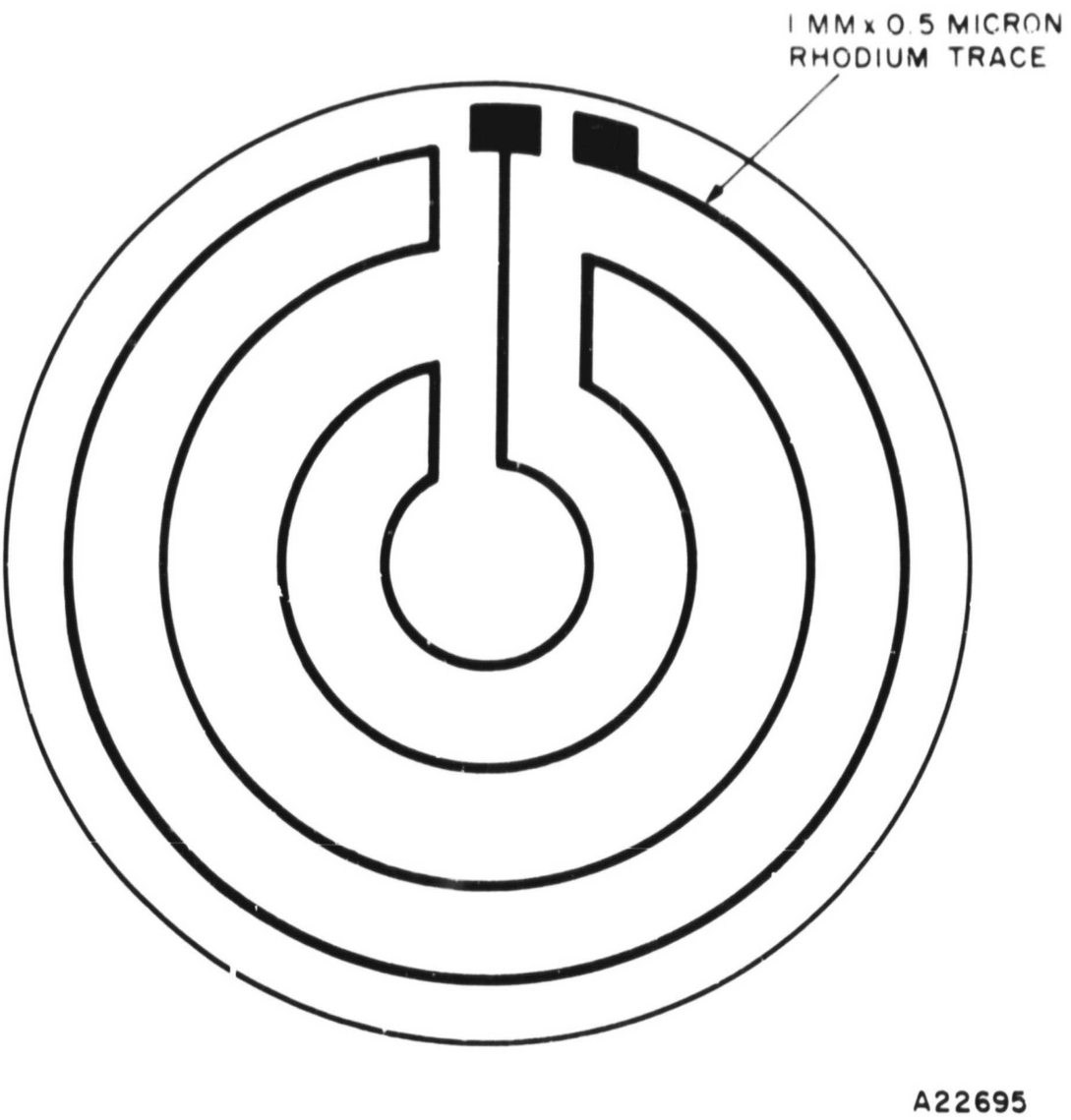

Figure 21. TYPICAL VACUUM DEPOSITED HEATER PATTERN

SECTION 6
SOURCE CONSTRUCTION

Each crystalline element will be heated by means of a vacuum-deposited heating element described in Section 5. A complete source will consist of a group of 2 or 3 heated elements.

There are a number of ways by which these elements may be housed. One design possibility consists of placing all the required materials in a single housing. Individual elements may be placed side by side or in a stack.

A second possibility is to make a separate housing for each material used. Economy could be realized by making the housing for each material identical in size. The proper total spectral distribution can be obtained by having a different number of sources of each material distributed throughout the array. In a given array, the number of sources of one type would correspond to the percent material surface area required in an individual source containing two or three elements.

An important consideration in any of the above arrangements is to design a mounting and housing which have a minimum of thermal conduction and radiation losses. This might be accomplished using the source configuration shown in Figure 22, a drawing of a two-element stacked source. The principle of construction, if required, could easily be extended to housing a stack of three heated elements.

The two heated elements are supported from a common base plate by means of a ceramo-plastic mica. At 800°K the estimated conduction loss is 10 watts.

Behind each crystalling element are mounted gold-plated, spun-aluminum reflectors. As described in Section 5, these reflectors serve to reduce radiation losses. To limit self emission from the reflectors, they are heat sunk to the base

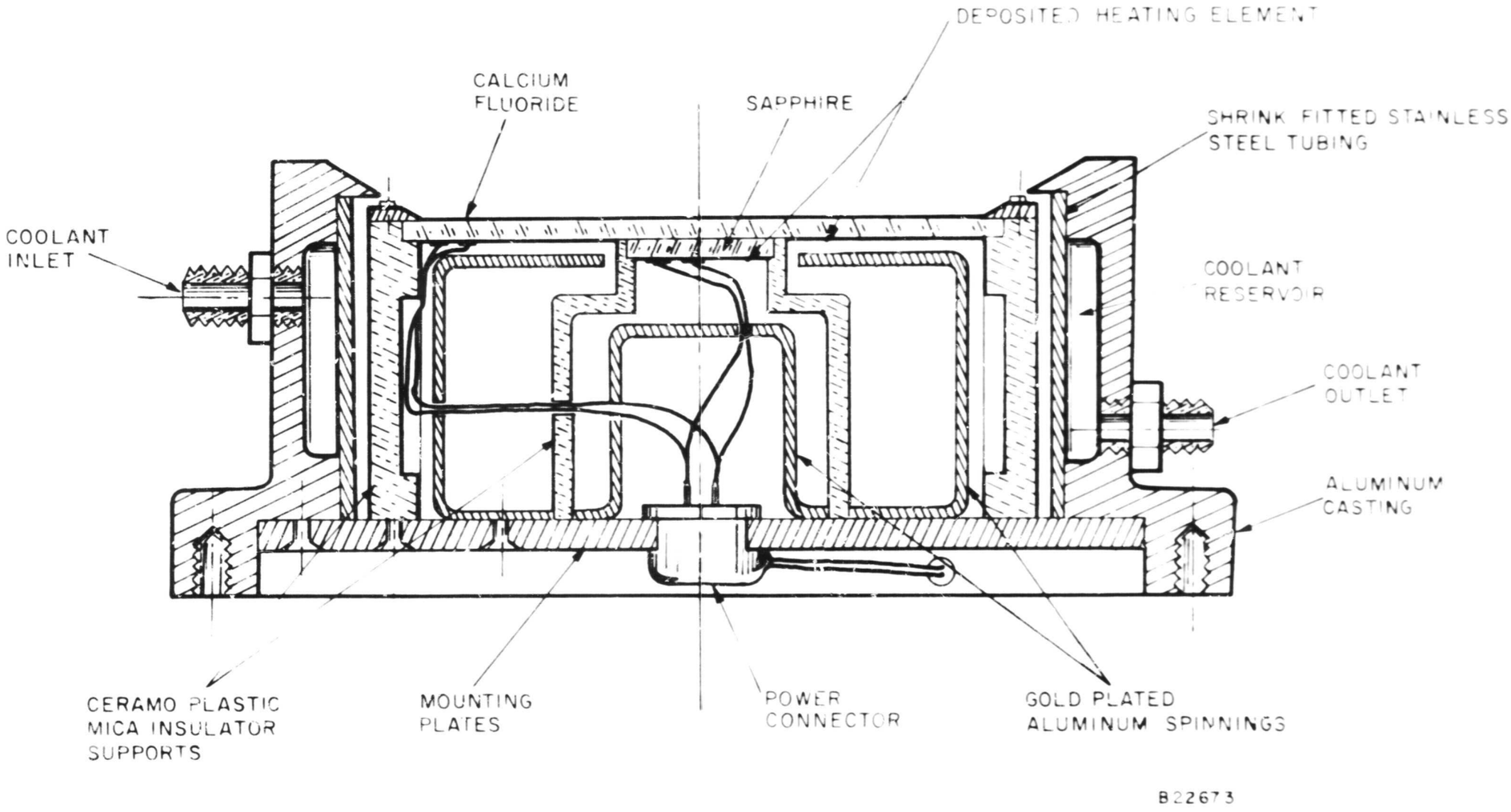

Figure 22 TWO ELEMENT EARTH SIMULATING SOURCE

plate by means of thermal grease. Both the base plate and the outer housing are cooled by the circulation of a liquid coolant such as, liquid nitrogen. The heater elements deposited on the crystalline materials are powered through welded leads and a right-angle booted connector.

An advantage of the construction shown in Figure 22 is that the internal structure may be easily removed from the outer housing by loosening screws in the common base plate.

The estimated efficiency of this two-element unit is on the order of 70 percent, for an operating temperature of 800°K.

After detailed design and material measurements, the operating temperature of the source may possibly be increased to obtain a higher effective emissivity. If this is the case, the source efficiency is expected to decrease. For operating temperatures in the range of 1000°K to 1400°K the efficiency will be approximately 30 to 50 percent. One limiting factor in achieving high efficiencies for temperatures in excess of 800°K is the availability of convenient materials having low thermal conductivities.

SECTION 7

CONCLUSIONS

After examining several possible methods for producing a special infrared source for simulating earthshine radiation, a method was discovered which appears feasible on both the basis of existing technology and practical economy.

A source containing two or three infrared transmitting elements, heated to 800°K, will have a radiant power output which falls within the tolerance bands defined by the spectral emittances of blackbodies operated at 250°K and 300°K in the wavelength region between 4 and 17 microns. In addition, the source's total radiant output may be matched to the earth's over a range of earth temperatures between 250°K and 300°K.

The sources described may easily be incorporated in an array to simulate earthshine in a thermal-vacuum chamber. Each source has a minimum field-of-view of 120°, a lambertian distribution, and can accommodate interchangeable field masks.

In the 4 to 17 micron region the source's spectral match exceeds the desired match specified in the contrast scope-of-work. This requirement specified that the source's output spectrum be within the tolerance band defined by a 250°K and a 350°K blackbody. The results predicted for the recommended source are particularly encouraging when it is recognized that the apparent temperature of the earth over most wavelengths lies between 250°K and 300°K. In addition, the difference in radiant emittance between a 350°K and 300°K blackbody is approximately twice that between a 300°K and a 250°K blackbody. It follows that, by achieving a maximum output tolerance less than 300°K, a much better spectral and total energy match to the earth may be obtained.

The maximum radiant emittance for a typical 800°K source was found to be .334 watts/cm^2. If the maximum specified active area of the source is used (.111 $ft.^2$ or 103.2 cm^2) the total source output will be 34.5 watts into a hemisphere (2π steradians). Unfortunately this output is considerably less than the 190 watts specified.

A total output greater than 34.5 watts for a source operating at temperatures higher than 800°K cannot be accurately determined at this time. Some improvement can be expected after a detailed design and materials measurement program. At present the operation to temperatures up to 1400°K is limited primarily by the uncertainty in the optical properties of Calcium Fluoride, and Sapphire at these temperatures.

The recommended sources are considerably smaller and less complicated than those envisioned at the beginning of the study. Should 800°K turn out to be the source's operational temperature limit, the requirement that a larger number of sources are needed may be offset by their simplicity and the resultant cost savings.

SECTION 8

RECOMMENDATIONS FOR FUTURE WORK

This report establishes the feasibility of fabricating an earth simulating source. The next step required to be taken in the development of a practical source is to quantitatively evaluate a number of the possible infrared transmitting materials. For this purpose it is recommended that a two-element prototype source be fabricated and tested

The prototype source could be designed for a nominal operating temperature of 800°K, but would also serve to evaluate spectral matching for operating temperatures up to 1400°K.

Once the heater-element art work and deposition masks are completed, the cost of evaluating different materials would be relatively inexpensive.

At present there is only limited published information available on the optical properties of infrared transmitting material heated to temperature in excess of 800°K. As a result, particular emphasis would be placed on determining the spectral emissivity of candidate materials at high temperatures. It should be noted that any increase in operating temperature above 800°K will rapidly increase the source's apparent emissivity, reduce the number of elements required in the earth-simulating array, and improve the source's long-wavelength spectral match.

The projected costs for a single prototype source or a complete array appear to be well within reason. The most expensive components are the infrared transmitting crystals. In small quantities a 2mm thick, 4-inch diameter disc of Calcium Fluoride

has been quoted at less than $100.

The duration of a prototype fabrication and measurement program is estimated at five to six months.