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Absorptive and Interference Coatings Applied on Replaceable Headlamp Bulbs

RATIONALE

The introduction and sale of tinted replaceable headlamp bulbs first appeared in the late 1990s. The lamps initially sold used standard replaceable capsules, which were coated with interference (multi-layer) coatings to produce a "HID color". A survey of bulbs that were being sold in the aftermarket showed that some of the bulbs did not meet performance specifications for light output or wattage. In the SAE Lighting Committee a Coated Bulb Task Force was formed. The Task Force was charged to investigate the effects of coatings applied on replaceable headlamp bulbs. The findings of this Task Force are presented in this information report. The findings have also been presented at the SAE 2004 World Congress and have been published [1].

1. SCOPE

This report investigates the use of single and multi-layer coatings on replaceable headlamp bulbs and how such coatings can affect the performance of bulbs in terms of light scattering, which can contribute to glare, and spectral separation in headlamps. Tests were developed to investigate the effects of absorptive and interference (multi-layer) coatings on bulbs, and on bulbs in headlamp systems. These tests provide validation for a proposed bulb color separation test, which establishes limits for spectral separation within the boundaries of SAE J578 white color requirements. The bulb color separation test provides a definitive selection criterion to identify bulbs that cause excessive light scatter (glare) and/or spectral separation in an optical system.

2. REFERENCES

2.1 Applicable Publications

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest version of SAE publications shall apply.

1. Bucher, K., Holt, D., King, G., Lüttgens, G., Rice, L., Schug, J., Terburg, B., Visser, A. de, Woodward, R., *"Investigation into the Effects of Absorptive and Interference Coatings Applied on Replaceable Headlamp Bulbs"*, SAE technical publication, SP-1875, #2004-01-0802, Society of Automotive Engineers, Warrendale, PA (2004).

2. Tessnow, T., Reiners, T., Hering, O., *"Optical Near Field Measurements and Ray-Tracing Simulation of Coated and Uncoated Halogen Lamps for Glare Analysis"*, SAE technical publication, SP-1787, #2003-01-0929, Society of Automotive Engineers, Warrendale, PA (2003).

3. ECE Economic Commission of Europe Regulation 5, http://www.unece.org/trans/main/wp29/wp29regs.html.

4. SAE Standard J578, *"Color Specification"*, Society of Automotive Engineers, Warrendale, PA, 2002.

5. ASTM E 308-66, "Method for Computing the Colors of Objects by Using the CIE System", American National Standards Institute, Inc., 25 West 43rd Street, New York, NY 10036-8002.

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6. FMVSS (Federal Motor Vehicle Safety Standards) (1998) Standard 108: "Lamps, reflective devices, and associated equipment". In: Code of Federal Regulations, 49CFR571, Washington, D.C.: Office of the Federal Register.

7. Terburg, B.P., et al. *"Review of Color Coated Bulb Test Methods and Data"*, report to United Nations Economic Commission for Europe's Working Party on Lighting and Light Signaling, report #GRE44/inf.1 (2000).

8. ECE Economic Commission of Europe Regulation 8, http://www.unece.org/trans/main/wp29/wp29regs.html.

9. ECE Economic Commission of Europe Regulation 20, http://www.unece.org/trans/main/wp29/wp29regs.html.

3. INTRODUCTION

The introduction and sale of tinted replaceable headlamp bulbs first appeared in the late 1990s. The lamps initially sold used standard replaceable capsules, which were coated with interference (multi-layer) coatings to produce a "HID color". A survey of bulbs that were being sold in the aftermarket showed that some of the bulbs did not meet performance specifications for light output or wattage. Another characteristic of the multiple-layer interference coating was that the light output was separated into bands of color which depending on the viewing angle could range from reddish to greenish to blue-ish white. The color separation was still noticeable when placed in a headlamp.

An oncoming vehicle could produce a change of color that could confuse drivers or more typically produced a higher level of offending glare.

Existing tests and regulations did not anticipate tinted headlamp bulbs. To address this issue an international group of engineers from the bulb manufacturers under auspices of SAE assembled a task force to investigate the effects and recommend the appropriate test methods for governing their design and use.

4. BACKGROUND AND TEST METHODS

The initial investigation of color separation focused on the investigation of the color separation as it pertains to the light output from the bulb. The typical US replaceable bulbs were used in the investigation. These bulbs were ANSI 9004, 9005, 9006 and 9007.

After the first round of tests were completed and a proposed method was documented, the scope of the investigation was broadened to include the consideration of the effects of glare from the bulb in a lighting system such as a headlamp. For this reason the testing was separated into Round 1 Testing and Round 2 Testing.

Round 1 testing initially investigated two types of methods: The Bulb Haze Method and Bulb Color Separation test. A color separation test standard was later adopted into European regulations and a US version was developed simultaneously. These methods are described below.

Round 2 testing investigated four potential test methods: the Bulb Haze Method, a Reference Reflector Method, Bulb Optical Properties and Near Field Imaging. Of these the Reference Reflector method and the Near Field Imaging were used. Near field imaging is widely accepted method in the study of the optical performance of bulbs [2].

5. PHYSICS OF COLOR SEPARATION

In understanding what causes spectral (color) separation in certain types of coated bulbs, one has to investigate the phenomena that occur when white light from a tungsten filament in a halogen bulb traverses the glass bulb wall of the coated bulb. A coated bulb has the outside bulb wall coated with a thin film that filters light either through absorption, or through interference. In the latter case the thin film is a multi layer film. In either case of filter technologies the purpose of the filter is to achieve a more bluish white color of light, either by absorbing some light in the yellow wavelengths (absorption coating), or by reflecting yellow and red light out of the spectrum (interference coating). The process of light traversing the coating is illustrated in Figure 1. Note that the schematics in Figure 1 are simplified to show the processes that occur in the coating layer only. Specular reflection and transmission on the surfaces of glass bulb wall have not been graphically depicted.

Figure 1a shows transmission of white light (shown as composed of its spectral components) through the wall of a bulb that has been coated with an absorption coating. In this case specular transmission is the dominant process, and the overall transmitted color is bluish white.

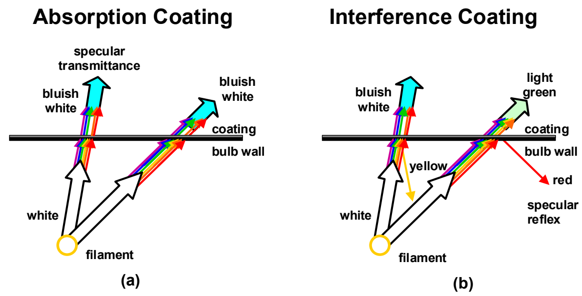

FIGURE 1 -TRANSMISSION OF WHITE LIGHT (SHOWN AS COMPOSED OF ITS SPECTRAL COMPONENTS) THROUGH THE WALL OF A BULB THAT HAS BEEN COATED WITH (A): AN ABSORPTION COATING. IN THIS CASE SPECULAR TRANSMISSION IS THE DOMINANT PROCESS. (B): AN INTERFERENCE COATING. IN THIS CASE SPECULAR TRANSMISSION AND SPECULAR REFLECTION OCCUR. YELLOW AND RED COMPONENTS OF THE LIGHT ARE REFLECTED BACK INTO THE INNER PART OF THE BULB.

Figure 1b shows transmission of white through the wall of a bulb that has been coated with an interference coating. In this case specular transmission and specular reflection occur. Yellow and red components of the light are reflected back into the inner part of the bulb. The light will appear bluish white, light green, reddish, or another color different from bluish white dependent on the angle that the bulb is viewed from. In regard to this it is worth noting that, when subjected to spherical photometry, bulbs using both technologies will show an integrated color of bluish white. The yellow and red components of the light that are reflected towards the inside of the interference-coated bulb generate virtual images of the filament in the respective colors. The virtual images are out of focus for the optical system design and give rise to color separation and glare when the bulb is used in an optical system (headlamp). Figure 2 shows an example of the virtual images generated in a H7 bulb with interference coating.

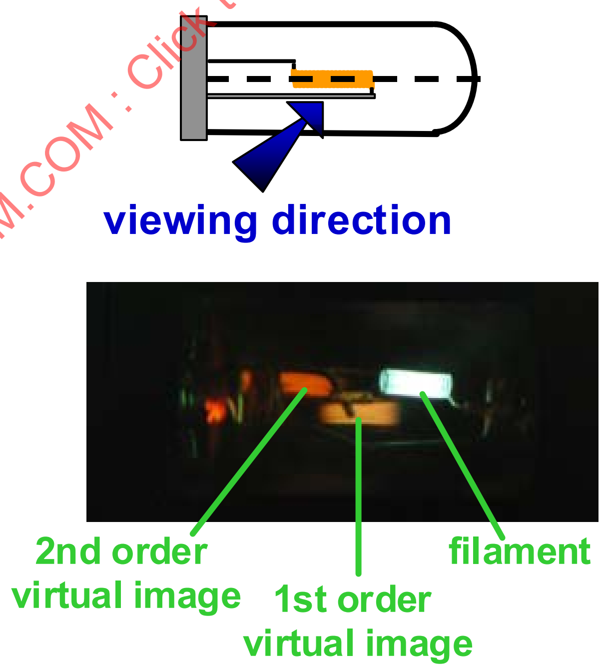

FIGURE 2 - PROJECTION ONTO THE WALL FOR A H7 BULB WITH INTERFERENCE COATING. THE FIRST (YELLOWISH) AND SECOND (REDDISH) VIRTUAL IMAGES ARE PRESENT FOR THE INTERFERENCE COATED BULB, BUT NOT FOR THE CLEAR AND ABSORPTION COATED BULB. A SKETCH OF THE VIEWING DIRECTION IS INCLUDED.

6. TESTING

6.1 Round 1 Testing

6.1.1 Bulb Haze Method

The bulb haze method is based on the assumption that glare is the end result of light scattering from bulb coatings. Measuring light scattering from the bulb will give information on the potential that a coating can create glare.

The measurement method is based on determining the brightness of light scattered from the bulb wall relative to the brightness of the filament. No widely accepted measurement method existed. The method described in this work was adapted from an ECE method used to measure haze caused by abrasion [3].

In the bulb haze (glare) measurement the filament is aligned such that the broad view is projected on a plane. The filament is energized and focussed on a detector that has a stripe that blocks the filament. Readings are taken with and without the light block. The haze or glare level is the ratio of light scattered from the bulb to the total light. The acceptable values could be confirmed by using the reference reflector to evaluate the effects on the system. Figure 3 shows a schematic of the measurement system used.

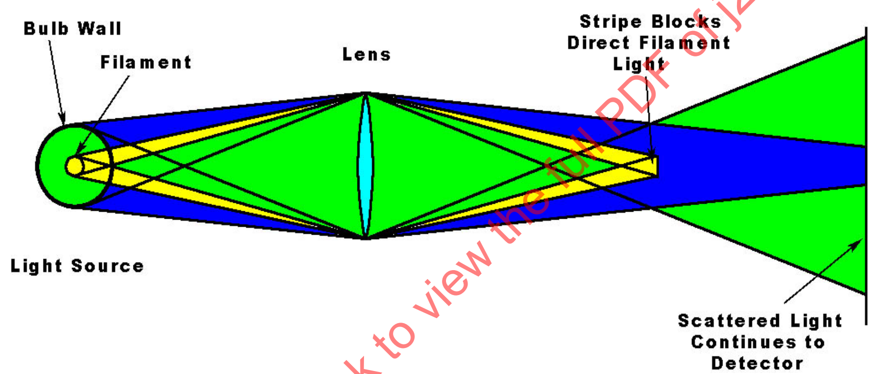

FIGURE 3 - BULB HAZE MEASUREMENT SYSTEM. AN ACHROMATIC LENS IS USED TO CREATE THE IMAGE.

TABLE 1 - BULB HAZE MEASUREMENT RESULTS

Tracking Number		Bulb Type	Coating Type	Measured Filament	Blocking Filter	No Filter	% Ratio
3	S	9004	Absorption	Low Beam	0.183	18.23	1.0
5	S	9004	Absorption	Low Beam	0.178	14.61	1.2
1	S	9004	Absorption	Low Beam	0.241	19.29	1.2
4	S	9004	Absorption	Low Beam	0.216	16.16	1.3
2	C	9004	Multi-Layer	Low Beam	0.249	9.41	2.6
13	E5	9004	Multi-Layer	Low Beam	0.454	9.08	5.0
14	E6	9004	Multi-Layer	Low Beam	0.552	8.59	6.4
11	P3	9005	Absorption	-	0.084	14.19	0.6
12	P4	9005	Absorption	-	0.079	12.71	0.6
8	C	9005	Multi-Layer	-	0.149	11.54	1.3
9	P3	9006	Absorption	-	0.062	11.91	0.5
10	P4	9006	Absorption	-	0.071	9.92	0.7
7	C	9006	Multi-Layer	-	0.104	7.3	1.4
6	C	9007	Multi-Layer	Low Beam	0.173	8.16	2.1
Measurments made at 12.80 volts							7-Dec-99

Data from a wide range of bulbs with absorption and multiple layer interference coatings were taken in order to make a comparison of the performance of the different coating technologies possible. Table 1 gives a summary of the results that were obtained with this method. The last column in the table lists the ratio between the light measured with the blocking filter to the light measured without the blocking filter. This is assumed to be proportional to the ratio of light scattered from the bulb to the total light. As can be observed, the ratio is considerably higher for the coated bulbs with multi-layer technology. This implies increased light scattering for those bulb types.

Although these results are encouraging, this method has several limits. The alignment of the optical system is difficult due to the small image size. In addition to that measurements are sensitive to alignment errors. Furthermore, the method requires different striped plates for each bulb type and each filament design. Lastly, the data cannot be evaluated using alternate methods.

6.1.2 BULB COLOR SEPARATION TEST

In the bulb color separation test chromaticity readings of an energized bare blue bulb are taken in directions that fall within a conical volume of revolution, where the axis of revolution is parallel to the bulb axis. Figure 4a illustrates the measurement arrangement. Within the conical volume, a measurement grid can be defined, for instance the one that was used in this study where the polar angle α and azimuthal angle β both vary over a range of ±30°. Figure 4b shows the grid of measurement directions that is constructed within the α and β intervals

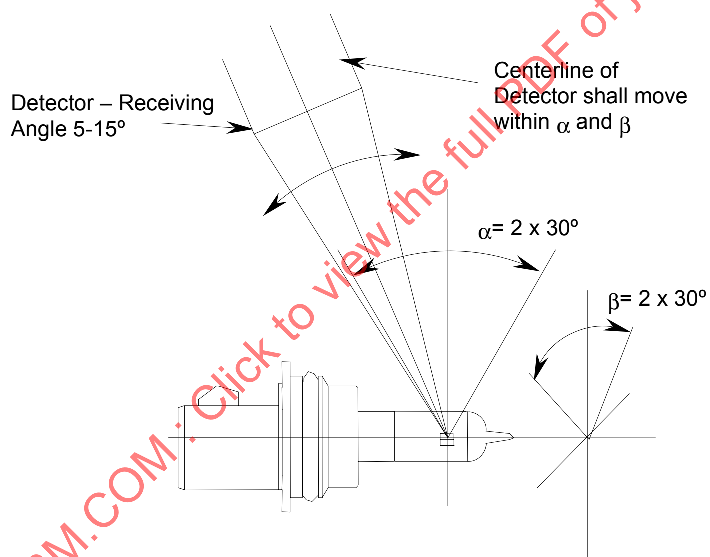

FIGURE 4A - BULB COLOR SEPARATION TEST MEASUREMENT SET-UP

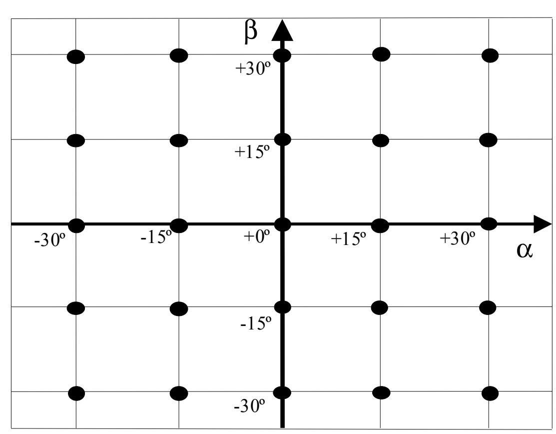

FIGURE 4B - BULB COLOR SEPARATION TEST MEASUREMENT GRID

The chromaticity readings are made with a receiver that is centered on an axis that is perpendicular to the bulb axis and the filament axis (in the case of a double filament lamp, the main or high beam filament is used). The detector-receiving angle should be between 5° and 15°. The test is designed so that it can be performed with a standard type A or type B goniometer, as well as on any dedicated goniometer set-up.

The test requires that measured bulb chromaticities fall inside a specified acceptance area that is situated within the SAE J578 white light area [4] in the CIE chromaticity diagram [5], and has its center located anywhere on the black body curve. Figure 5 shows a section of the CIE chromaticity diagram, with outline of the SAE J578 white light area as a solid line. The bulb color separation test acceptance area within the white light area is indicated by the dashed rectangle, and has its center on the black body curve. An arbitrary position of the acceptance area is shown.

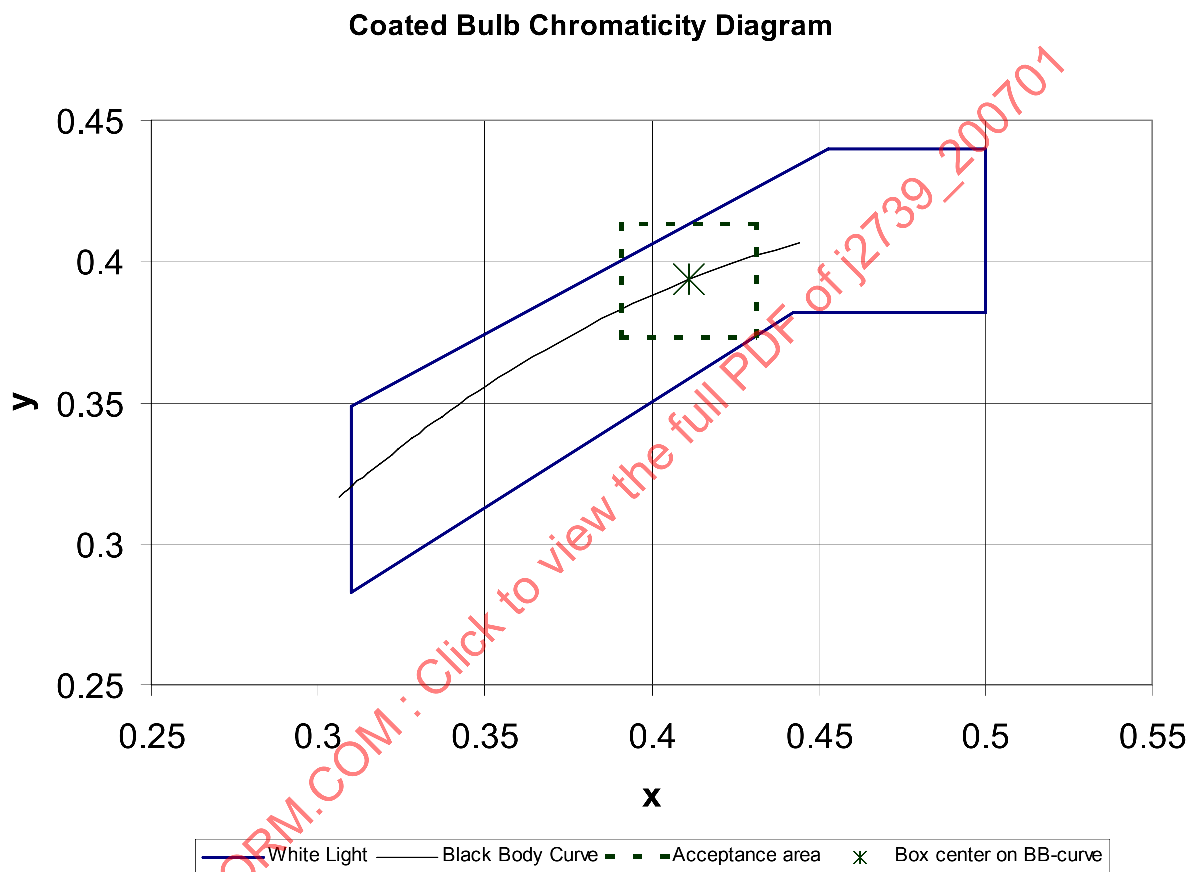

FIGURE 5 - DETAIL OF THE CIE 1931 CHROMATICITY DIAGRAM SHOWING THE SAE J578 WHITE LIGHT AREA; ALSO SHOWN IS BULB COLOR SEPARATION TEST ACCEPTANCE AREA, HERE LOCATED WITH ITS CENTER AT AN ARBITRARY POSITION ON THE BLACK-BODY CURVE

For brevity, results of the Round 1 color separation testing will not be discussed, as they are similar to the outcome of the Round 2 color separation testing that will be discussed in detail in a later section.

6.2 Round 2 Testing

6.2.1 Introduction to Round 2 Testing

In follow-up to the results of the first round robin the SAE Coated Bulb Task Force initiated further studies and launched a second round robin to establish a quantitative correlation between the quantity measured with the bulb color separation test, and headlamp glare. The assumption was made that the physical properties of the color filter mechanism that is used in the construction of the bulb will control both color separation of the bare bulb, and headlamp glare for a headlamp equipped with that type of bulb. The study involved three parts that built on each other, and was carried out with commonly used single and double filament headlamp bulb types. The first part consisted of gathering near field filament image data of energized bulbs. The goal was to identify and examine higher order filament images, which are often the cause of glare. The brightness of these secondary filament images can be affected by the added filter technology used in the coated halogen lamp. Part two of he study involved U.S. beam photometry with a reference reflector. Beam photometry readings at the seeing point, as well as points corresponding to rear view mirror glare and opposing driver glare were taken. In part three the round robin bulbs were subjected to the bulb color separation test.

In the round 2 testing the selection of commonly used U.S. headlamp bulbs included the 9004, 9005, 9006, and 9007. The bulbs in the round robin were circulated to the various laboratories that carried out the tests. The details of these bulbs and their designations used throughout this report, are listed in Table 2. Note that all, or a selection of these bulbs, were used, dependent on the test they were subject to. Interference type bulbs were split into two categories, "heavy" and "light". When the color for a bulb with a "heavy" interference coating is measured in an integrating sphere the chromaticity is more shifted towards the blue, than for a bulb with a "light" interference coating.

TABLE 2 - BULBS USED IN THE ROUND 2 TESTING, LISTED BY BULB TYPE THEIR STUDY DESIGNATION, AND THE TYPE OF FILTERING TECHNOLOGY USED

Bulb Type	Bulb designation	Bulb Coating type
9004	CLR-Ref 1	None
9004	CLR-Ref 4	None
9004	ABS-1	Absorption
9004	ABS-3	Absorption
9004	ABS-4	Absorption
9004	ABS-5	Absorption
9004	Light-INT-E5	Interference (light)
9004	Light-INT-E6	Interference (light)
9004	Heavy-INT-E2	Interference (heavy)
9004	Heavy-INT-4004	Interference (heavy)
9005	ABS P	Absorption
9005	ABS	Absorption
9006	CLR-R	None
9006	ABS 1	Absorption
9006	ABS-2	Absorption
9006	ABS-3	Absorption
9006	INT-5	Interference (heavy)
9007	CLR-Ref 2	None
9007	CLR- Ref	None
9007	CLR-BTF 301	None
9007	CLR-BTF-302	None
9007	CLR-BTF-303	None
9007	ABS-BTF-304	Absorption
9007	ABS-BTF 305	Absorption
9007	ABS-BTF 306	Absorption
9007	INT-E6	Interference (light)

6.2.2 Goniometer Scans

In comparison to the Bulb Haze measurement method, the goniometer measurement method which is decribed in this section has the advantage that it uses a widely available measurement system, with low cost additional equipment (lens and fixture). Measurements are easy to replicate and the data can be evaluated using many techniques. With the goniometer optical set-up a near field image of the filament can be measured.

Figure 6 shows a picture of the goniometer measurement set-up. A bulb is clamped in a fixture that is mounted on a goniometer table. In front of the bulb a 12 mm diameter Vis-Nir Coated Plano Convex lens was mounted with 30 mm focal length.

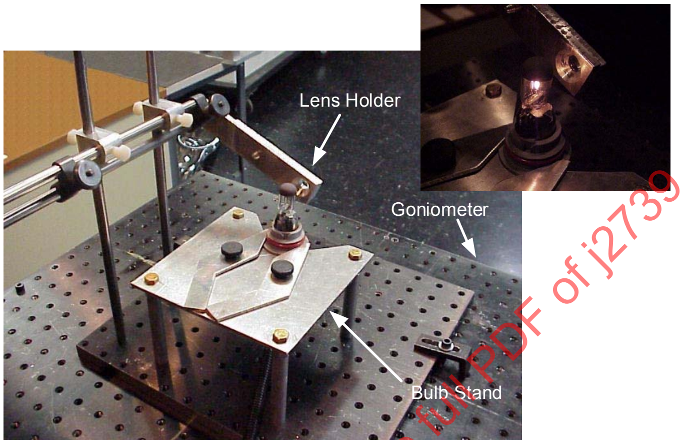

FIGURE 6 - GONIOMETER SCAN TEST SET-UP;
INSET: CLOSE-UP VIEW OF BULB AND LENS HOLDER

FIGURE 7 - SCREEN PICTURE OF A TYPICAL FOCUSED FILAMENT
IMAGE MADE WITH THE GONIOMETER SCAN SET-UP

During the measurement the bulb was energized and the image of the energized filament was focused and centered on a screen at 25 ft A typical picture of a filament focused on the screen is shown in Figure 7. After focusing the filament, the baffel was put in place and the isocandela diagram recorded. For double filament bulbs the low beam filament was energized.

A typical isocandela diagram that results from this method is shown in Figure 8 (top). The left side of the figure shows the isocandela lines for the filament image of a bulb with negligible scatter and the right side the diagram for a bulb with noticeable scatter.

In order to facilitate analysis of the complex data distribution in the 2-dimensional isocandela diagram the lumens are summed and normalized for a cross section in the direction of the narrow view of the filament. Examples of typical normalized lumen distributions that result from this procedure are shown in the lower part of Figure 8.

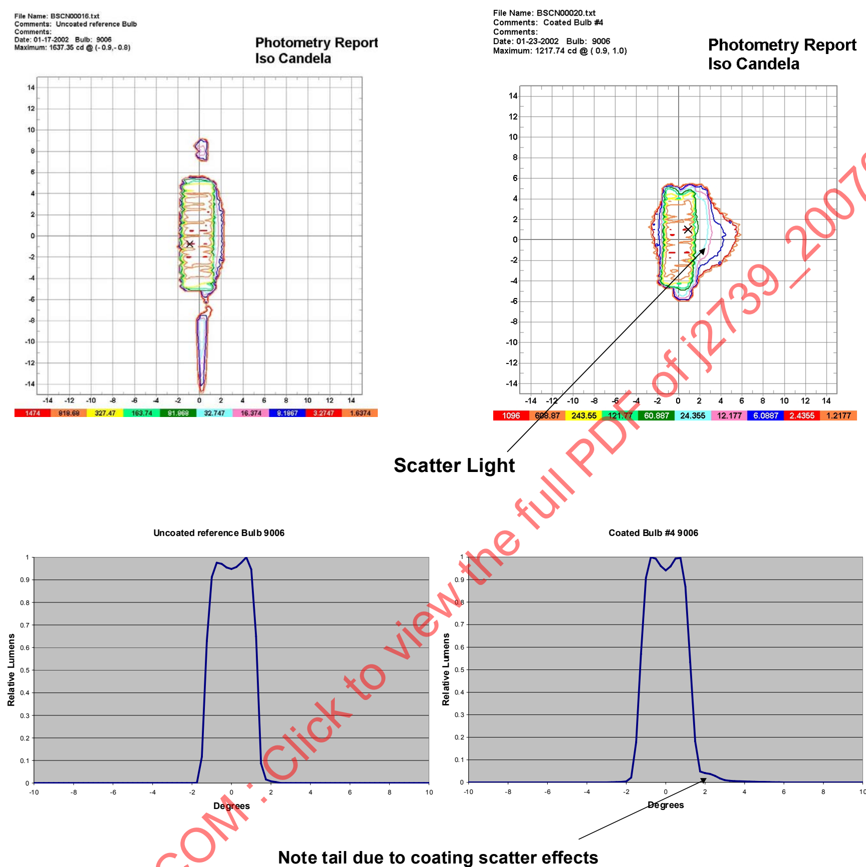

FIGURE 8 - (TOP): TYPICAL BULB SCAN ISOCANDELA PLOTS OF THE FILAMENT IMAGE FOR BULBS WITH NEGLIGIBLE SCATTER (LEFT) AND SCATTER (RIGHT). (BOTTOM): NORMALIZED LUMEN TOTALS FOR A CROSS SECTION IN THE DIRECTION OF THE NARROW VIEW OF THE FILAMENT, FOR THE ISOCANDELA PLOTS SHOWN IN THE TOP PART OF THIS FIGURE.

The graphical representation of the normalized lumen totals provides means for a straightforward qualitative visual comparison between the isocandela diagrams of bulb types of different coating technologies. This is illustrated in the lower part of Figure 8, where a comparison of the left vs. right lumen distribution can be made.

Additionally a quantitative numerical analysis of the normalized lumen totals was performed. Bulbs were rated by two different methods. The Width Ratio method and the Lumen Ratio method.

In the Width Ratio method the ratio of the width of the curve at the 50% maximum intensity level to the width of the curve at the 3% max intensity level is calculated. A rationale for using this method is that optical engineers design lamps based on expected optical characteristics such as the location and brightness of filament image, bulb wall reflections and illuminated internal structures. Significant changes to these characteristics will cause performance unlike the design intent and will potentially cause glare. The width ratio method is graphically illustrated in Figure 9.

In the Lumen Ratio method the ratio of the energy in the scatter light area (as defined outside the 10% maximum intensity area) to the energy in the main filament area (as defined greater than 10% of the maximum intensity) is calculated.

A rationale for using this method is that optical engineers design lamps based on the extents of the physical filament. The 10% line can be considered the physical limit of the filament. Significant amounts of light found outside the physical limits of the filament may cause glare. The lumen ratio method is graphically illustrated in Figure 10. The main filament area in the center is shaded light, and the scatter light areas flanking the main filament area peak are shaded dark.

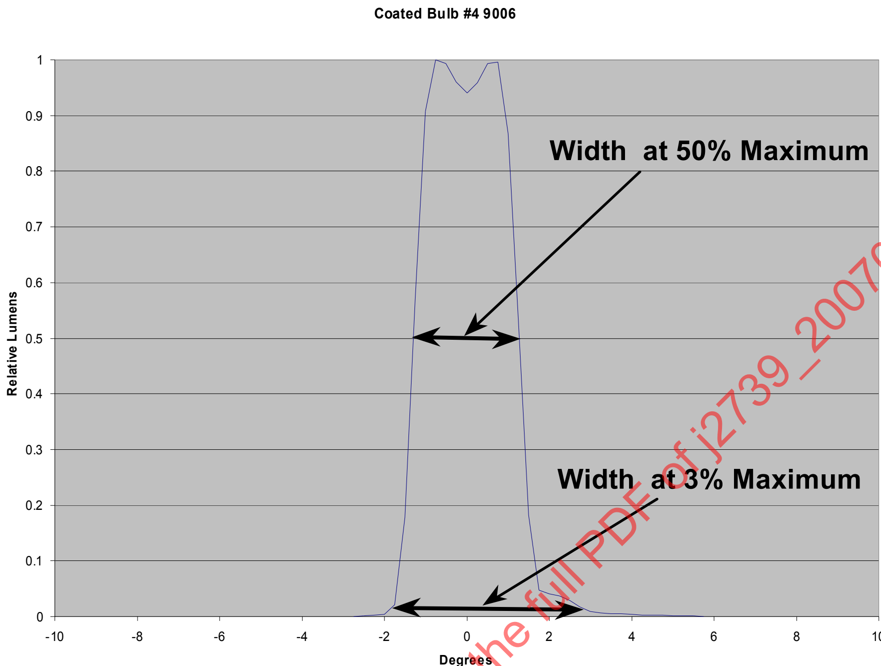

FIGURE 9 - NORMALIZED LUMEN TOTALS CURVE SHOWING THE PARAMETERS OF THE CURVE, WIDTH AT 50% OF THE MAXIMUM, AND WIDTH AT 3% OF THE MAXIMUM, WHICH ARE USED TO CALCULATE THE WIDTH RATIO

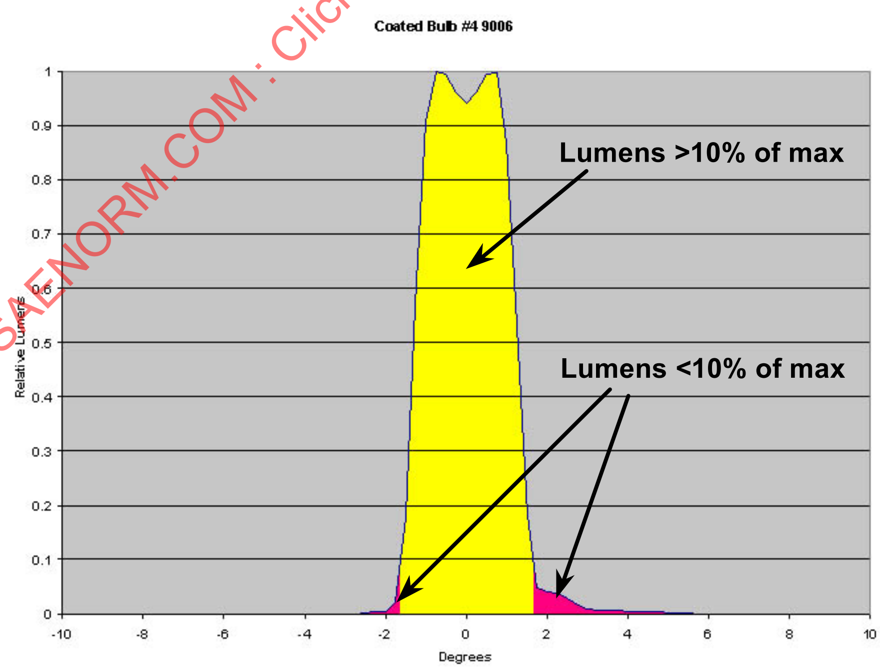

FIGURE 10 - NORMALIZED LUMENS TOTAL CURVE SHOWING THE MAIN FILAMENT AREA (INTENSITY GREATER THAN 10% OF THE MAXIMUM LUMENS) AND THE SCATTER LIGHT AREA (INTENSITY LESS THAN 10% OF THE MAXIMUM LUMENS) THAT ARE USED IN THE CALCULATION OF THE LUMEN RATIO

Goniometer isocandela scans of the majority of the round robin bulbs listed in Table 2 were performed. The data was analyzed using both the width ratio and lumen ratio methods. The results of these measurements and the calculated ratios are listed in Tables 3 through 5. In addition to the coating type and bulb identification, the tables list the view of the filament from which the data was taken, and the horizontal and vertical ratios for each of the ratio calculations. The horizontal value is the ratio calculated for the normalized lumen totals curve of the narrow view of the filament, and has been used in the analysis in this study. The normalized lumen totals curve of the broad view of the filament was also extracted from the isocandela data, from which the vertical ratio value was calculated. The vertical ratio values were not used in the analysis as the extent of the filament in broad view was less well-defined leading to a potentially larger error in the choice of the parameters for the ratio calculation.

Examining the tables, individual trends in the behavior of the horizontal lumen ratio and horizontal width ratio with coating type can be observed for each of the bulb types. The difference in trends is likely attributed to the different types of construction and internal geometry of each bulb type.

In Table 3 it is observed for the 9006 bulb that the horizontal width ratio shows an increasing trend going from a clear bulb to a bulb with absorption coating, to a bulb with interference coating (here labeled "dichroic"). For the interference coated bulbs the width ratio assumes a value considerably higher (1.7 to 2.2) than the average 1.3 for clear and 1.4 for absorption coated bulbs. This result agrees with the expectation that the location and brightness of the filament image, bulb wall reflections and illuminated internal structures are not as crisp and well defined for the bulb with the interference coating due to the presence of the strong virtual filament images.

When the horizontal lumen ratio results in Table 3 are examined, again a trend is observed. In this case the lumen ratio drops going from a clear bulb to a bulb with absorption coating, to a bulb with interference coating. The lower horizontal (and vertical) lumen ratios for the interference coated bulb agree with the expectation that due to the presence of the strong virtual filament images in that type of bulb significant amounts of light are found outside the physical limits of the filament. For the purpose of this analysis 9006 bulb #1 with absorption coating was considered an outlier due to the unusually low horizontal lumen ratio number in combination with the large deviation from the mean in vertical lumen ratio.

TABLE 3 - RESULTS OF THE GONIOMETER SCAN ANALYSIS FOR THE 9006 BULBS TESTED

Bulb 9006						
			Width Ratio		Lumen Ratio	
View	Coating	Bulb ID	Horz	Vert	Horz	Vert
side	Uncoated	Reference	1.29	1.29	87.31	100.84
side	Absorption	#1	1.39	1.38	43.02	141.09
side	Absorption	#2	1.35	1.30	133.52	99.06
side	Absorption	#3	1.37	1.40	95.92	108.76
side	Dichroic	#4	1.64	1.33	41.18	75.81
side	Dichroic	#5	2.22	1.36	14.32	84.99

For the 9004 and 9007 bulbs the analysis becomes less straightforward due to presence of a second filament and additional metal lead wires and filament support structure inside the glass envelope. The results of the analysis are listed in Tables 4 and 5 for the 9007 type and 9004 type bulbs under evaluation, respectively.

The horizontal width ratio data for the 9007 bulb types in Table 4 does not indicate a noticeable trend in the side view. The trend in the horizontal lumen ratio, however shows a definite increase for the interference coated (dichroic) bulb when compared with the uncoated and absorption coated bulbs tested in side view. The increase is not well understood and will be further investigated. However, it can be used as a means to make a distinction between bulbs with the different coating types.

As for the 9007, the horizontal (as well as vertical) width ratio data for the 9004 bulb types in Table 5 do not indicate a noticeable trend in the top view. Top view was used for the 9004 bulbs because of the transverse mounting of the filament in this bulb type.

The 9004 horizontal lumen ratio shows a trend towards a decrease in ratio for the interference coated (dichroic) bulb when compared with the uncoated and absorption coated bulbs tested. This trend is in agreement with the expectations as was observed for the 9006 bulbs as well.

TABLE 4 - RESULTS OF THE GONIOMETER SCAN ANALYSIS FOR THE 9007 BULBS TESTED

Bulb 9007						
			Width Ratio		Lumen Ratio	
View	Coating	Bulb ID	Horz	Vert	Horz	Vert
side	Uncoated	BTF302	3.01	2.39	5.91	14.98
side	Uncoated	Reference	2.03	1.43	13.42	40.70
side	Uncoated	BTF301	1.78	1.34	16.65	57.62
side	Uncoated	BTF303	1.76	2.52	8.00	12.89
side	Absorption	BTF306	2.52	2.49	5.61	11.92
side	Absorption	BTF304	2.42	1.93	6.16	12.58
side	Absorption	BTF305	2.06	2.26	8.66	12.29
side	Dichroic	#6	2.56	1.75	25.80	62.10
top	Uncoated	BTF303	1.95	1.30	11.32	20.11
top	Uncoated	BTF302	1.88	1.28	9.82	20.15
top	Uncoated	BTF301	1.87	1.27	18.58	74.92
top	Absorption	BTF304	2.02	1.33	7.39	17.77
top	Absorption	BTF305	1.81	1.35	11.95	20.39
top	Absorption	BTF306	1.72	1.27	11.69	22.39

TABLE 5 - RESULTS OF THE GONIOMETER SCAN ANALYSIS FOR THE 9004 BULBS TESTED

Bulb 9004						
			Width Ratio		Lumen Ratio	
View	Coating	Bulb ID	Horz	Vert	Horz	Vert
Top	Uncoated	Reference	1.28	1.34	107.12	48.61
Top	Uncoated	Ref #4	1.28	1.91	103.86	13.58
Top	Absorption	#1	1.22	1.64	116.85	12.20
Top	Absorption	#3	1.26	1.30	216.79	11.03
Top	Absorption	#4	1.24	1.46	145.97	9.23
Top	Absorption	#5	1.20	1.57	239.39	12.48
Top	Dichroic	#2	1.31	1.50	99.58	13.51
Top	Dichroic	#E6	1.25	1.35	107.82	13.16
Top	Dichroic	#E5	1.38	1.19	113.31	13.74

It is clear that the goniometer scan method is a powerful method to determine the presence of uncontrolled light in halogen bulbs. It allows for qualitative as well as rigorous quantitative analysis. For the type of quantitative analysis of the bulb scan data chosen here (narrow and broad view normalized lumen totals) the type of bulb and internal construction of the bulb need to be taken into consideration when looking for trends in the data. No sole, unique trend can be defined that would capture the behavior of for different types of bulbs and bulb constructions. However it is possible to arrive at a conclusion for coated versus uncoated types within a family of bulbs as was shown in this work for the 9004, 9006 and 9007 bulb families.

6.2.3 Reference Reflector

In this part of the study U.S. beam photometry was performed with a reference reflector and a selection of the round robin bulbs.

The use of a reference reflector is a well-known design strategy to evaluate different bulbs in a typical lamp. The evaluation should provide insight into expected performance differences between bulbs for most headlamps. Using a typical headlamp will expose which bulb features are significant, and which features have no significance.

The procedure applied to the round robin bulbs was as follows. The same reference reflector was used for testing bulbs of the same type (e.g. 9006). The bulb location was adjusted to correct for filament variations. Then the headlamp was aimed for consistent performance.

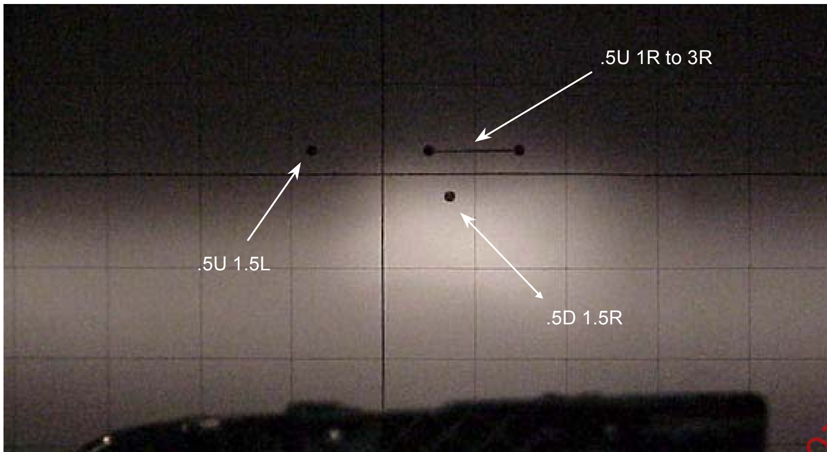

FIGURE 11 - TEST POINTS FOR THE 9007 REFERENCE REFLECTOR

Beam photometry readings [6] were taken at the seeing point (0.6D, 1.3R or 0.5D, 1.5R.), at the opposing driver glare point (light level at 0.5U, 1.5L.) and in the area corresponding to the rear view mirror glare, the light level at 0.5U, 1R-3R, which is the interior mirror test line. An example of the test points evaluated using the 9007 reference reflector is given in Figure 11.

TABLE 6 - RATIOS OF SEEING LIGHT TO OPPOSING GLARE AND SEEING LIGHT TO MIRROR GLARE MEASURED USING THE REFERENCE REFLECTOR APPROACH

Bulb	Type	Designation	Ratio Seeing to Opposing Glare	Ratio Seeing to Mirror Glare
9004	CLR	CLR-Ref 1	17.2	9.6
9004	CLR	CLR-Ref 4	13.1	7.7
9004	ABS	ABS-1	17.4	10.1
9004	ABS	ABS-3	10.2	5.4
9004	ABS	ABS-4	17.5	9.4
9004	ABS	ABS-5	20.0	10.5
9004	INT	INT-E5	14.5	7.8
9004	INT	INT-E6	9.0	7.4
9004	INT	INT-E2	6.6	4.7
9004	INT	INT-4004	5.2	5.3
9006	CLR	CLR-R	21.7	20.4
9006	ABS	ABS 1	14.4	19.9
9006	ABS	ABS-2	25.1	25.1
9006	INT	INT-5	6.2	8.4
9007	CLR	CLR- Ref 2	6.3	3.2
9007	ABS	ABS-BTF-304	4.5	3.7
9007	ABS	ABS-BTF 305	3.6	3.5
9007	INT	INT-E6	5.4	3.2

NOTE: Seeing Light is the level at 0.6D, 1.3R or 0.5D, 1.5R. Opposing glare is the light level at 0.5U, 1.5L. Mirror glare is the light level at 0.5U, 1R-3R (interior mirror test line).

From the beam photometry readings two ratios were calculated, the ratio of the seeing light level to the opposing glare level and mirror glare level respectively. A low ratio would be an indication that the light source in the reflector would cause excessive glare.

The ratios that were calculated from the reference reflector tests are listed in Table 6. The results from the reference reflector evaluation of these bulb types were dependent upon bulb type and coating.

In all cases but one, the 9004 exhibited significantly worse opposing driver glare with an interference coating. The bulbs with absorption coatings had roughly comparable ratios to the bulbs with no coating. The 9004 mirror glare results were ambiguous. Mirror glare was high, most likely due to reflections from the upper beam filament, support wires, and bulb wall. The 9004 is becoming obsolete, so it is unfortunate that it was the bulb type most easily obtained with various coatings.

The 9006 exhibited a large difference for the interference coated bulbs versus the bulbs with absorption or no coating. The number of test samples was limited.

The 9007 results were ambiguous. The 9007 bulb suffers from many internal reflections due to its construction, masking the effects of coatings. This happens to some extent with all dual filament bulbs, but the 9007 is the most extreme example currently in use.

Summarizing the above results, it is observed that the 9006 bulb design exhibited a better glare to seeing light ratio for uncoated and absorption coated bulbs than either of the dual filament bulbs. This was not unexpected, because of the absence of additional metal structure (support, other filament) in the single filament design. First experiences of the set makers with H13 bulbs is that it has better seeing light to glare light ratios than currently used dual filament bulbs. Results with this bulb may be reasonably anticipated to be similar to the 9006. Overall, the performance of coated bulbs can be quite good, provided that the coating quality is controlled.

6.2.4 Color Separation Testing

COLOR SEPARATION TESTING

The commonly used U.S. headlamp bulbs (9004, 9005, 9006, 9007) listed in Table 1 were subjected to the bulb color separation test.

A schematic view of the test set-up used in the test is shown in Figure 12. The bulbs are mounted on the table of a type-A goniometer. A colorimeter is placed at 3.05 m distance from the center of the table. At this distance the angular acceptance of the colorimeter is 1.3°. Even though this acceptance is less than the preferred 5-15°, a previous report has shown that the results are not compromised by this choice of acceptance [7]. In this measurement set-up the detector is fixed and the bulb is rotated with the goniometer table. The bulb positions are accomplished by combined rotations around the X-axis and the Z-axis (through the major filament, perpendicular to the goniometer table).

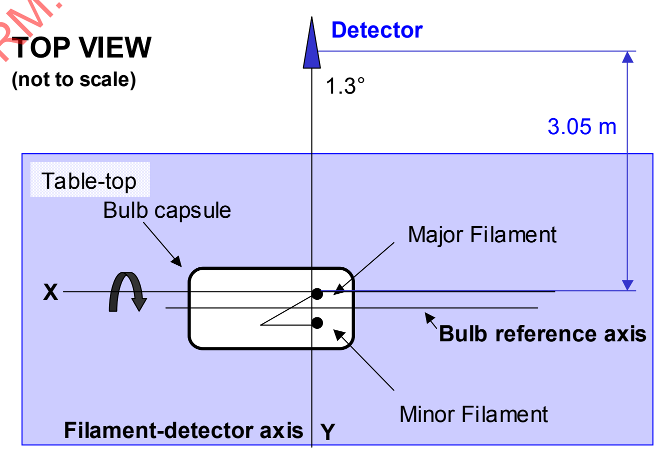

FIGURE 12 - SCHEMATIC VIEW OF THE EXPERIMENTAL ARRANGEMENT USED FOR THE BULB COLOR SEPARATION TEST. THE FIGURE SHOWS THE SET-UP FOR A DOUBLE FILAMENT 9004 BULB. DURING THE MEASUREMENT THE BULB IS ROTATED AROUND AXIS X AND AXIS Z (NOT LABELED, THE Z AXIS IS THROUGH THE MAJOR FILAMENT, PERPENDICULAR TO THE X AND Y AXIS).

Both single filament (9005 and 9006) and double filament (9004 and 9007) bulbs were tested. For the double filament bulbs the major filament is energized during the tests. All bulbs are positioned in normal (horizontal) operating position, with reference axis perpendicular to the detector axis, when the goniometer is at (x = 0, y = 0). For double filament bulbs, each bulb is positioned so that the major filament axis is perpendicular to the detector axis as well. During the measurements the bulb is rotated and tilted in front of the fixed detector. Color coordinates are measured over a grid that falls within a cone, which has its symmetry axis coinciding with the detector axis, and top-angle located in the center of the filament. A set of grid points coinciding with the grid shown in Figure 10.b. were used, with the exception of the twelve points that have α = ±30° and β ≠ 0 or β = ±30° and α ≠ 0, as they have a combined polar angle larger than 30°.

The results of the bulb color test on the bulbs listed in Table 2 are graphically depicted in Figure 13. As a first observation of the data shows that the bulbs with no coating, or with an absorption type coating have the chromaticities clustered rather tightly together, whereas bulbs with an interference coating (light or heavy) have a stretched cluster of chromaticities. This feature can be attributed to the physical mechanism of the interference type coatings that tend to create spectral separation.

Figure 13a shows the chromaticity distributions for the 9004 type bulbs. All bulbs pass the requirements, except for bulbs E2, 4004, E6. The latter is expected as these are bulbs with heavy and light interference coatings respectively. Figure 13b shows the chromaticity distributions for the 9006 type bulbs. The 9006 bulb INT-5 also does not meet the criteria because of a chromaticity outside the white light area. Finally Figure 13c shows the chromaticity distributions for the 9007 bulbs. Here each bulb has its cluster of x and y coordinates fall inside the color white boundaries. The light interference coated bulb (9007 Light INT E6) has a stretched cluster of chromaticities that marginally falls on the boundaries on the acceptance area, therefore this bulb fails the requirements.

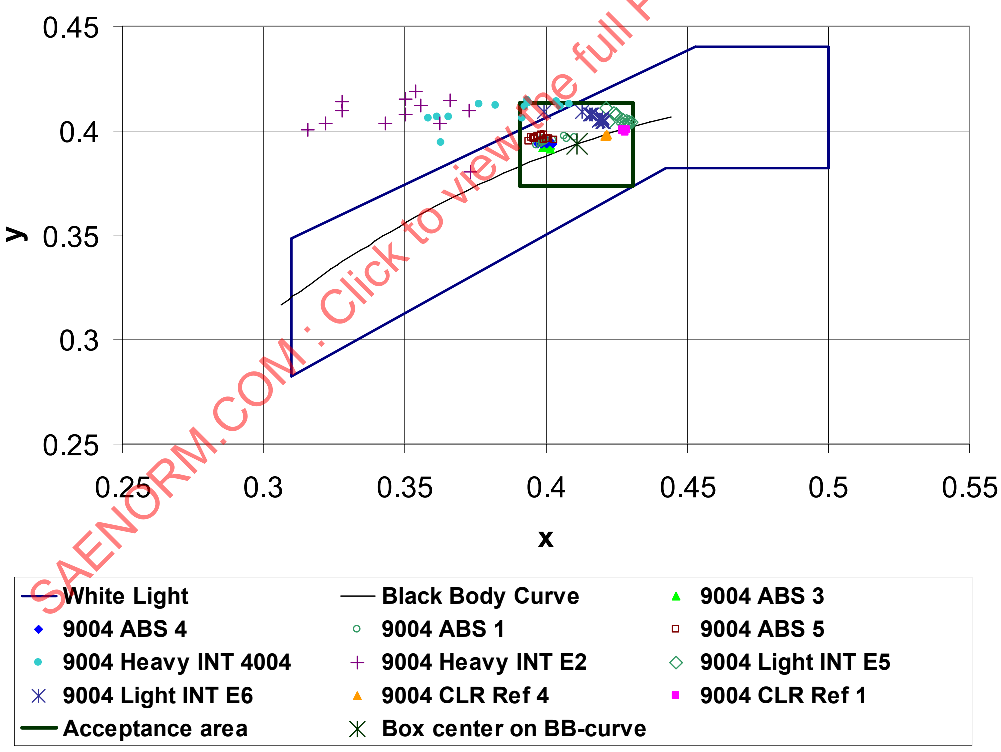

FIGURE 13A - DETAIL OF CIE 1931 CHROMATICITY DIAGRAM SHOWING CHROMATICITY DISTRIBUTIONS FROM THE BULB COLOR SEPARATION TEST FOR THE 9004 BULBS TESTED

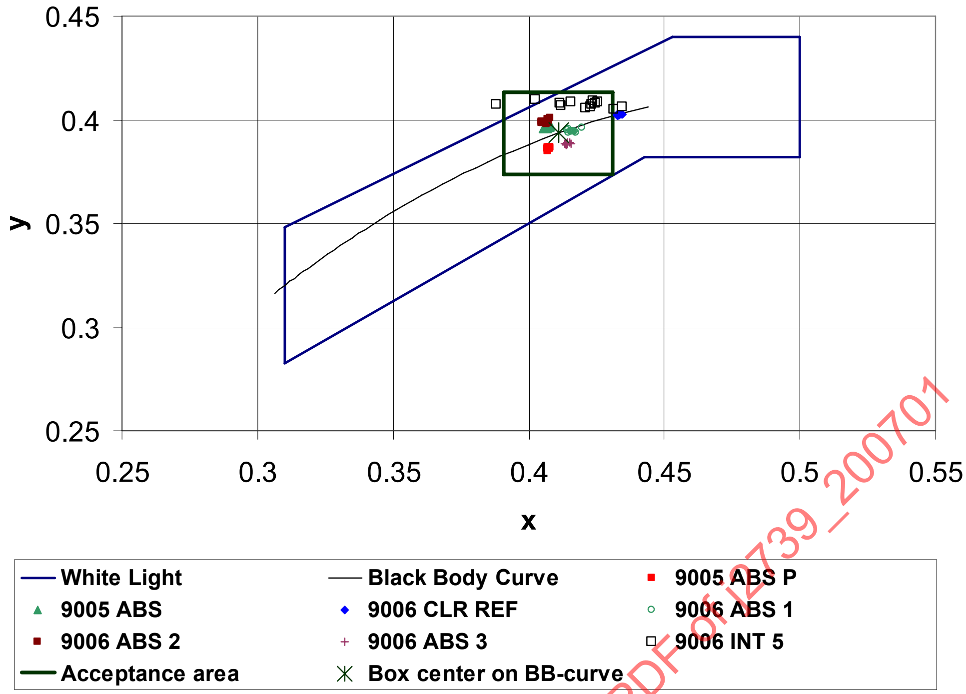

FIGURE 13B - DETAIL OF CIE 1931 CHROMATICITY DIAGRAM SHOWING CHROMATICITY DISTRIBUTIONS FROM THE BULB COLOR SEPARATION TEST FOR THE 9005 AND 9006 BULBS TESTED; THE ACCEPTANCE AREA SHOWN IS FOR THE EVALUATION OF BULB “9006 INT 5”

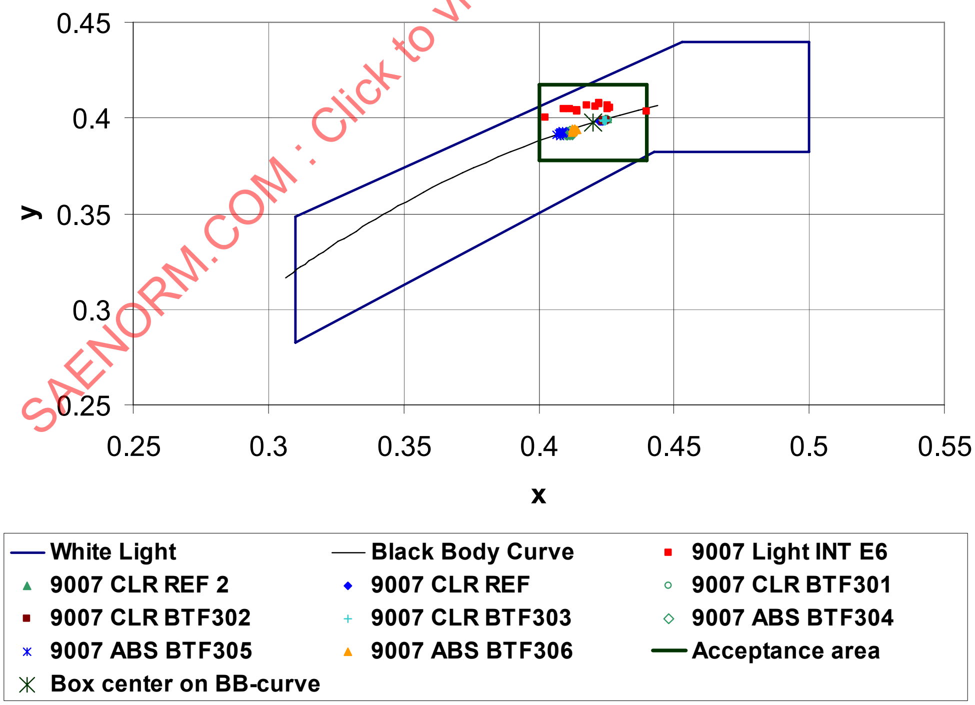

FIGURE 13C - DETAIL OF CIE 1931 CHROMATICITY DIAGRAM SHOWING CHROMATICITY DISTRIBUTIONS FROM THE BULB COLOR SEPARATION TEST FOR THE 9007 BULBS TESTED; THE ACCEPTANCE AREA SHOWN IS FOR THE EVALUATION OF BULB “9007 INT E6”

6.3 Additional Tests with ECE Bulb Types

The goal of the additional tests described in this chapter was to evaluate if spatially resolved measurements of the color of a bulb really can be used to distinguish between coated bulbs operating well and those causing glare and bad road illumination.

Different coated and non-coated bulbs have been tested. The results of the color separation test have been compared to the quality of the beam patterns achieved using these bulbs in an appropriate headlamp in order to show the correlation between these two items.

6.3.1 Beam Pattern Measurements

To show the influence of the coating on the beam patterns of headlamps we carried out measurements with different non-coated and color-coated bulbs using a goniometer. The measurements were performed using European headlamps because of the more demanding ECE requirements (ECE R8, R20) [8,9]. E.g., European headlights have to realize a more pronounced contrast between the hot spot and the zone above the cutoff than US headlights. Figure 14 shows the beam pattern of a typical H4/HB2 headlamp with an uncoated brand P "Standard" H4 bulb (Figure 14a) compared to the beam patterns produced with brand P Absorption coated H4 bulb using an absorptive coating (Figure 14b) and a "brand X" interference coated H4 (Figure 14c) bulb mounted in the same headlamp. The H4 bulb type is very popular in Europe. In an ideal system the cutoff is generated by a cap which blocks the light emitted towards the lower part of the parabolic reflector which is used for the driving beam with the high beam filament. The specific lamp type used in this test has the dimensions of a large rectangular headlamp and is used in import vehicles from the US to Europe.

The brand P "Standard" and "Absorption" beam patterns show hardly any difference. They are well-defined and exhibit a clear cutoff. In the region on the right shoulder of the street which is important for traffic sign and pedestrian recognition an illuminance of more than 25 lx has been measured.

On the other hand the beam pattern achieved with the "brand X" bulb is totally smeared out (Figure 14c, Figure 15). The beam consists of light of different colors (red and green) (Figure 15). Part of the red light is projected into the glare region above the cutoff. This light will dazzle the oncoming traffic. The maximum acceptable illuminance at the B50L measurement point (50 m in front of the car on the right curb) and in the zone III (above horizon including the HV point) are exceeded (Table 7). Compared to the brand P "Standard" and "Absorption" bulbs the headlamp equipped with the "brand X" bulb shows lower illumination of the street. For example, the greatest part of the illuminated region exhibits an illumination of less than 20 lx on an measuring screen at a distance of 25 m. The lamp also does not meet the illumination requirements for the 75R measurement point (Table 7). As a consequence, a plain street exhibits an illuminance of more than 1 lx up to a distance of only 90 m, while the 1 lx - illumination range of the other bulbs is about 115 m (Figure 14 right column). The bad road illumination may partly be due to the poor luminous flux of the "brand X" bulb (845.5 lm compared to 997 lm resp. 937.1 lm luminous flux of the brand P bulbs, see Table 7).

As an example for one-filament-bulbs similar measurements with H7 bulbs have been carried out. The H7 bulb is widely used in European complex-shape-reflector headlamps. Figure 16 shows the beam pattern of a non-coated brand P "Standard" H7 bulb mounted in a headlamp for a large volume European compact car (Figure 16a) compared to the beam patterns of an brand P H7 Absorption coated bulb (Figure 16b) and a "brand X" H7 (Figure 16b) mounted in the same headlamp. Again the brand P "Standard" and the "Absorption" coated bulbs exhibit a very similar, well-defined beam pattern with a clear cutoff, whereas the "brand X" beam pattern is totally washed out. Also in this case there is a too much light in the glare region (Table 8), but the illumination of the road is very bad and does not exceed 30 lx in any direction, whereas the "Standard" and "Absorption" bulbs mounted in the same lamp reach illuminances of more than 60 lx. The luminous flux of the "brand X" bulb is only 767 lm compared to a luminous flux of more than 1400 lm of the brand P bulbs (Table 8). That means that the bulb does not meet the legal requirements although it carries an approval mark. This results in a reduced 1 lx – illumination range of about 90 m compared with 115 m in case of the brand Ps bulbs.

To quantify the quality of the beam pattern, at least three different criteria were applied:

- It was checked if the photometric values measured in certain directions meet the legal requirements prescribed in ECE regulations R8 and R20. The results of this test are given in Tables 7, 8 and summarized in column 4 of Table 9. One can see that the headlamps meet the legal requirements when equipped with the non-coated or absorption-coated test bulbs and do not when equipped with the interference coated test bulbs.

- The flux integrated over upper left quarter of the beam pattern (horizontal angle –15°..0°, vertical angle 0°..+5°) can serve as a measure for the amount of light emitted into the glare region (Table 9, column 5). One can see that the headlamps equipped with non-coated or absorption-coated bulbs exhibit significantly less glare light than the headlamps equipped with the interference-coated test bulbs. This measure is rather insensitive to the aiming of the headlamp.
- The intensity emitted into the direction B50L (which is located inside the glare region) compared to the absolute maximum intensity of the light pattern can serve as a measure of the ratio glare/maximum intensity, which should be quite low. This ratio is insensitive to the aiming, too. In Table 9, column 6, these values normalized to the brand P standard bulb values are given. One can see that the absorption coated bulbs lead to a comparable amount of glare light when compared to the hot spot of the light pattern, while the ratio glare/light in the hot spot is significantly higher with the interference coated bulbs.

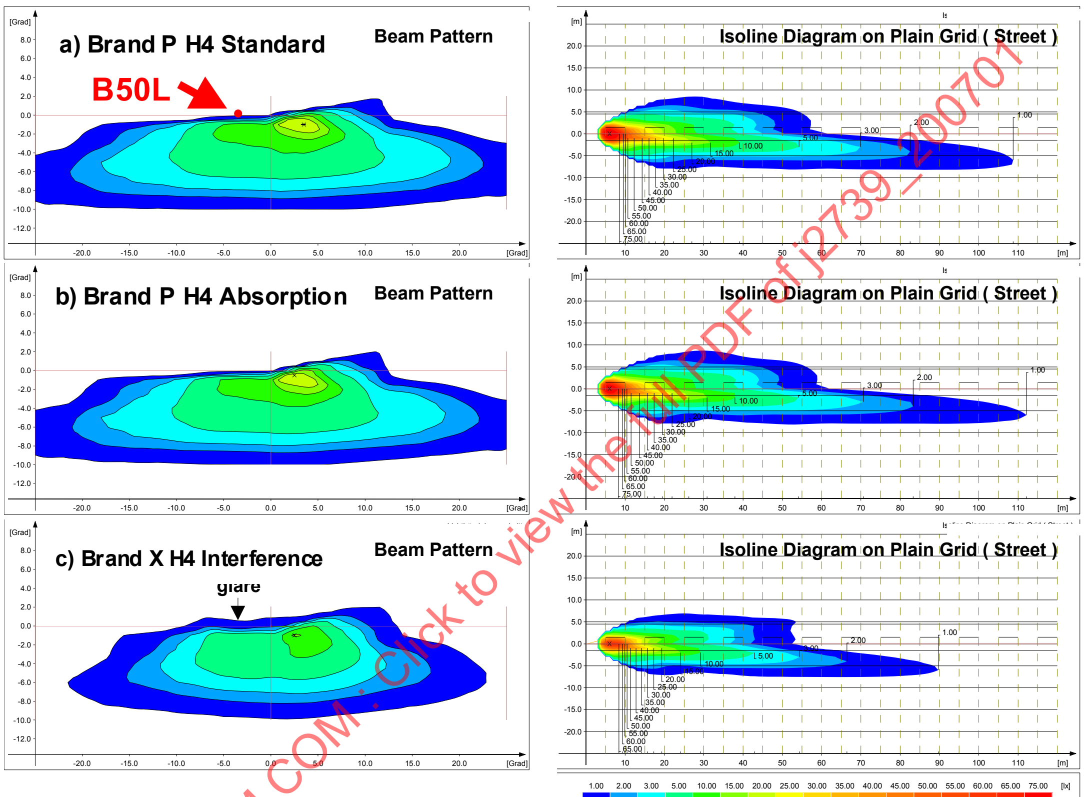

FIGURE 14 - BEAM PATTERNS OF AN H4 HEADLAMP EQUIPPED WITH A BRAND P H4 STANDARD, A BRAND P ABSORPTION COATED H4, AND AN INTERFERENCE COATED “BRAND X” H4 BULB. THE USE OF THE STANDARD AND THE ABSORPTION COATED BULBS LEADS TO A WELL-DEFINED BEAM PATTERN WITH A CLEAR CUTOFF AND A GOOD ROAD ILLUMINATION, WHILE THE USE OF THE “BRAND X” BULB WASHES OUT THE BEAM PATTERN COMPLETELY, CAUSES GLARE AND LEADS TO A BAD ROAD ILLUMINATION AND A REDUCED ILLUMINATION RANGE. IN THE UPPERMOST BEAM PATTERN THE B50L POSITION IS MARKED WITH A RED DOT.

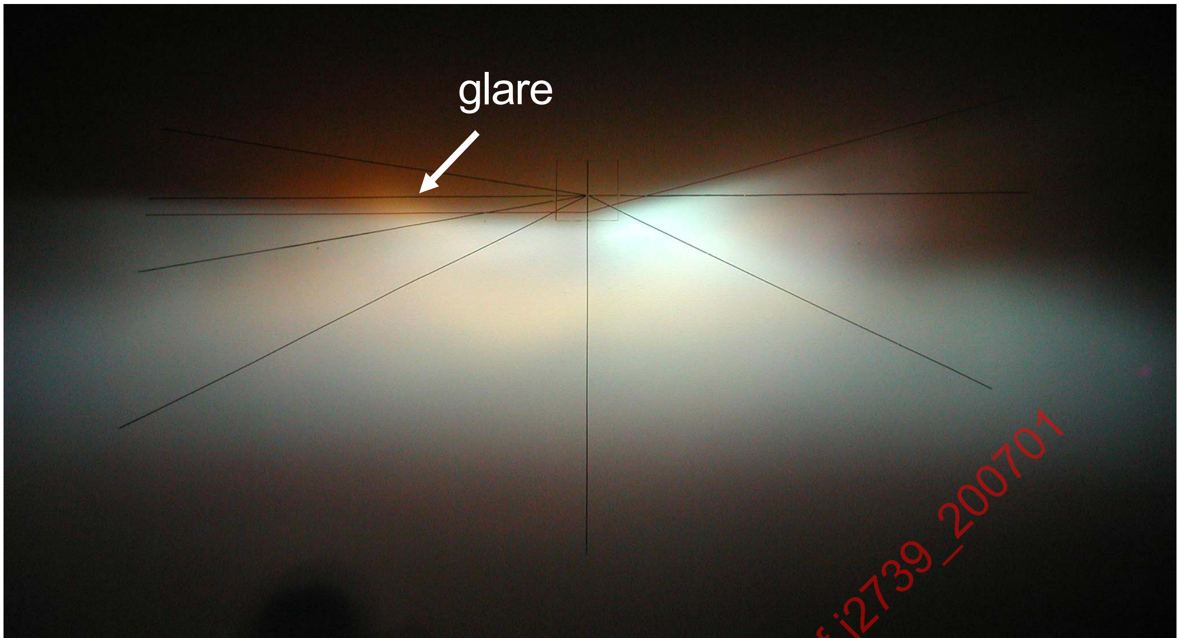

FIGURE 15 - BEAM PATTERN OF AN INTERFERENCE COATED “BRAND X” BULB. NOTE THE DIFFERENT COLORS IN THE BEAM PATTERN. THE REDDISH LIGHT WILL CAUSE GLARE TO THE ONCOMING TRAFFIC.

TABLE 7 - ILLUMINANCES AT THE 50R-, 75R- AND B50L-POINT AND IN THE ZONE III OF AN HEADLAMP EQUIPPED WITH DIFFERENT H4-BULBS (ALL OF THEM OPERATING AT 55 W). THE “BRAND X” BULB DOES NOT REACH THE ILLUMINANCE REQUIRED IN THE 75R-POINT WHICH IS IMPORTANT PEDESTRIAN AND TRAFFIC SIGN RECOGNITION. IT EXCEEDS THE MAXIMUM TOLERABLE ILLUMINANCE IN THE B50L-POINT AND THE ZONE III AND THEREFORE CAUSES GLARE.

	min. illuminance (ECE R20)	max. illuminance (ECE R20)	Brand P H4 “Standard”	Brand P H4 “Absorption”	“brand X” H4 “Interference”
luminous flux			997.4 lm	937.1 lm	845.5 lm
50R	9.60 lx		23.91 lx	24.68 lx	11.60 lx
75R	9.60 lx		16.50 lx	17.88 lx	**5.16 lx**
B50L		0.60 lx	0.38 lx	0.31 lx	**0.95 lx**
Zone III (maximum)		1.00 lx	0.72 lx	0.66 lx	**1.28 lx**

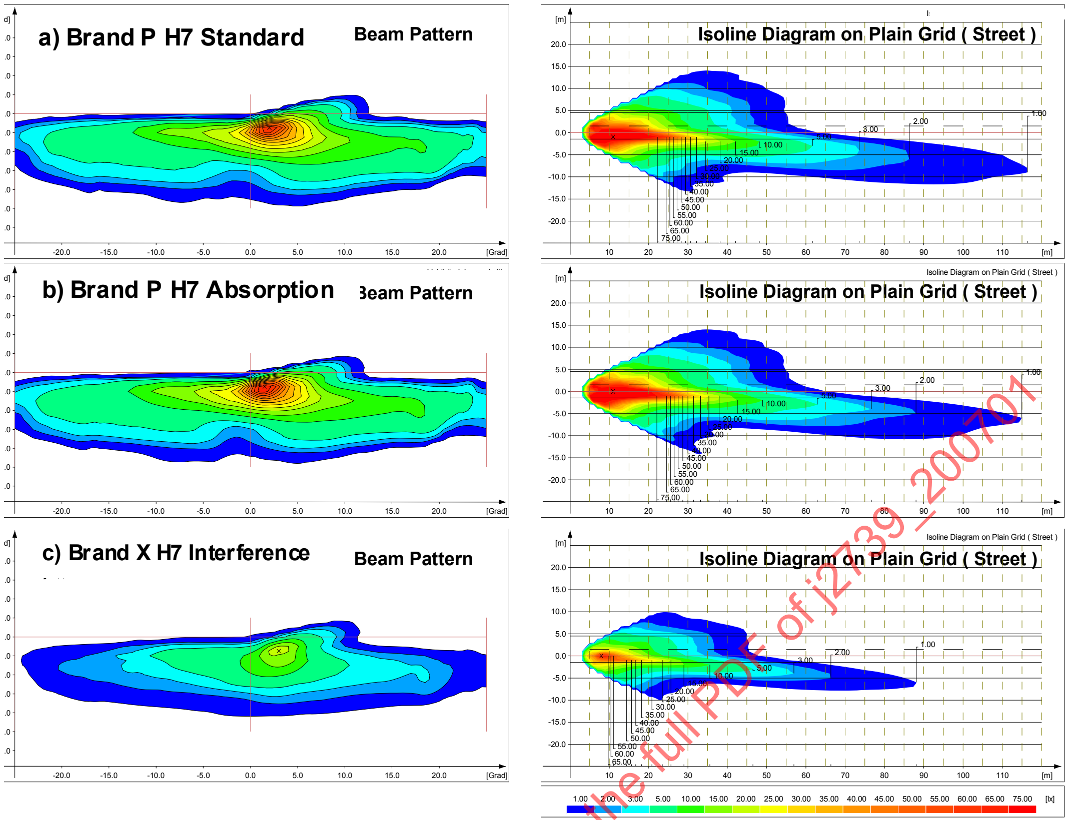

FIGURE 16 - BEAM PATTERNS OF A HEADLAMP FOR THE EUROPEAN COMPACT CAR USED IN THIS STUDY, EQUIPPED WITH A BRAND P H7 STANDARD, A BRAND P H7 WITH ABSORPTION COATING, AND AN INTERFERENCE COATED “BRAND X” H7 BULB; AGAIN THE ROAD ILLUMINATION IS MUCH WORSE AND THE ILLUMINANCE RANGE LOWER THAN THE ONES ACHIEVED WITH THE STANDARD AND THE ABSORPTION COATED BULB

TABLE 8 - ILLUMINANCE AT THE 50R-, 75R- AND B50L-POINT AND IN THE ZONE III OF A HEADLAMP EQUIPPED WITH DIFFERENT H7-BULBS; AGAIN THE “BRAND X” BULB DOES NOT REACH THE ILLUMINANCE REQUIRED IN THE 75R-POINT AND EXCEEDS THE MAXIMUM TOLERABLE ILLUMINANCE IN B50L

	min. illuminance (ECE R8)	max. illuminance (ECE R8)	Brand P H7 “Standard”	Brand P H7 “Absorption”	“brand X” H7 “Interference”
luminous flux			1443.1 lm	1480.3 lm	767.1 lm
50R	9.60 lx		36.31 lx	41.21 lx	10.19 lx
75R	9.60 lx		15.39 lx	17.77 lx	**4.22 lx**
B50L		0.60 lx	0.49 lx	0.53 lx	**0.62 lx**
Zone III (maximum)		1.00 lx	0.96 lx	0.82 lx	0.85 lx

TABLE 9 - PARAMETERS DESCRIBING THE BEAM QUALITY (COMPLIANCE WITH LEGAL REQUIREMENTS, INTENSITY INTEGRATED OVER THE GLARE REGION AND RATION INTENSITY IN GLARE REGION/ HOT-SPOT) AND RESULTS OF COLOR SEPARATION TEST FOR VARIOUS COATED AND UNCOATED TEST BULBS; THERE IS A CLEAR CORRELATION BETWEEN THE RESULT OF THE COLOR SEPARATION TEST AND THE QUALITY OF THE BEAM PATTERN

	Bulb	Coating	Photometric values (ECE R8 / R20)	Integrated flux in glare area	Intensity(B50L) / max. Intensity, normalized to Brand P H4/H7 standard bulb	Color separation test passed?
H4	Brand P H4	none	OK	4.45 lm	100 %	YES
	Brand P H4 “Absorption”	absorption	OK	4.13 lm	88 %	YES
	H4 “Brand X”	interference	**NOT OK**	**6.23 lm**	**189 %**	**NO**
H7	Brand P H7	none	OK	3.26 lm	100 %	YES
	Brand P H7 “Absorption”	absorption	OK	3.23 lm	100 %	YES
	H7 “Brand X”	interference	**NOT OK**	**3.80 lm**	**354 %**	**NO**

6.3.2 The Color Separation Test

The spatial chromaticity distribution of the test lamps within a well-defined angular region around the bulb was determined by measuring the color coordinates as seen from different directions. Measurements were carried out with the bulb in fixed position, while the detector rotated around it (Figure 17). Measurements using a fixed detector and a rotating and tilting bulb are also possible.

In our measurements the detector scanned an area from 60° to 120° in polar direction and from -180° to 180° in azimuthal direction. The step width was 10°, while the detector had an angle acceptance of 15° in each direction.

To pass the color separation test, each measured value shall lie within the ECE / SAE white light area. Moreover the measured values shall not deviate more than 0.020 units in the x and/or y direction from a point of choice on the Planckian locus (In the following this area is in referred to as “acceptance area around an point on the Planckian locus”.).

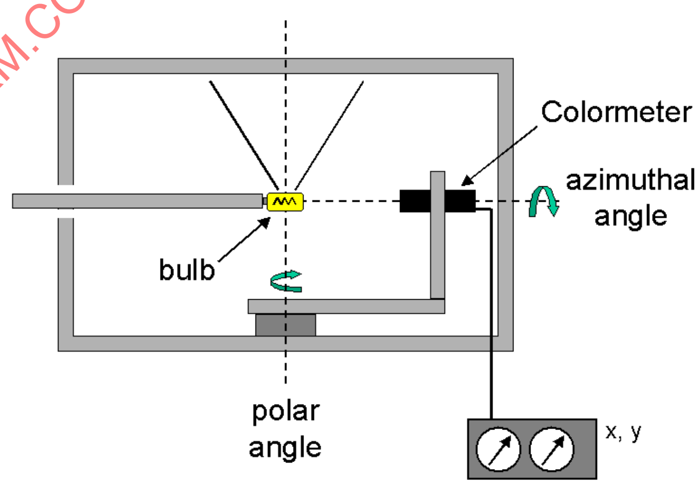

FIGURE 17 - PRINCIPLE OF THE COLOR SEPARATION TEST; THE SPATIAL CHROMATICITY DISTRIBUTION WITHIN A WELL-DEFINED ANGULAR REGION AROUND THE BULB IS DETERMINED WITH A ROTATING AND TILTING COLORIMETER

Figure 18 shows the color coordinates of the H4 brand P “Standard”, “Absorption” and “brand X” bulbs. The color coordinates of the “Standard” (green squares) and the “Absorption” (blue squares) bulbs exhibit only little spread. All color coordinates lie well within the white light area. None of them deviates more than 0.020 units in x or y direction from the Tc = 3250 K-point on the Planckian locus.

On the other hand the color coordinates of the “brand X” bulb (yellow triangles) are spread over a huge area. They fall largely outside the white light area. An acceptance area around a point on the Planckian locus cannot be found. Measurements using an integrating sphere do not provide information on the color of individual rays of light and so do are not suited as criterion for the color separation.

In Figure 19 the color coordinates of the H7 “Standard”, “Absorption” and “brand X” bulbs are shown. Again the color coordinates of the “Standard” and “Absorption” bulbs show very little spread and fall well within the white light area as well as an acceptance area around the Tc = 3400 K-point on the Planckian locus, while the “brand X” color coordinates cover a wide range in the chromaticity diagram and fall nearly completely out of the white light area.

The findings are summarized in the last column of Table 9.

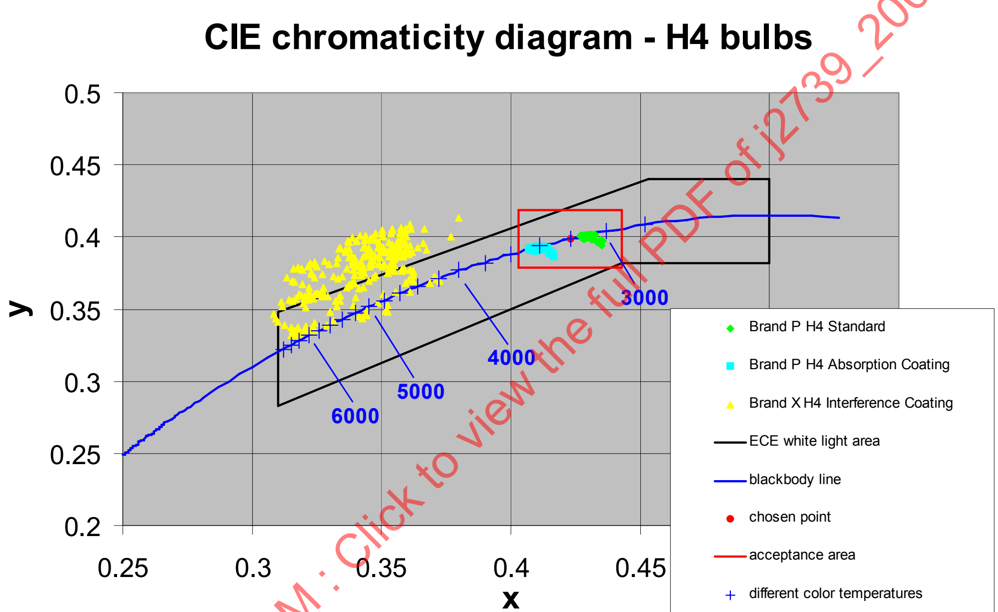

FIGURE 18 - SPATIAL CHROMATICITY DISTRIBUTION OF A BRAND P H4 STANDARD BULB, A BRAND P H4 ABSORPTION COATED BULB, AND A H4 “BRAND X”. THE SPREAD IN COLOR COORDINATES OF THE “STANDARD” (GREEN SQUARES) AND THE “ABSORPTION” (BLUE SQUARES) BULBS IS LITTLE. ALL COLOR COORDINATES LIE WELL WITHIN THE WHITE LIGHT AREA. ON THE OTHER HAND THE COLOR COORDINATES OF THE “BRAND X” BULB (YELLOW TRIANGLES) EXHIBIT A HUGE SPREAD. THEY FALL LARGELY OUTSIDE THE WHITE LIGHT AREA.