Optimizing the thermal performance of apochromatic glass-liquid optical systems.

Robert D. Sigler

Lockheed Martin Advanced Technology Center
Palo Alto, California 94304-1191

and

Maria V. Petrova, Andrei G. Plyukin, Michael N. Tolstoy

Vavilov State Optical Institute
St. Petersburg, Russia

ABSTRACT

In the design of high performance optical systems, the goals of superior color correction and reduced cost can be achieved when abnormal dispersion liquids are incorporated into a design. A complicating factor in these designs is the potential for degraded performance due to the significant changes in refractive index of all liquids with temperature (dN/dt). The thermally induced performance changes of glass-liquid systems can be virtually eliminated through a combination of proper liquid selection (i.e. at least two liquids are required: one to provide color correction, and one to provide thermal compensation) and multi-temperature optimization (i.e. zooming in temperature).

In this presentation, the required optical and thermal characteristics for the correcting and compensating liquids are developed and the optimization techniques are discussed. Finally, the optical performance of glass-liquid objectives using several correcting and compensating liquid pairs are contrasted with a similar all-glass design.

Kewords: liquids, abnormal dispersion, athermalization, optical design, color correction

1. INTRODUCTION

The incorporation of abnormal dispersion liquids into the design of optical systems can be quite effective in achieving a high degree of color correction at relatively low cost. Frequently, these optical systems are expected to maintain both their focal position and good aberration balance over a significant temperature range. This can be a challenge as liquids always have a large thermal coefficient of refraction (dN/dt) and, unlike glasses, these coefficients are always negative.

In previous papers[1-2], the use of two liquids in an optical design (to form both a positive and a negative liquid lens) has been presented. In most cases, the use of two liquids permits the lens system's focal position to be maintained in the presence of thermal changes at a given wavelength. With a judicious selection of the opto-thermal characteristics of the two liquids and optimization at multiple temperatures (i.e. "zooming" in temperature), the aberration balance as well as the focal position of the design can be maintained. This paper will attempt to describe this selection and optimization process.

2. THE SELECTION OF LIQUIDS FOR APOCHROMATIC COLOR CORRECTION AND AN ATHERMAL FOCAL POSITION.

Apochromatic color correction requires the use of at least one optical material that has abnormal dispersion (i.e. its position on a partial dispersion vs. Abbe number diagram lies well away from the normal line for glasses). The problem has always been that known abnormal dispersion materials (i.e. glasses and crystals) have limited availability, high cost, and poor mechanical properties. Fortunately this is not the case with many optical liquids. Liquids are readily available , have low cost, and have dispersion properties that are usually quite different from that of any optical glass. This later point is dramatically illustrated by the Abbe and partial dispersion plots for both glasses and liquids shown in figures 1 and 2.

Using normal dispersion glasses and one abnormal dispersion liquid, it is a straight forward procedure to develop a design that has both dramatic color correction and low material cost. With only a single liquid, such a design can be expected to exhibit significant changes in focal position (and aberration balance) as a function of temperature. When two liquids are used, one liquid provides the secondary color correction and the other liquid provides the thermal compensation.

In the last few years, the design of athermal glass-liquid apochromats has been simplified by having a greater selection of liquids that have accurately measured dispersion and dN/dt data. This has been accomplished through a cooperative research arrangement between the Lockheed Advanced Technology center and the Vavilov State Optical Institute[3-10]. As a result of this cooperation, more than 30 liquids have now had their dispersion and dN/dt characteristics measured over each liquid's useful transmission range (UV to IR). These data will be the subject of a future joint paper. The dN/dt data for the liquids identified on the dispersion plots of Figures 1 and 2 are plotted in Figure 3. When these data are compared with the dN/dt data for optical glasses, it is noted that the values for a liquid are typically a hundred times larger.

In the design of athermal, apochromatic glass-liquid systems, the first step is to select a liquid that is both as abnormal and as dispersive as possible. This will result in the liquid forming a lens with very low positive power (and therefore minimal volume). Keeping the power of the liquid lens low will minimize the thermal influence of the liquid (i.e. the liquid's thermal environment will be dominated by the mass of its surrounding glasses). It is assumed that the glasses used in these designs would be low cost, normal dispersion ones. In such a glass-liquid design, the glass elements provide the bulk of the monochromatic and primary color correction, and the abnormal dispersion liquid provides the secondary color correction. A second liquid, usually called the compensator, is picked to be as different in its degree of abnormality as possible. Usually this means that the compensator has nearly normal dispersion (i.e. it lies close to the normal line). Considering these principles alone (as was done in some early designs) leads to selecting a pair of liquids like 642134 and 295990. This combination, when used in conjunction with normal dispersion glasses, is capable of yielding very good color correction along with a nearly constant focal position over a limited temperature range.

An example of a lens based on the 642314/295990 combination is the very large, high performance, telephoto lens designed by Panavision[11], shown in Figure 4. During the optimization of this lens, it was discovered that there was a significant loss in chromatic correction at the violet and red end of the spectrum over its large operational environment (0 to 40°C). The reason for can be traced to the difference in shape of the dN/dt vs. wavelength curves for the two liquids. The need for similarly shaped dN/dt curves is easy to see by examining some simple thin lens relationships. For a series of glass and liquid thin lenses that are closely spaced (and, as a rule, the liquids in a design are closely spaced), the focal length of the assembly at a given wavelength is constant as a function of temperature when:

$$\sum_{i}^{n} \beta_i \phi_i = 0 \qquad (1)$$

Where φ is the power of the i^{th} lens and β is the thermo-optic coefficient of the lens material. The thermo-optic coefficient is given by:

$$\beta = \frac{dN / dt}{N-1} - \alpha \qquad (2)$$

Here, α is the linear coefficient of expansion and N is the index of refraction. For a liquid, the value α is taken as the average of the two glass containing the liquid. Typically, the value of α is so much smaller than the dN/dt term, that it can be ignored. For simplicity, the contribution of the glasses can also be ignored as the thermal properties of the liquids will totally dominate the athermalization process. These simplifications allows Eq. 1 to be re-written as:

$$\left(\frac{dN_1 / dt}{dN_2 / dt}\right) = -\left(\frac{\phi_2}{\phi_1}\frac{(N_1-1)}{(N_2-1)}\right) \qquad (3)$$

For any visible wavelength, the right side of Eq. 3 will be essentially constant with a given pair of liquids. Therefore, athermalization over a spectral region can only be achieved if the dN/dt ratio of the two liquids is also essentially constant. The graphical interpretation of this requirement is that the two liquids must have similarly shaped dN/dt curves as a function of wavelength. An inspection of the curves for 642134 and 295990 reveals them to have quite different shapes and therefore athermalization problems can be expected. At the time this lens was designed there were very limited choices for liquid pairs and the solution to the athermalization difficulties was to incorporate a glass element that had very abnormal thermal characteristics (Ohara FPL53). The resulting design displayed impressive color correction and optical performance over its entire operating temperature range, but the inclusion of an abnormal dispersion glass was inconsistent with the goal of low material cost.

The difficulties associated with the 642134/295990 combination inspired a new search for liquids which could satisfy both the selection criteria and have similarly shaped dN/dt curves. An optical design such as the example given in Figure 4 is much too complicated to use as a tool to explore the effectiveness of new liquid combinations, so a simple telescope objective was used instead.

3. THE SELECTION OF LIQUIDS FOR APOCHROMATIC COLOR CORRECTION, ATHERMAL FOCAL POSITION, AND ATHERMAL BALANCE.

The telescope objective used for the performance evaluations was a 6 inch diameter, f/10 triplet. The glasses used in these designs were Schott[12] BK7 and F2 (both of which are low in cost and have normal partial dispersion). The opto-thermal performance of this objective with no liquids (i.e. with air-spaced elements) is shown in Figure 5. This was used as a baseline for performance comparisons. This objective's performance is limited by secondary color, as expected with simple achromatic color correction. This baseline objective also shows a surprising variation in performance with temperature. In all cases, the focal plane is assumed to be metered from the objective by an aluminum structure.

In addition to maintaining its focal position with temperatures, it is usually required that the total aberration balance of a lens be maintained as well. An analytical expression of requirements for this to be achieved is quite complex and well beyond the scope of this paper. Fortunately some lens design programs are now capable of optimizing a lens at multiple temperatures[13] simultaneously. For the examples used here, each lens was optimized to have maximum Strehl ratio over the visible spectrum in multiple configurations (similar to that done with a zoom lens). Each configuration had a uniform temperature of 0°, 50°, and 100° F. No re-focusing was allowed between temperatures and the performance at 50° F was given the greatest weight.

The performance of an optimized objective similar to the baseline triplet, but with the liquids 642134 and 295990 in place of the air-spaces is shown in Figure 6. Compared to the baseline objective, there is a dramatic improvement in this objective's performance at the nominal temperature (50°F) as well as a significant improvement in the performance at the temperature extremes. However, the temperature extremes do reveal some loss in overall color correction.

To provide better insight in the selection of optimum liquid pairs, it is helpful to replot the dispersion and dN/dt data for liquids. Shown in Figure 7 is a plot of a liquid's distance from the normal line (a measure of its abnormality) versus the slope of the liquid's dN/dt curve over the g to C spectral region (a measure of the change in of dN/dt with wavelength).
Promising liquid pairs on this plot will be well separated vertically have a small separation horizontally (i.e. the line connecting the two points will be long as possible and nearly vertical). Figure 7 suggests that the combinations of 557211/614207 and 604155/603163 can be expected to yield glass-liquid lens designs that have good apochromatic color correction and are significantly more athermal than an equivalent design based on the 642134/295990 combination.

Shown in Figure 8 is the opto-thermal performance of an objective based on the 557211/614207 combination. The liquid lenses of this combination have slightly more optical power than those of the 642134/295990 combination, but the performance over the temperature range is much improved.

Inspection of the line connecting the points for 604155/603163 in Figure 7 shows it to be similar to that of the 557211/614207 combination. As a result, both combinations can be expected to have similar performance as a function of temperature. This prediction for the 604155/603163 combination is verified by the performance data shown in Figure 9.

4. CONCLUSION

Finally, it is should be emphasized that the improvements in color corrections and athermalization shown by these glass-liquid objectives over similar all-glass designs have been achieved through the addition of less than 10 milliliters of liquid and a re-optimization of the prescription parameters. Similar levels of improvement can be achieved when these techniques are applied to even more complex lens systems such as camera lenses, microscope objectives, relay lenses, etc.

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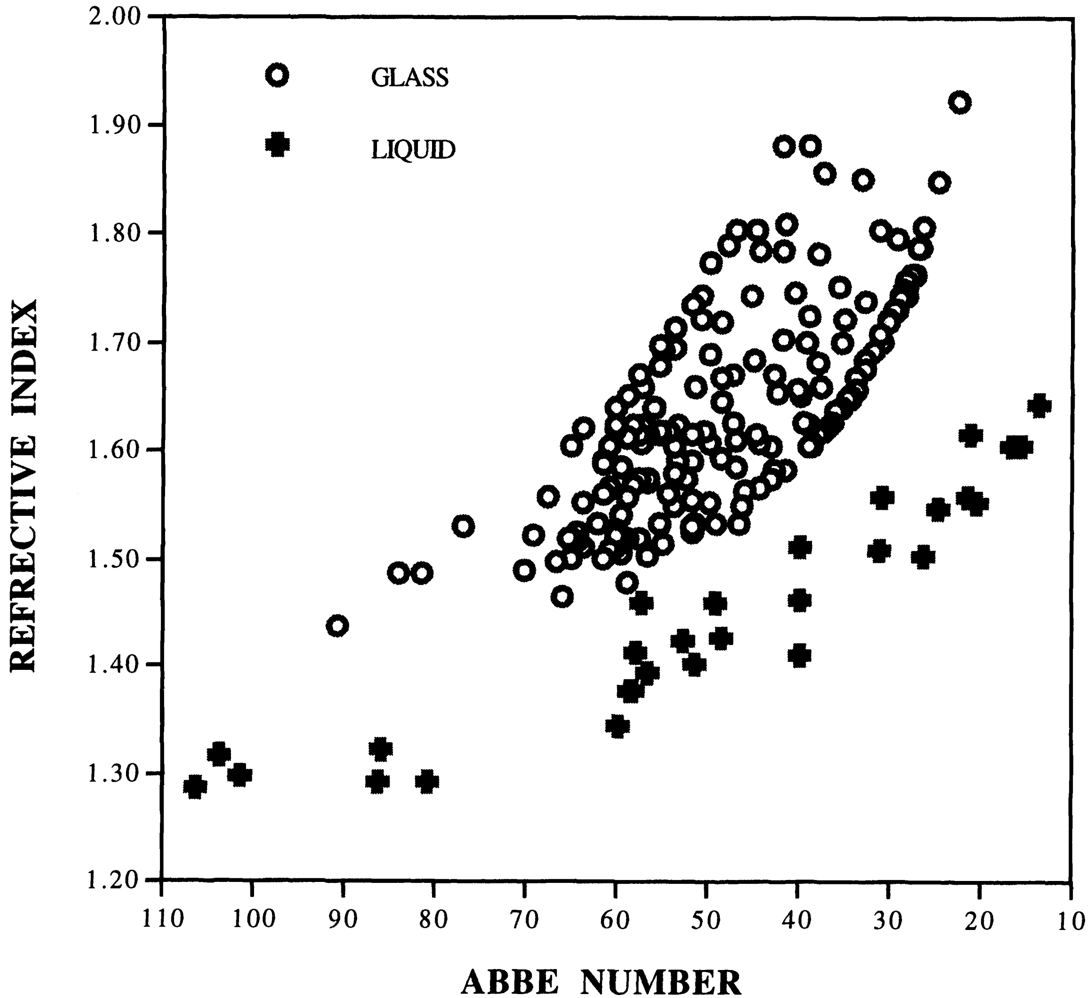


FIGURE 1. A COMPARISON OF ABBE DISPERSION NUMBERS FOR GLASSES AND LOCKHEED LIQUIDS.

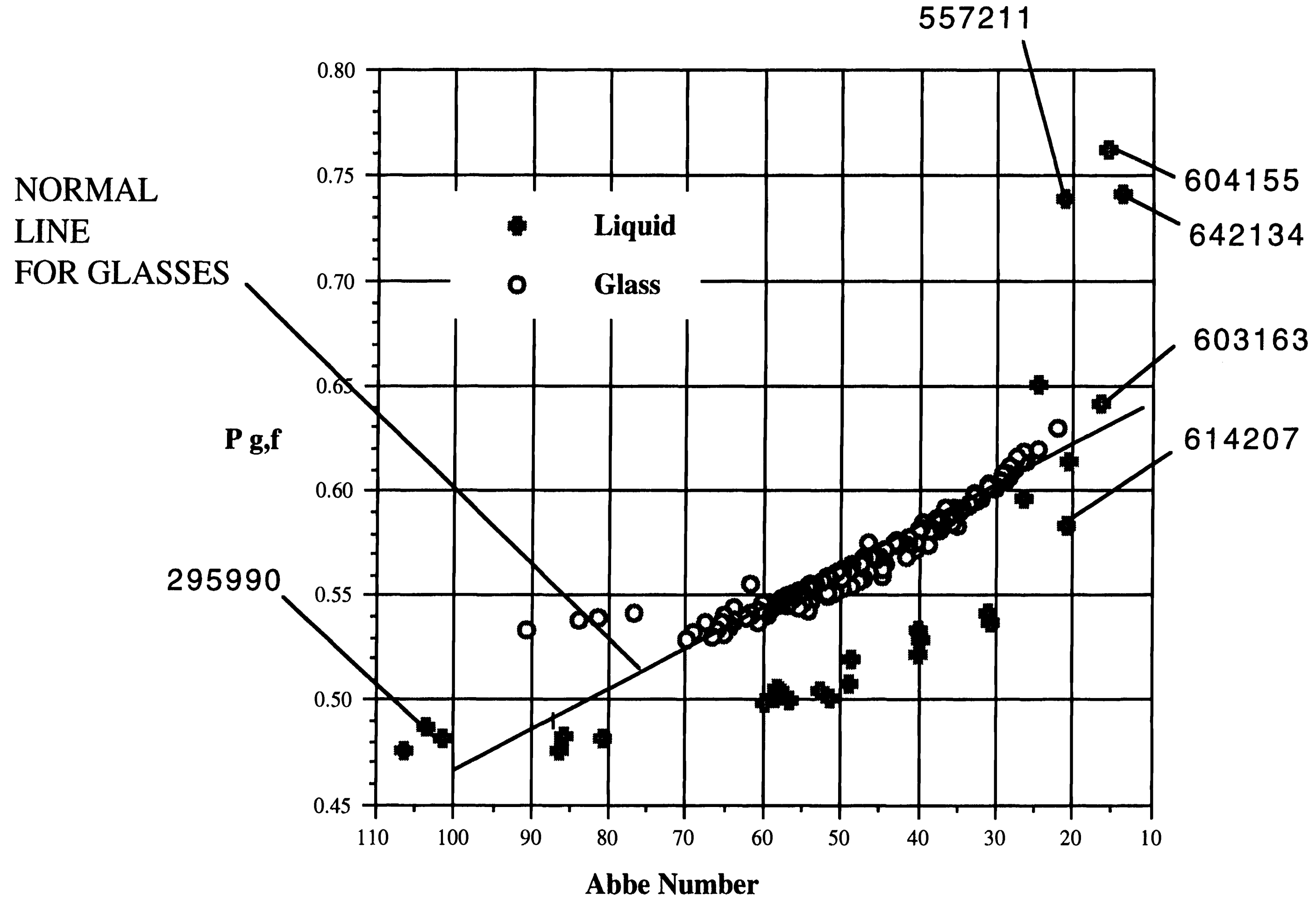


FIGURE 2. A COMPARISON OF PARTIAL DISPERSION VALUES FOR GLASSES AND LOCKHEED LIQUIDS.

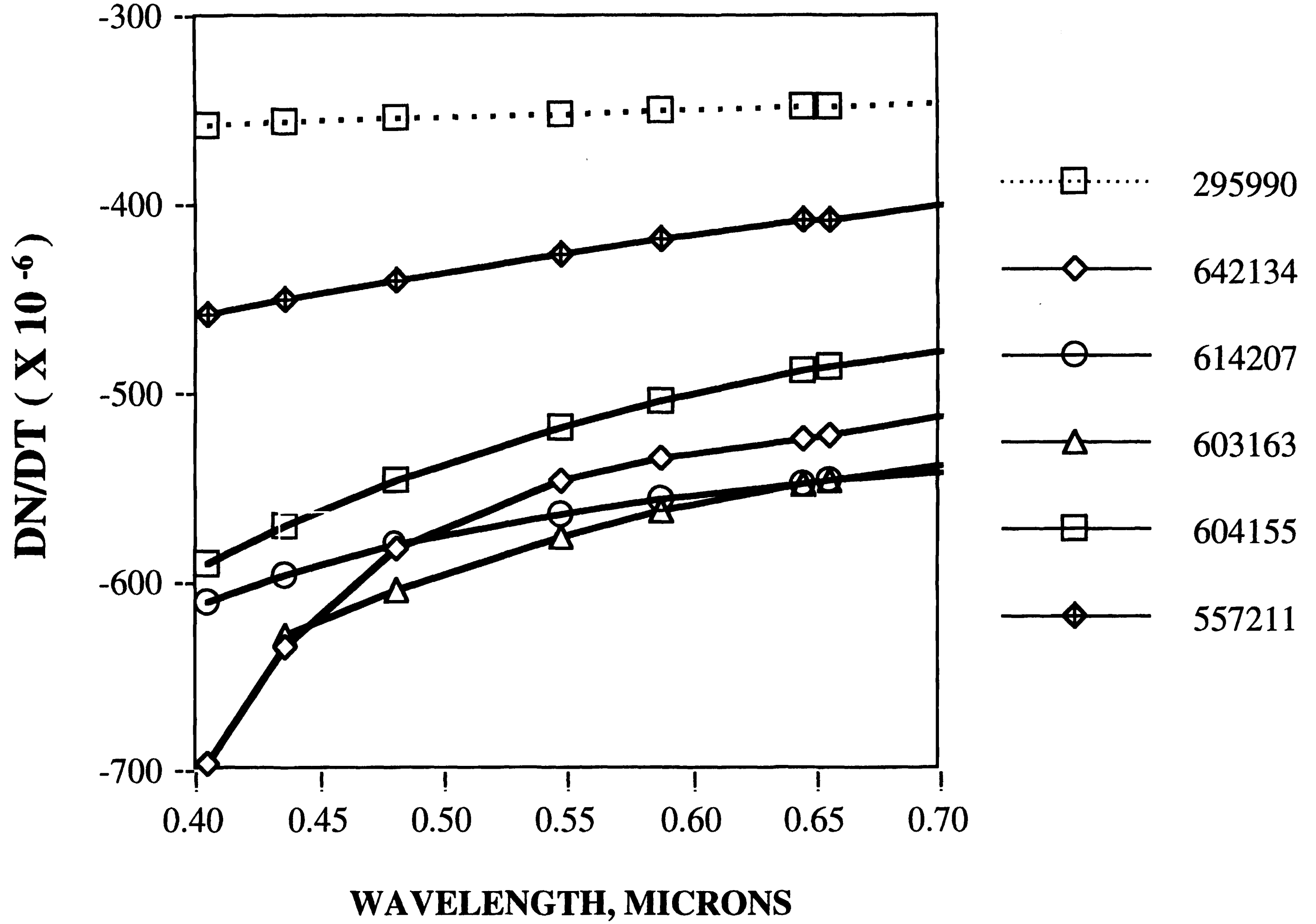
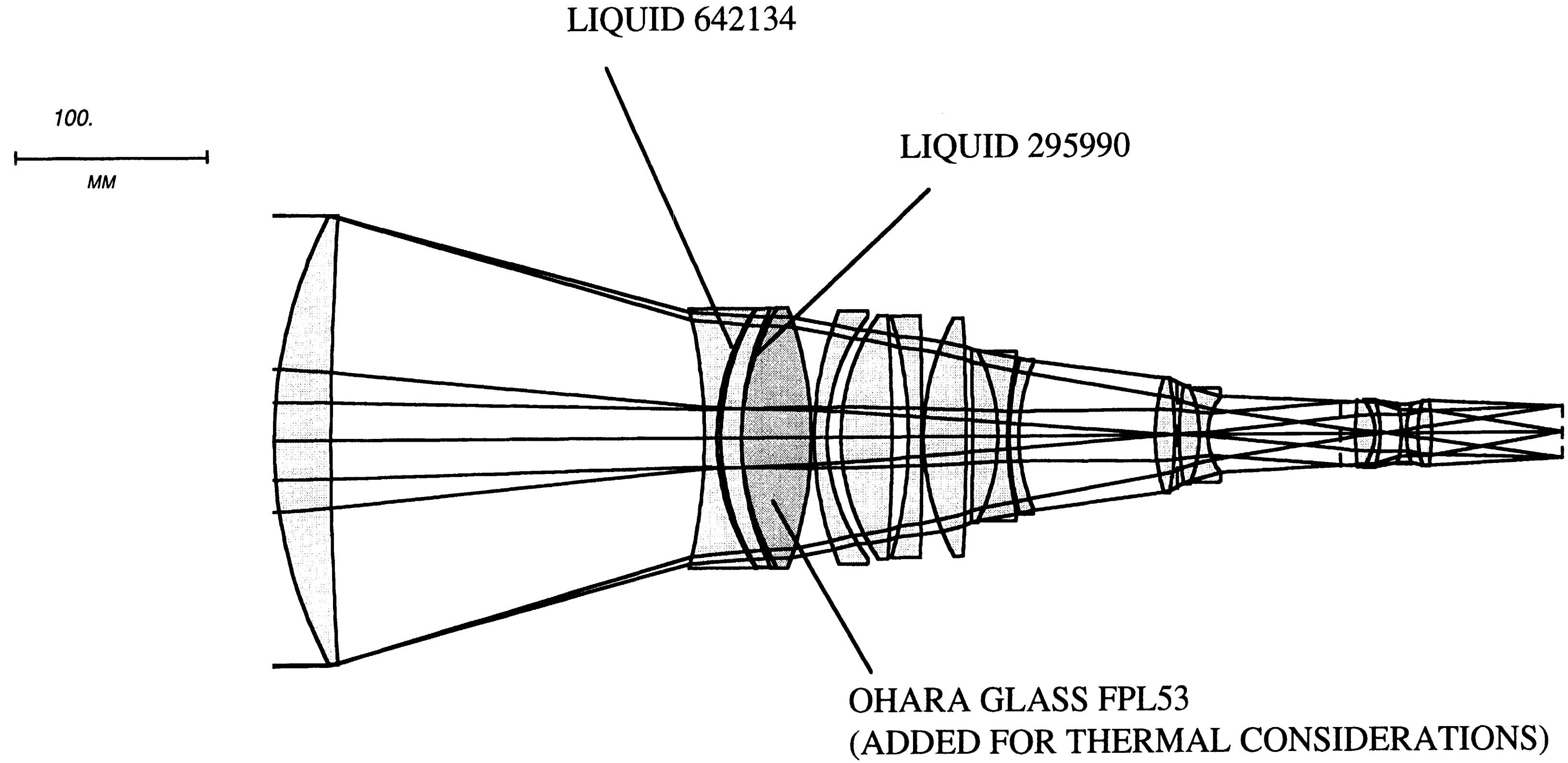


FIGURE 3. DN/DT VS. WAVELENGTH FOR SELECTED LOCKHEED LIQUIDS.



PANAVISION F/2.75 700 MM TELEPHOTO LENS

FIGURE 4. AN EXAMPLE OF AN ULTRA-HIGH PERFORMANCE, ATHERMAL, GLASS-LIQUID OPTICAL DESIGN.

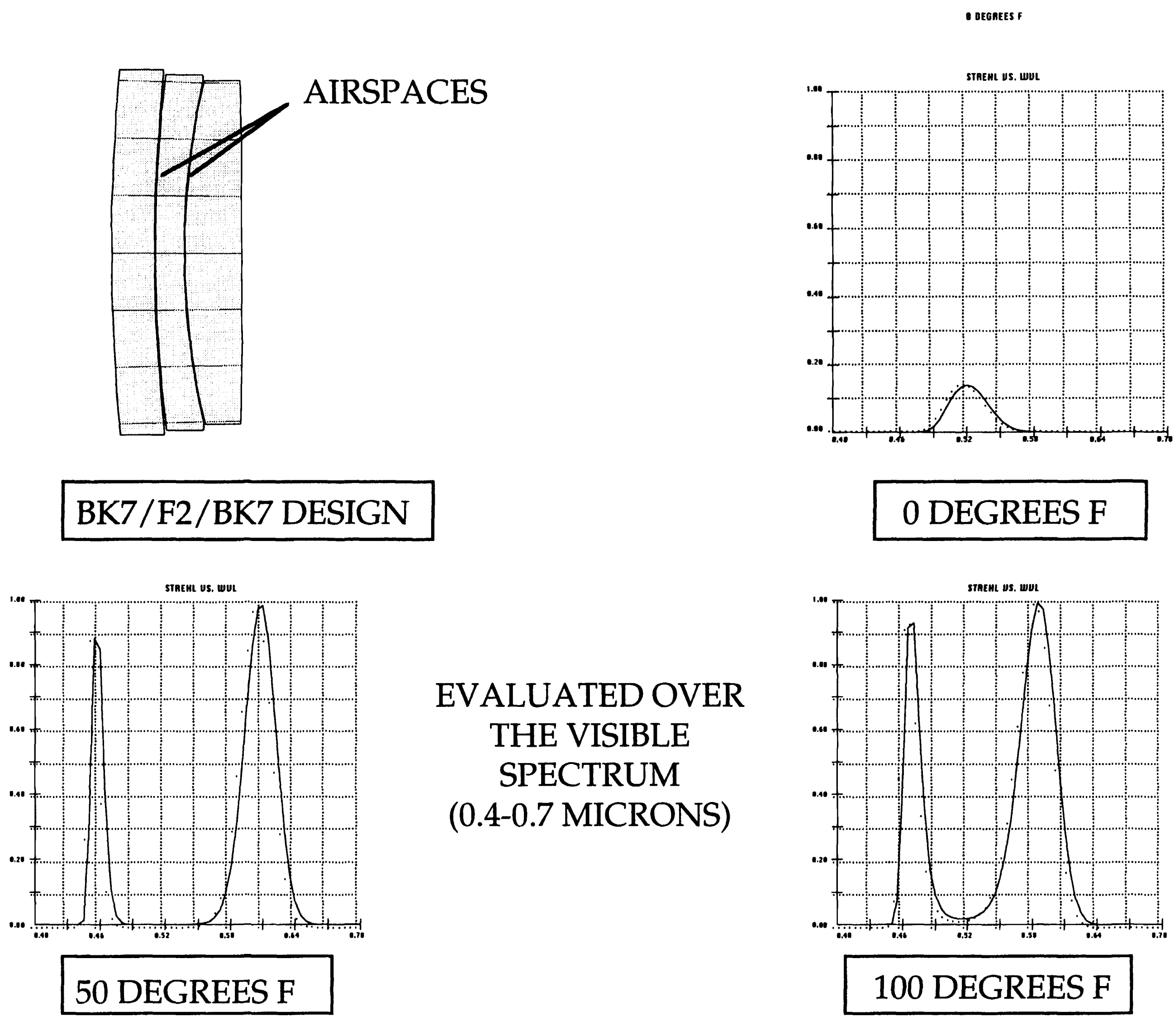


FIGURE 5. STREHL RATIO VS. WAVELENGTH FOR AN AIRSPACED, ALL GLASS OBJECTIVE (BASELINE DESIGN) AT SEVERAL TEMPERATURES.

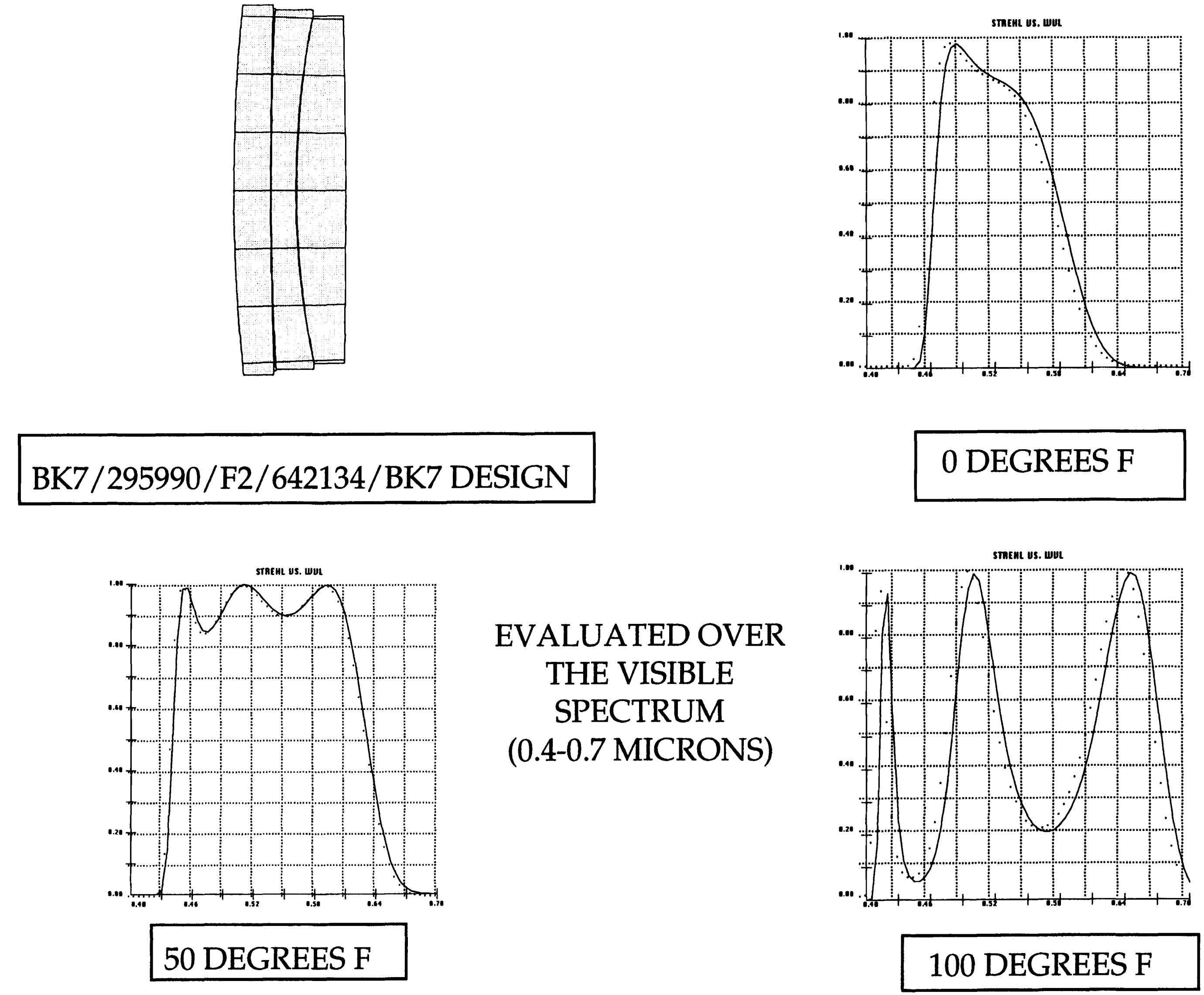


FIGURE 6. STRHEL RATIO VS. WAVELENGTH FOR AN OBJECTIVE USING 642134/295990 AT SEVERAL TEMPERATURES.

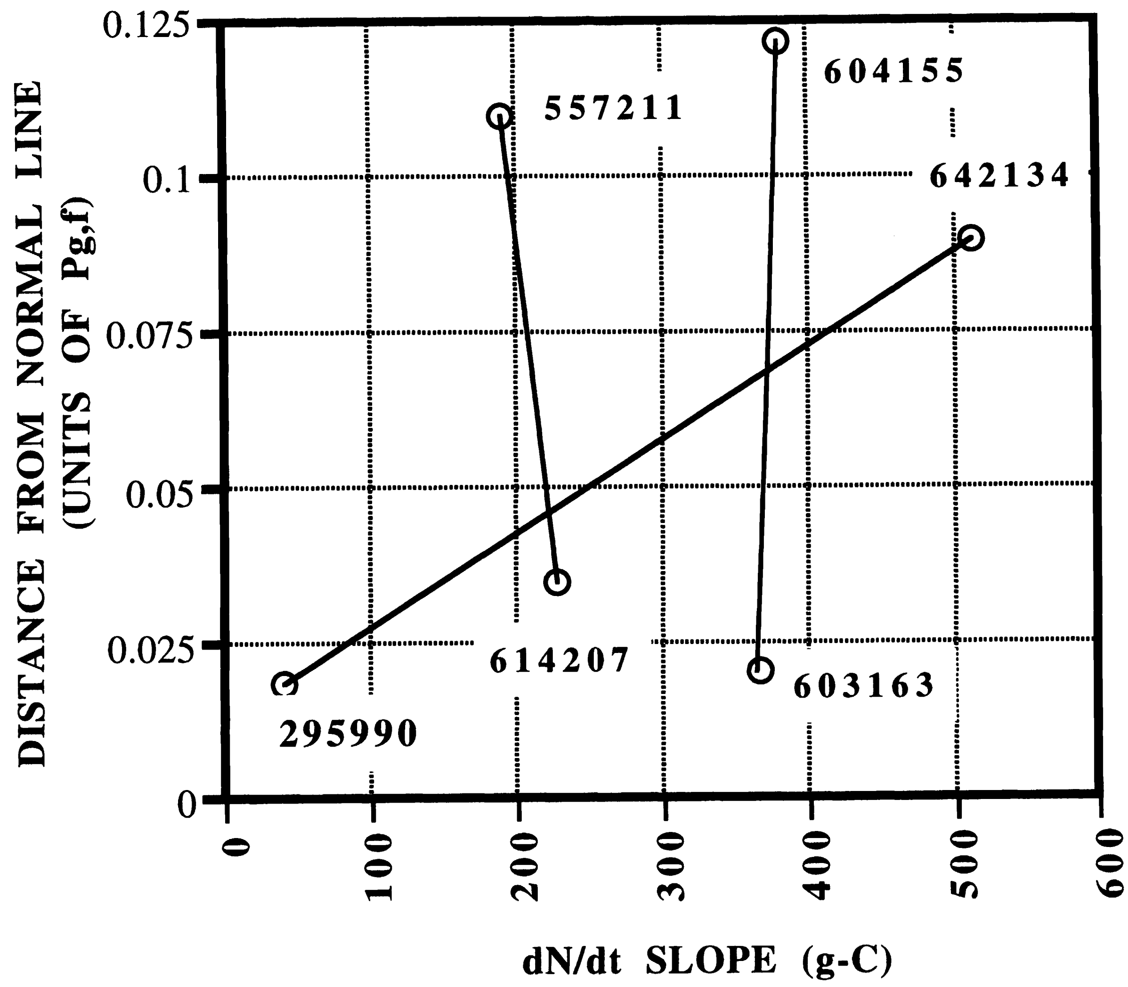
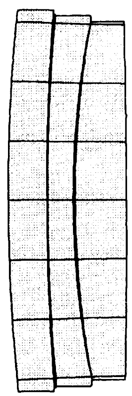
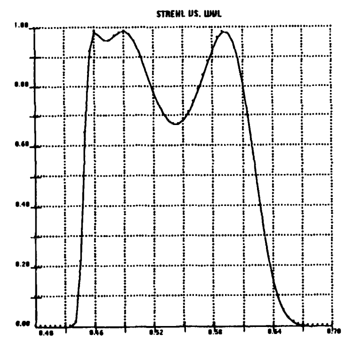


FIGURE 7. DISTANCE FROM THE NORMAL LINE VS. DN/DT SLOPE FOR SELECTED LOCKHEED LIQUIDS.

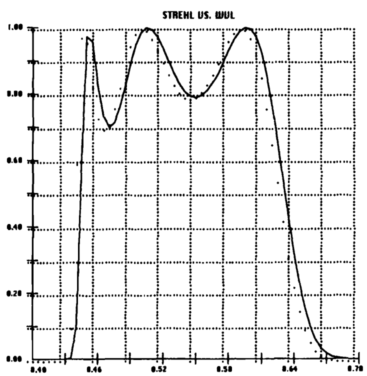


BK7/614207/F2/557211/BK7 DESIGN

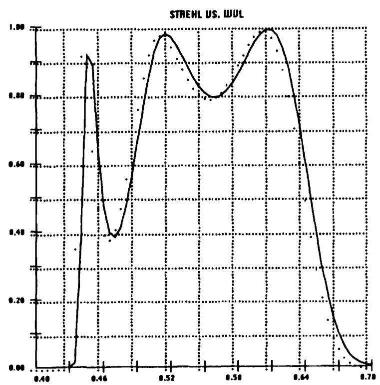


0 DEGREES F

EVALUATED OVER
THE VISIBLE
SPECTRUM
(0.4-0.7 MICRONS)



50 DEGREES F



100 DEGREES F

FIGURE 8. STREHL RATIO VS. WAVELENGTH FOR AN OBJECTIVE USING 557211/614207 AT SEVERAL TEMPERATURES.

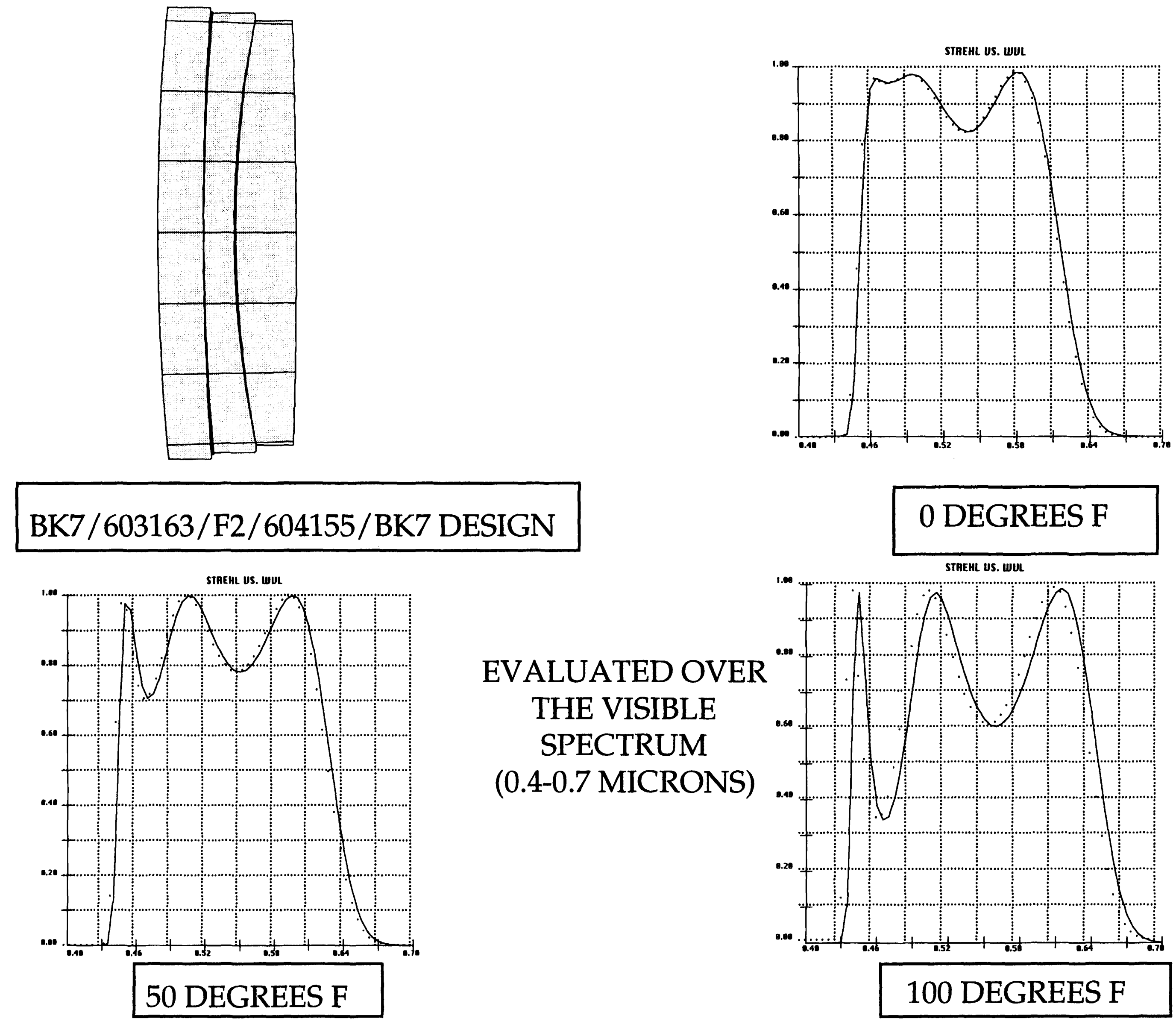


FIGURE 9. STREHL RATIO VS. WAVELENGTH FOR AN OBJECTIVE USING 6041155/603163 AT SEVERAL TEMPERATURES.