SMPTE EG 432-1:2010
Revision of
EG 432-1-2007

SMPTE ENGINEERING GUIDELINE

Digital Source Processing — Color Processing for D-Cinema

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Foreword

SMPTE (the Society of Motion Picture and Television Engineers) is an internationally-recognized standards developing organization. Headquartered and incorporated in the United States of America, SMPTE has members in over 80 countries on six continents. SMPTE's Engineering Documents, including Standards, Recommended Practices and Engineering Guidelines, are prepared by SMPTE's Technology Committees. Participation in these Committees is open to all with a bona fide interest in their work. SMPTE cooperates closely with other standards-developing organizations, including ISO, IEC and ITU.

SMPTE Engineering Documents are drafted in accordance with the rules given in Part XIII of its Administrative Practices.

SMPTE EG 432-1 was prepared by SMPTE Technology Committee 21DC.

Intellectual Property

At the time of publication no notice had been received by SMPTE claiming patent rights essential to the implementation of this Standard. However, attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. SMPTE shall not be held responsible for identifying any or all such patent rights.

Introduction

The work that led to the writing of the SMPTE standards on the color encoding for Digital Cinema has been guided by a few underlying principles. They are:

1. The most important desire was to define a color encoding that allows for excellent image quality in all exhibition theatres. The color quality of the image ought not be limited by the encoding. The image produced in one theatre should, within tight tolerances, match the image produced in any other theatre. This led to some decisions that create technical challenges for the production workflows today and that may lead to (slightly) increased cost of a complete system, but it was felt that the ability to produce excellent quality in a theatre is sufficiently important that these challenges were accepted.

2. It was desired that the encoding be designed so that it would encompass a color gamut at least as large as existing digital projectors and preferably include all possible film colors. In addition, there was a desire to write a standard that would allow future improvements in display technology to be carried in the digital cinema encoding that is now being defined.

3. It was desired that the encoding should not be tied to any particular device or technology. This has become known as device-independent encoding. Device-independent encoding does not, in itself, lead to a robust encoding, but when coupled with other parameters, it can lead to a robust encoding.

4. It was desired that the digital cinema color encoding be designed to be relatively simple to implement so that images can be processed and projected in real time.

5. The color encoding standardized by SMPTE is only for the Digital Cinema Distribution Master. There has been considerable discussion of the encoding for the Digital Source Master, the digital master that precedes the Distribution Master. However, that master is produced in a post-house and it was felt that the post-house could create that Source Master in any file format and color space it wanted. Likewise, the production of the Distribution Master from the Source Master is dependent on the form of the Source Master, so that transform cannot be standardized. However, because it is an important topic for many people, comments on the transform from the Source Master to the Distribution Master will be given in this guideline.

This Engineering Guideline only deals with the color processing of digital images that a digital projector will display in a theatre. Therefore, the container for the digital images, the file format of the code values, and the transport of that container are not a part of this guideline.

Digital Cinema, or D-Cinema as it is also known, is based on the technology of defining an image by a set of code values (numbers). The definition of any single color requires three, and only three, code values. In addition, a set of three code values defines one, and only one, color. There has to be a color system defined in which the code values are directly related to the colors. The SMPTE documents ST 428-1, ST 431-1, ST 431-2, and ST 431-3, listed in the Annex A (Bibliography), define this color system. This guideline explains how to use those documents to implement that color system.

The overarching objective is to define a system in which an image will be displayed in any theatre by any projector and the result will be the same within a reasonable set of tolerances. In order to achieve this objective, there are three elements of the system that have to be defined: (1) The relationship between the code values and the encoded color. (2) The measurement of the light reflected off the screen. (3) The aims and tolerances around each measurement. The cited SMPTE documents and this guideline explain each of these elements of the system and how to put all the elements together to make a working system.

The color encoding for the D-Cinema system is based on the definition of the image that is to be displayed on the screen. Therefore, the SMPTE documents standardize how to define the relationship between the code values and the desired colors, but do not deal with how one is to define the desired colors. It is realized that in the normal production of moving images, the image has to somehow be created before the colors in the D-Cinema image can be defined. The term, Digital Source Master, has been used to define this original image because it may be the source of many different digital images, the D-Cinema images, the HDTV images, the DVD images, etc. There are three reasons why the Digital Source Master has not yet been defined by any of the SMPTE documents: (1) The Digital Source Master comes before the D-Cinema images. (2) The method by which the images in the Digital Source Master are created is up to the creator. (3) The Digital Source Master can be defined in a large number of different, useful ways.

To a large extent the encoding and decoding of the D-Cinema images revolves around the Reference Projector. The Reference Projector is a working, practical projector that is defined by its capabilities, not by its technology. It is recognized that there may be many technical solutions to the problem of constructing a projector that has the capabilities that the Reference Projector must have. The Reference Projector capabilities are the minimum capabilities any physical projector must have, but these capabilities are not meant to be limiting capabilities. A physical projector may have capabilities beyond the capabilities of the Reference Projector. Therefore, the technologies used to build a physical projector are not discussed in any of the SMPTE documents; only the capabilities are described. There have to be uniform methods by which the light reflected by a screen can be measured in order to know if the capabilities of any physical projector meet the capabilities of the Reference Projector. In addition, it is recognized that because physical devices will always have variation in performance across different devices and across time for any single device, there have to be reasonable tolerances within which all devices can work and which will ensure that the images are visually the same in all theatres.

The RGB or XYZ or similar triplets of numbers in this Engineering Guideline are always in the order in which they are listed. For example, if a variable is called RGB and the numbers [100 200 300] are an example of the RGB values, the 100 represents the R value, the 200 represents the G value and 300 represents the B value. The matrices that operate on the RGB or XYZ values are defined for the same order of individual variables. The reason for stating what seems so obvious is that some devices do not follow the order RGB. Where this can cause problems is in the definition of the matrices that go from RGB to XYZ and XYZ to RGB. Therefore, when a matrix is put into a projector (or other device), the user must be certain the matrix and the device are using the individual variables in the same order.

The CIE XYZ tristimulus values, described in the CIE references in the Bibliography, are linearly related to light. But because the human visual system does not respond to light in a linear fashion, the encoding of the CIE XYZ values is more efficient if a function of the XYZ values is encoded instead of the XYZ values themselves. These encoded XYZ values are given the symbols *X'Y'Z'* in the SMPTE documents relating to Digital Cinema. This encoding is the main subject of this Engineering Guideline.

This EG is entirely Informative. Stated values are not to be used for equipment design. The user should refer to the appropriate Standard or RP for target values and tolerances.

1 Scope

This document provides guidelines on the encoding of the color information for the Digital Cinema Distribution Master (DCDM) and for the decoding of the color signal in the projector. A series of standards and recommended practices define exactly what to do to encode and decode the color for digital cinema. This document leads the user through all of those documents so that an image, once created, will both match the creator's intent and will be displayed as the same image in every theatre within the recommendations of these documents. In addition to the guidelines on how to do the color encoding and color processing, this document will give some historical background on the development of the color encoding. In order to make this document more readable, the historical information will be put in a series of annexes after the guidelines. Therefore, this document describes the color transformations required for encoding an image into the DCDM *X'Y'Z'* code values in mastering and the reciprocal process of decoding these code values in the exhibition projector. Because the appearance of any color patch is dependent on the viewing conditions under which the color patch is seen, this document will also describe how the contents of the standards and recommended practices relating to the display of images using digital projection relate to the color encoding and decoding. The purpose of this guideline is to show how to use all of the Digital Cinema color-related documents in order to achieve the objectives of interoperability and color consistency.

2 Conformance Notation

Normative text is text that describes elements of the design that are indispensable or contains the conformance language keywords: "shall", "should", or "may". Informative text is text that is potentially helpful to the user, but not indispensable, and can be removed, changed, or added editorially without affecting interoperability. Informative text does not contain any conformance keywords.

All text in this document is, by default, normative, except: the Introduction, any section explicitly labeled as "Informative" or individual paragraphs that start with "Note:"

The keywords "shall" and "shall not" indicate requirements strictly to be followed in order to conform to the document and from which no deviation is permitted.

The keywords, "should" and "should not" indicate that, among several possibilities, one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required; or that (in the negative form) a certain possibility or course of action is deprecated but not prohibited.

The keywords "may" and "need not" indicate courses of action permissible within the limits of the document.
The keyword "reserved" indicates a provision that is not defined at this time, shall not be used, and may be defined in the future. The keyword "forbidden" indicates "reserved" and in addition indicates that the provision will never be defined in the future.

Unless otherwise specified, the order of precedence of the types of normative information in this document shall be as follows: Normative prose shall be the authoritative definition; Tables shall be next; followed by formal languages; then figures; and then any other language forms.

3 Order in which the Color Processing Steps are Described

This guideline explains how to use the standards and recommended practices contained in the four normative references. In order to give the reader a very basic overview of the Digital Cinema system, one version of the flow of color through the system will be described in Section 4. The color encoding equations will be described in Section 5. This guideline will show how these equations can be used to calculate the colorimetry that should be measured off the screen when a set of code values are sent to the projector. In Section 6 the proper measurement techniques will be described. The proper measurement techniques and the measured values for a properly operating projector in its environment are both necessary to ensure that the same content shown in different theatres will look the same. The measurement results and their tolerances will also be described in Section 6.

The DCDM color encoding is based on XYZ values. However, each three-primary projector will be working internally with its own set of primaries and linear RGB code values. Therefore, the method by which the XYZ code values can be converted to a specific projector's internal RGB code values will be described in Section 7. Section 8 gives an overview of gamut mapping and the value of placing the mastering projector primaries, white point, and contrast ratio in metadata in the DCDM. Finally, Section 9 will run through a set of calculations showing how the color processing might be done based on the standards and recommended practices that have been written for the processing of color in the D-Cinema system. In addition, a considerable amount of background and explanatory information will be given in the Annexes. The information in the Annexes is not necessary for the implementation of the standards and recommended practices, but might help the user better understand and implement these standards and recommended practices.

4 Flow of Color through the Digital Cinema System

This section gives a very general overview of the flow of the color information through the digital cinema system. There are many ways in which this flow can be implemented and the steps shown can be either expanded into more steps or can be combined into fewer steps. The intention is to give an overview of the system so that the detailed discussions below can be put into context. It is very important to remember that the DCDM encoding defines the light that is reflected off the screen in the theatre above the theatre black level. Therefore, it includes the light from the projector when the image signal is sent to the projector, the light from the projector when code value b (0 or whatever is the smallest code value allowed by the system) is sent to the projector, (although code value b implies black and thus no light output from the projector, in practice a projector will put out some light even when a b code value is received), and light from any other sources in the theatre. Therefore, all of the measurements of light in these standards refer to light measured off the screen, not a direct measurement of the light coming out of the projector.

4.1 Digital Source Master (DSM)

The following informative paragraph comes from the SMPTE ST 428-1 document: "In the process of creating theatrical releases, a Digital Source Master, or DSM, is produced from which many distribution elements are created, (e.g. Film Distribution Masters, Digital Cinema Distribution Masters (DCDM), Home Video Masters, Airline Version Masters and Broadcast Masters). It is not the goal of this specification to define the DSM. It is recognized that the DSM may consist of any color space, pixel matrix (spatial), frame rate (temporal), bit depth and many other metrics." The following discussion of the flow of color information through the D-Cinema system assumes certain characteristics of the DSM, but the DSM could have different characteristics and still must produce acceptable DCDM source images. Some comments about the DSM and how the information in the DSM can be converted to the DCDM color encoding are given in Section 9.

4.2 D-Cinema Image Color Flow Diagram

Figure 4-1 shows the flow of color through the digital cinema system. The Digital Cinema image color data flow starts with play-out from the DSM and proceeds with the development of the Image DCDM, expressed in code values. The first transform, shown as an exampled progression step, converts the DSM image representation data to CIE linear XYZ tristimulus values. The second exampled progression step transforms those XYZ values into gamma 1 / 2.6 encoded *X'Y'Z'* values. As will be discussed in Section 9, although Figure 4-1 shows the color encoding passing through two steps, DSM to linear XYZ and linear XYZ to *X'Y'Z'*, an implementation of the color encoding does not have to pass through these steps. Therefore, these steps are shown here to emphasize the transforms that have to be made, but not how the transforms must be implemented. The steps in the white boxes from Compression to Decompression do not involve color encoding, but are shown here so that it can be seen where these steps occur relative to the color encoding and decoding. Therefore, the steps shown in the white boxes will not be discussed in the guideline.

4.3 Reference Projector Input Color Data Flow

Once the DCDM is encoded, the data could be directed along two distinct flow paths. The first is a path to the Reference Projector, most likely located in the Review Room. In this data flow the DCDM *X'Y'Z'* data goes through a two-step process where the image data is first transformed from non-linear *X'Y'Z'* coded data to XYZ linear coded data and then transformed from XYZ linear coded data to linear projector RGB data for input to the light modulator of the Reference Projector, which will project light onto the viewing screen. Due to the projector RGB exhibiting a smaller gamut than the DCDM XYZ data, the XYZ to RGB transform has the effect of limiting the gamut and thereby requiring gamut mapping. When the DCDM data represents colors at or outside the gamut boundary for the projector's RGB primary set and white point chromaticity, unpredictable results may occur. The content creator may choose to shape or pre-limit the DCDM data to fit within the reference projector gamut in order to provide a more predictable result for display.

4.4 Exhibition Projector Input Color Data Flow

The second path for the DCDM data path goes to the distribution network where compression, encryption, packaging, transport to the intended theatre, and finally storage on disk drives at the digital cinema theatre takes place. This transport is not discussed in this Engineering Guideline.

On digital cinema play-out the DCDM data, in compressed and encrypted form, will first be decrypted and then uncompressed. At this system point, the image DCDM data will have returned to its *X'Y'Z'* state, except that it will exist as a codestream instead of being in its original frame-file form. The DCDM data will be processed as was described above for the Reference Projector, which is being transformed first from non-linear *X'Y'Z'* to linear XYZ data and then being further transformed (and possibly gamut limited) from XYZ to RGB data for input to the exhibition projector light modulator. The projector then projects respective light images onto the screen for audience viewing.

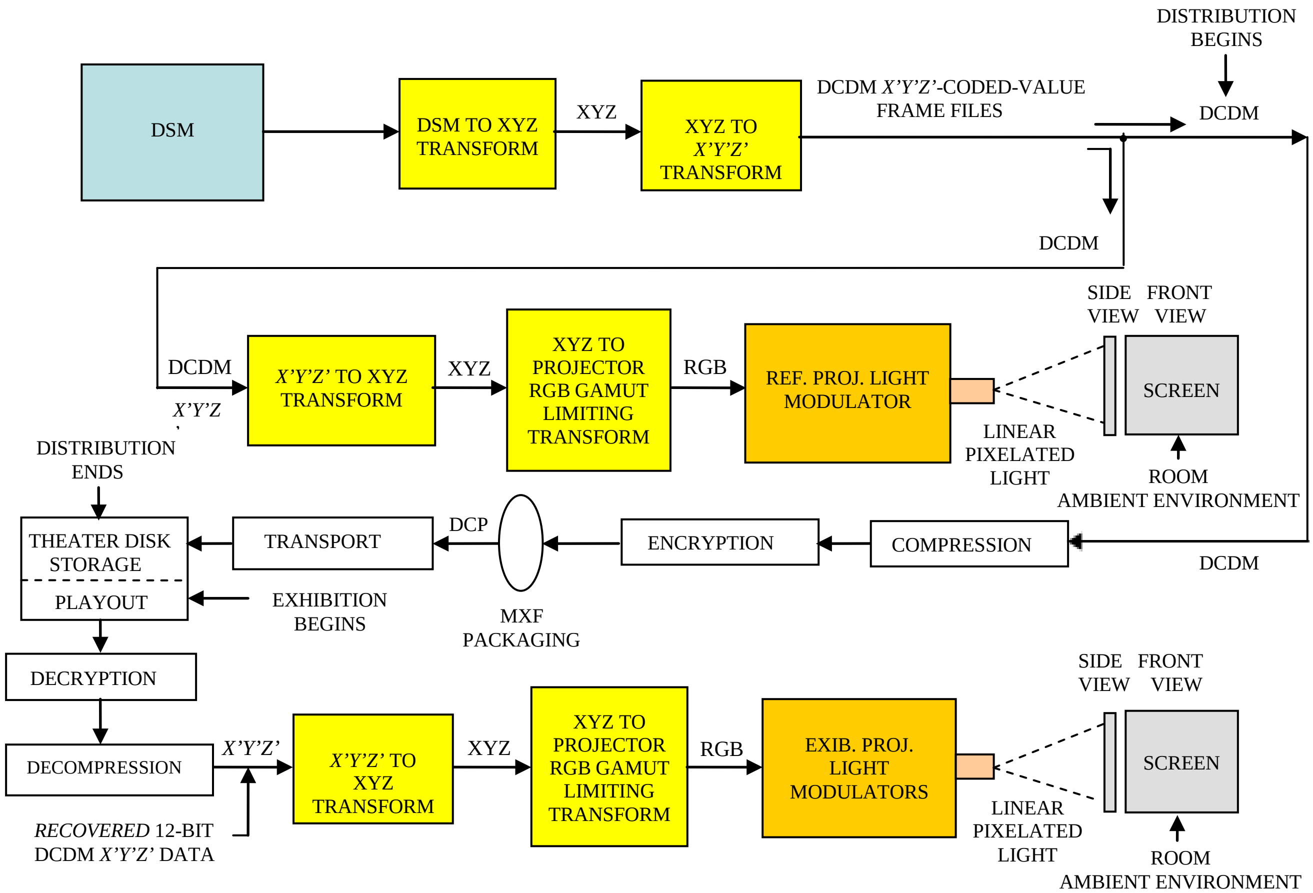

Figure 4-1 – D-Cinema Image Color Data Flow

5 D-Cinema Colorimetry Encoding

The basis for the DCDM color encoding system is the CIE XYZ tristimulus value system. In the DCDM system there are three DCDM code values that define the color of any one pixel and in this document those code values will be given the variable names *X'*, *Y'*, and *Z'*. In addition, the convention used in this guideline to define an explicit set of code values will be [*X' Y' Z'*]. When determining the set of code values that produces the minimum amount of light from the projector, there are two considerations: (1) The minimum code value allowed is set by the requirement of the hardware in the system that specifies that all code values be at or above some minimum value. The minimum value might be 0 or it might be some higher value. (2) The maximum code value is the largest code value that when sent to the projector produces an amount of light from the projector that is indistinguishable, both by measurement and by visual judgment, from the light from the projector when the projector is sent the minimum code values. This defines a set of maximum code values that are indistinguishable from code value 0. Combining these two considerations leads to a set of code values that are the maximum that the system will accept and that result in the minimum amount of light from the projector. This set of code values will be designated by [b b b]. The term "theatre black" refers to that light which is reflected from the screen in the theatre when the theatre is in operating mode with all safety lights on and the [b b b] code values are sent to the projector. These code values define the colorimetry of the theatre black and *X' Y' Z'* code values greater than this define the light that would be measured off the screen that is in addition to the theatre black. Although the encoding will be described below, it can be stated here that it is very doubtful that any projector will ever put a measurable difference in light on a screen when sent code values [0 0 0], [25 25 25], or [50 50 50]. Even values as high as [100 100 100] will most likely be below what can be seen or measured relative to any lower set of code values. Therefore, in this guideline, the theatre black set of code values, defined by [b b b], indicates the set of maximum code values a system allows that correspond to the minimum amount of light the projector can put on the screen. In general, a projector will put more light on the screen when turned on and sent this set of code values than when the projector is turned off. Therefore, the theatre black will be higher than the theatre ambient light. The measurement of both of these light levels will be described in Section 7 and in Annex I. This encoding of light in addition to theatre black is the same as occurs with film projection today. The film projected in a theatre is, in principle, the same film that is projected in every theatre independent of the theatre black level. There is no adjustment made to the film print as a function of a theatre's black level. Likewise, in the DCDM encoding, there is a fixed encoding that represents the colorimetry above the theatre black and no adjustment is made to the code values as a function of a theatre's black level. This means that the appearance of a projected image will change from theatre to theatre if the different theatres have different theatre black levels. In addition to the *X' Y' Z'* code values, there can be metadata associated with the DCDM file that will define the theatre black. From this metadata, the absolute colorimetry can be calculated because tristimulus values add – the absolute XYZ tristimulus values that one would expect to measure off a screen are the XYZ tristimulus values of the theatre black plus the XYZ tristimulus values encoded by the DCDM code values as described below.

All of the Y values reported in this Engineering Guideline will be calculated from the *Y'* values with no correction for the theatre black luminance. Therefore, the Y values reported in some of the tables here differ from the Y values in some of the tables in other SMPTE ST 431 documents because in those documents an assumed theatre black of 0.024 cd/m^2 has been included in the tabulated Y values.

5.1 Equations for DCDM Color Encoding

SMPTE ST 428-1 defines the DCDM color encoding equations. The use of those equations means that the image must be defined in terms of the CIE XYZ tristimulus values. The CIE XYZ tristimulus values represent the colorimetry above theatre black and must be calculated with a normalizing constant that sets the Y tristimulus value of the white to 1. With this specification of the color, the following equations define the encoding transfer function where X, Y, Z are the tristimulus values above theatre black.

$$CV_{X'} = INT\left[4095 * \left(\frac{L * X}{52.37}\right)^{1/2.6}\right] \quad (5\text{-}1)$$

$$CV_{Y'} = INT\left[4095 * \left(\frac{L * Y}{52.37}\right)^{1/2.6}\right] \quad (5\text{-}2)$$

$$CV_{Z'} = INT\left[4095 * \left(\frac{L * Z}{52.37}\right)^{1/2.6}\right] \quad (5\text{-}3)$$

where the INT operator returns the value of 0 for fractional parts in the range of 0 to 0.4999… and +1 for fractional parts in the range 0.5 to 0.9999…, i.e. it rounds down fractions less than 0.5 and rounds up fractions at or above 0.5 and where L is the luminance of the projector white as defined by SMPTE ST 431-1. At the time of writing this Engineering Guideline the value of L is 48. The 48 comes from the fact that the white luminance of the projector is defined as 48 cd/m^2 in SMPTE ST 431-1. For simplicity of writing the encoded code values, it is common to use *X'* for $CV_{X'}$, *Y'* for $CV_{Y'}$, and *Z'* for $CV_{Z'}$. It is important to remember that these encoded XYZ tristimulus values are the tristimulus values measured off the screen above the theatre black tristimulus values.

5.2 Equations for DCDM Color Decoding

SMPTE ST 431-2 defines the DCDM color decoding equations. The equations for the decoding of the encoded color information are the inverse of the encoding equations

$$X = \left(\frac{52.37}{L}\right) * \left(\frac{X'}{4095}\right)^{2.6} \qquad (5\text{-}4)$$

$$Y = \left(\frac{52.37}{L}\right) * \left(\frac{Y'}{4095}\right)^{2.6} \qquad (5\text{-}5)$$

$$Z = \left(\frac{52.37}{L}\right) * \left(\frac{Z'}{4095}\right)^{2.6} \qquad (5\text{-}6)$$

5.3 Comments on the DCDM Encoding and Decoding Equations

A considerable amount of work went into the final decision on the exact encoding and decoding equations to use for the DCDM colorimetry. Although one only needs to know the equations in order to use them, it was felt that some knowledge of the discussion and reasons for the form of the equations and the constants in the equations would be of value to the user. This Engineering Guideline is structured to have most of the information one needs in Sections 4 – 9 and a considerable amount of supporting and background information in the annexes.

- Annex A lists a number of references that may be of interest to the reader. These references give more details on some of the discussion here and give more information on color science and colorimetry in particular.
- Annex B describes the encoding schemes considered and the reasons for selecting the scheme chosen, which can be described as an Output Referred Encoding defined by three primaries with the Equal Energy white point and a non-linear encoding equation.
- Annex C describes the background on the choice of the three encoding primaries. The primaries chosen define a very large color gamut, one that was thought to be greater than anything that would be needed in the future.
- Annex D describes the choice of the 2.6 constant in the equations. This value allows a long luminance range to be defined without visual artifacts.
- Annex E describes the background on the 4095 constant in the equations. This defines a 12-bit per primary encoding that eliminates visual artifacts in the encoded colors.
- Annex F describes the minimum linear RGB bit depth that is needed in the Reference Projector. This bit depth is based on the need to retain all the information that comes from the 12-bit DCDM code values.
- Annex G describes the background on the choice of the 52.37 constant in the equations. The trade-off with this constant is the number of colors that can be encoded at the 48.00 cd/m^2 luminance level vs the number of code values that will never be used and are therefore wasted.

- Annex H describes the encoding white points that were discussed. The Equal Energy white point was chosen because it simplified the hardware in the projector.
- Annex I gives more detail on the implications of the choice of the encoding of the colors above the theatre black. The simplicity of the processing with the encoding above theatre black was preferred over the much more difficult processing that would have been needed in a projector with an encoding that defined the absolute colorimetry on the screen plus a considerable loss in image quality when the theatre black in the exhibition theatre is higher than the theatre black in the mastering theatre.
- Annex J shows how to do the conversions among xyY, XYZ, and *X'Y'Z'*. In this way, the reader is provided with a set of code values and colorimetry with which the reader's encoding or decoding calculations can be compared.
- Annex K shows how to calculate the matrix to convert from the XYZ code values to the RGB code values needed by the projector.
- Annex L describes the CIELab space and the delta E*ab.
- Annex M explains the calculations behind the statements in Annex B of SMPTE ST 428-1. That annex said that in normal practice no *Y'* code values would exceed 3960 (with the Reference Projector white point the *X'* and *Z'* maximum code values will be lower than 3960, but there are some other possible white points at which the *Z'* code value can be as high as 4092), thus leaving 135 code values of *Y'* headroom at the top end of the 12-bit scale and no code values would need to be below 45 with a 2000:1 contrast ratio projector, thus leaving 45 code values of headroom at the bottom end of the 12-bit scale.
- Annex N is a glossary of terms and a list of the acronyms used in this guideline.

6 Measurements of Projected Images

There are three SMPTE documents, SMPTE ST 431-1, SMPTE RP 431-2, and SMPTE RP 431-3, that describe the measurements and the expected values of those measurements for determining if a projector and the theatre it is in are performing to the level of consistency that is expected and needed to ensure that all content shown on this projector in its theatre will closely match the content shown on any projector in its theatre. In this guideline, these three documents will be referred to as the SMPTE ST 431 documents.

SMPTE ST 431-1 D-Cinema Quality – Screen Luminance Level, Chromaticity, and Uniformity is a standard that specifies the reference values and tolerances for the screen luminance level, white point chromaticity, and luminance and chromaticity uniformity of the projected light for the presentation of digital motion pictures in review rooms and commercial cinemas. The goal of SMPTE ST 431-1 is to achieve the tone scale and contrast in the projected image that will correspond to that intended during the mastering process.

SMPTE RP 431-2 D-Cinema Quality – Reference Projector and Environment for Display of DCDM in Review Rooms and Theatres is a recommended practice that defines the Reference Projector and its controlled environment, along with the acceptable tolerances around critical image parameters for Review Room and Theatre applications. The goal of SMPTE RP 431-2 is to provide a means for achieving consistent and repeatable color image quality.

SMPTE RP 431-3 D-Cinema Quality – Projection Image Measurements is a recommended practice that describes how to make the measurements, but does not specify what the expected measurement results are. The goal of SMPTE RP 431-3 is to provide practices for theatre on-screen measurements so as to maintain proper operating conditions. These practices are independent of the projector technology and are not intended to be used for evaluating a projector against its published specifications.

The following sections will describe the methods by which the measurements are to be made and the expected results from those measurements based on the specifications in these three SMPTE ST 431 documents. Those documents may change over time, therefore before a measurement is made or a measurement result compared to the value listed in this guideline, the appropriate document should be consulted to see if the standard value has changed. This guideline will show how the information in those documents can be used and the methods and expected results will be given here, but these may change over time. The approach in this guideline will be to take each measurement of a test pattern and explain it using the information from all three SMPTE documents. The measuring equipment, the locations in the theatre from which the measurements are to be made, and the projector and theatre environment are the same for all measurements and test patterns. These will be explained first. Then each measurement and test pattern will be explained.

The DCDM color encoding is designed to eliminate color artifacts. The recommended measurements and tolerances around those measurements indicate whether the system is performing as defined. However, there is still the possibility of having a system that works perfectly at those measured points, yet still has visible color artifacts. Therefore, several of the recommended measurements and tests are visual tests.

A number of the tables in this section have been copied directly from the SMPTE ST 431 documents. Those tables define tolerances and have columns labeled “Reference”, “Review Room”, and “Theatre” or very similar words. It is recognized that different applications within the industry have different requirements for tolerances around the specifications. One must choose the appropriate tolerance based on the application and the need for different projectors to match to different levels of precision. Tighter tolerances produce closer matches in the projected images. However, the cost of achieving and maintaining these tighter tolerances must be balanced against the need for those closer matches of images. In order to simplify communciation, these column labels were chosen to define the varying levels of tolerance. These words mean:

Reference — The desired parameter level or value. This is the value relative to which the tolerances are defined. As an example, Table 6-5 shows that the Reference Sequential Contrast is 2000:1. As such, all screen-reflected objects occurring in the near-black regions of a scene will be recognized by observers with normal vision.

Review Room — The Review Room Tolerances are the permissible plus-or-minus variation from the associated Reference parameter level, which involves the Reference Projector and workstation visual displays.

Theatre — Theatre Tolerances are the permissible plus-or-minus variation from the associated Reference parameter level, which involves all Digital Cinema Theatre visual displays.

Ideally, workstation visual displays in post-production will have the same color appearance capability as the Reference Projector. The respective room environments will also ideally be equivalent to that for the Reference Projector. Also ideally, all workstation visual displays will be digital projectors with appropriately sized viewing screens and have parameters and color gamuts equal to those of the Reference Projector.

When this happens, colorists and cinematographers will very likely be assured that creative decisions made together at work stations in post-production will pass the test when later viewed for final approval on the Reference Projector screen.

6.1 Measuring Equipment

SMPTE RP 431-3 recommends that only two measurements be made: the measurement of luminance and the measurement of chromaticity. It is recommended that the luminance be measured with either a photometer or a spectroradiometer having the spectral luminance response of the standard observer (photopic vision), as defined in CIE S002. CIE S002 has information on two colorimetric observers, the 1931 observer (the 2-degree observer) and the 1964 observer (the 10-degree observer). The 2-degree observer is the observer data to use. The meter needs to have a minimum accuracy of ± 0.5 cd/m² (±0.2 fL) for white field measurements and ± 0.007 cd/m² (± 0.002 fL) for black field measurements. The chromaticity needs to be measured with a spectroradiometer with a minimum accuracy of ± 0.002 for the measurement of the x and y chromaticity coordinates at luminances above 10 cd/m². Color temperature meters do not have sufficient accuracy to meet these requirements for the measurement of either luminance or chrominance.

In all cases, the measurements are made of light reflected from the screen. Therefore, the measuring instrument must be pointed at the screen when the measurement is made.

6.2 Measuring Locations within the Review Room or Exhibition Theatre

SMPTE RP 431-3 recommends that in a review room the measurements be taken at a height of approximately 1.1 m (43 in) above the floor, at a distance of 1.5 to 3.5 screen heights from the screen, and at the place the color-grading operator would normally sit.

SMPTE RP 431-3 recommends that in an exhibition theatre there are six measurement locations: three in the center row of the theatre and three in the rear row of the theatre. The three locations within each row are: left edge seat, right edge seat, and center seat. At each measurement location, it is recommended that the measuring equipment be approximately 1.1 meters above the floor.

6.3 Projector and Theatre Environment

The projector should be set up and run according to the manufacturer's specifications. For these measurements the projector has be turned on and allowed to stabilize for at least 20 minutes before any measurements are taken. The room lights in the theatre need to be turned off except for lighting provided for safety reasons in order to equal the normal theatre operating conditions. The projector needs to receive images defined by the *X'Y'Z'* code values so that the entire D-Cinema system is being tested. Some projectors may be built with built-in test patterns. Although these built-in test patterns may be very useful for some tests, they may not be testing the entire D-Cinema system if the *X'Y'Z'* signals are not sent through the entire projector processing path.

6.4 Measurement of Ambient Light

This is a measure of the light reflected from the screen due to sources such as exit signs and foot lights, but not due to the projection mechanism. The light is measured under normal presentation conditions but with the projector lamp doused or turned off; it is measured from the locations defined in Section 6.2; and it is measured from the center of the screen. For Review Rooms, the ambient light level reflected by the screen needs to be less than 0.01 cd/m^2 (.0029 fL). For Exhibition Theatres, the ambient light level reflected by the screen needs to be less than 0.03 cd/m^2 (.01 fL). Safety regulations and the placement of exit lights or access lights may result in a higher ambient light level, but note that this will reduce the contrast of the projected image. Annex I gives more detail on the effect of higher ambient light on the contrast of the image in the theatre.

6.5 Measurement of the Luminance of White

There are two measurements for the white luminance, the absolute luminance, which is measured from the center of the screen, and the luminance uniformity, which is measured at the center of the screen, the sides of the screen for theatres and review rooms, and the corners of the screen for review rooms. The corner locations are defined as those points inset 5% ±1% of the screen width from both of the adjacent screen edges. The side locations are apparently the points equidistant from and closest to two adjacent corner locations. Annex J shows the *X'Y'Z'* code values, [3794 3960 3890], that define a white and show the calculation of those code values given the xyY values (from Tables 6-1 and 6-2) of the white. There has been considerable discussion of some processing operations that would cause an overshoot of allowed code values. However, this difference between 4095, the maximum allowed 12-bit number, and 3960, the code value for the maximum luminance, seems to allow a reasonable degree of headroom.

The reference luminance values and the tolerances for review rooms and theatres are given in Table 6-1.

Table 6-1 – White Luminance Values

Parameter	Reference	Review Room Tolerances	Theatre Tolerances
Luminance, center 100% white	48.0 cd/m² (14.0 fL)	±3.5 cd/m² (± 1.00 fL)	±10.2 cd/m² (± 3.00 fL)
Luminance sides	85% of center	80% to 90% of center	75% to 90% of center
Luminance corners	85% of center	80% to 90% of center	not specified

The reference chromaticity values and the tolerances for review rooms and theatres for the center of the screen are given in Table 6-2.

Table 6-2 – White Chromaticity Values for the Center of the Screen

Parameter	Reference	Review Room Tolerances	Theatre Tolerances
White Chromaticity, center	x=.314 y=.351	±.002 x ±.002 y	±.006 x ±.006 y

The tolerances for review rooms and theatres for the corners of the screen are given in Table 6-3. The tolerances for the corners are stated as a deviation from the chromaticity of the center because the center has a tolerance associated with it. In order to make the screen appear as uniform as possible, it is better to have the corners differ from the center within a defined limit than to have the corners within an absolute limit.

Table 6-3 – White Chromaticity Tolerances for the Corners of the Screen

Parameter	Reference	Review Room Tolerances	Theatre Tolerances
White Chromaticity, corners	within ±.000 x ±.000 y of the center	within ±.008 x ±.008 y of the center	within ±.015 x ±.015 y of the center

Although the luminance uniformity and the chromaticity uniformity are defined in relation to the center and an additional four or eight points on the screen, it is also stated that they be symmetrically distributed about the geometric center of the screen and exhibit no abrupt changes. The problem that has been observed with some digital projectors is that the light on the screen at the specified locations falls within the specified tolerances, but between those points there are variations in color (chromaticity) that may be objectionable. Therefore, in an effort to minimize the number of measurements and the complexity of defining a series of measurements that would identify the problem, it is easier to simply look at a white field on the screen and see if there are obvious color deviations from white across the screen.

6.6 Measurement of the Luminance of Theatre Black

In Section 5 the theatre black was defined as the light reflected from the screen when the projector was sent code values [b b b]. Therefore, in the measurement of the theatre black a frame of those code values at every pixel must be sent to the projector and the luminance must be measured. There is no explicit specification of the value of this measurement, but from the sequential contrast ratio specification given in Table 6-5 in Section 6.7, there is a maximum Reference luminance (0.024 cd/m^2) for the theatre black as well as a maximum Review Room luminance (0.032 cd/m^2) and a maximum Theatre luminance (0.040 cd/m^2). This is higher than the maximum ambient light luminance allowed in Section 6.4 because the theatre black includes both the ambient light and the light from the projector when it is sent the code values [b b b]. The projector may (most likely will) put some light on the screen even when sent the code values [b b b]. Therefore, the theatre black luminance will be higher than the ambient light luminance.

Just as there was concern about headroom in code values between the maximum 12-bit number and the maximum code value for the white, there has been concern at the black end. There is also concern that at code value 0 the contrast goes to infinity. Although the code value 0 defines a luminance of 0, it really defines the luminance of the theatre black and the 0 means 0 cd/m^2 above theatre black. Table 6-4 shows the relationship between Y and Y' at the very low Y' values. Based on the minimum luminance accuracy of the photometer for the black measurements of 0.007 cd/m^2, based on one measurement alone, a person could not distinguish between a code value of 0 and a code value of 125. From Equation D-1 and Figure D-1 in Annex D it can be estimated that at the maximum reference black luminance of 0.024 cd/m^2 the minimum change in luminance that a person can see under ideal conditions is about 0.00048 cd/m^2. From this and the values in Table 6-4 it can be seen that the luminance encoded by a code value of 0 and the luminance encoded by a code value of slightly below 50 cannot be seen as different even under ideal conditions. Therefore, on the black end, there are at least 50 code values and possibly as many as 125 code values that in practice define the same perceived or measured value.

Table 6-4 – Y' Code Values and the Encoded Luminance

Y'	Y, cd/m^2
0	0.0000
25	0.0001
50	0.0006
75	0.0016
100	0.0034
125	0.0060
150	0.0097

6.7 Measurement of the Sequential Contrast

The sequential contrast is defined as the luminance of the white divided by the luminance of the theatre black. The specification of the sequential contrast and its tolerances are given in Table 6-5. From the sequential contrast values in Table 6-5 and the white luminance value in Table 6-1, the maximum theatre black was calculated and specified in Section 6.6. It must be emphasized that all of these measurements are made with the measuring instrument pointing at the screen.

Table 6-5 – Sequential Contrast Values and Tolerances

Parameter	Reference	Review Room Tolerances	Theatre Tolerances
Sequential Contrast	2000:1 minimum	1500:1 minimum	1200:1 minimum

6.8 Measurement of the Intra-frame (Checkerboard) Contrast

The intra-frame contrast is measured using a checkerboard pattern with a 4x4 grid of alternating white and black patches. The code values for the white patches are [3794 3960 3890] and the code values for the black patches are [b b b]. The intra-frame contrast is computed by summing the luminances of the white patches and dividing by the sum of the luminances of the black patches. The specification of the intra-frame contrast and its tolerances are given in Table 6-6. It must be emphasized that these measurements are made with the measuring instrument pointing at the screen.

Table 6-6 – Intra-frame Contrast Values and Tolerances

Parameter	Reference	Review Room Tolerances	Theatre Tolerances
Intra-frame Contrast	150:1 minimum	100:1 minimum	100:1 minimum

6.9 Visual Verification of Gray Scale Tracking

The appearance of a neutral scale through the entire luminance range of the projector is essential to the display of high quality images. It has been found that a visual estimate of the neutrality of a scale from white to black is a better test of the neutrality than any measurements that can be made. Therefore, the recommendation on the verification of the gray scale tracking is a visual test. The appearance of gray is relative to the color and luminance of the area surrounding the gray being assessed. Therefore, for the assessment of the gray scale tracking, the background is set to a gray of the same chromaticity coordinates as the projector white point and two gray scales are recommended, a black to white scale and a black to dark gray scale. Two scales are necessary because it is difficult to judge dark grays in the presence of bright whites. The black to white scale has a background luminance of 4.8 cd/m^2 (code values [1565 1633 1604]) and the black to dark gray scale has a background luminance of 0.0064 cd/m^2 (code values [122 128 125]) above theatre black. It is recommended that each gray scale test pattern be centered on the screen and occupy a rectangle sized 20% of the screen height by 80% of the screen width. Each step needs to be 8% of the screen width. The black to white gray scale patches can be defined by the code values in Table 6-7. The black to dark gray scale patches can be defined by the code values in Table 6-8. Although this is a visual verification of gray scale tracking, Tables 6-7 and 6-8 show the chromaticity coordinates and luminance values of each of the steps. Although these tables have been copied from SMPTE RP 431-2, the luminance values in Tables 6-7 and 6-8 are the luminance values one can calculate from the Y' values. Therefore if measurements of the luminance values are to be made in an actual theatre, the luminance of the theatre black luminance value must be added to the luminance values in these two tables in order to calculate the expected measured luminance values. If measurements are made, the measurements need to be made in the center of each gray patch.

Table 6-7 – Black-to-White Gray Step-Scale Test Pattern Code Values, Luminance Values, and Chromaticity Coordinates

	Input Code Values			Output Chromaticity Coordinates		Output Luminance
Step Number	**X'**	**Y'**	**Z'**	**x**	**y**	**Y,** cd/m²
1	379	396	389	0.314	0.351	0.12
2	759	792	778	0.314	0.351	0.73
3	1138	1188	1167	0.314	0.351	2.10
4	1518	1584	1556	0.314	0.351	4.43
5	1897	1980	1945	0.314	0.351	7.92
6	2276	2376	2334	0.314	0.351	12.72
7	2656	2772	2723	0.314	0.351	18.99
8	3035	3168	3112	0.314	0.351	26.87
9	3415	3564	3501	0.314	0.351	36.50
10	3794	3960	3890	0.314	0.351	48.00

Table 6-8 – Black-to-Dark Gray Step-Scale Test Pattern Code Values, Luminance Values, and Chromaticity Coordinates

	Input Code Values			Output Chromaticity Coordinates		Output Luminance
Step Number	**X'**	**Y'**	**Z'**	**x**	**y**	**Y,** cd/m²
1	122	128	125	0.314	0.351	0.006
2	245	255	251	0.314	0.351	0.038
3	367	383	376	0.314	0.351	0.111
4	490	511	502	0.314	0.351	0.234
5	612	639	627	0.314	0.351	0.418
6	734	766	753	0.314	0.351	0.670
7	857	894	878	0.314	0.351	1.002
8	979	1022	1004	0.314	0.351	1.418
9	1101	1150	1129	0.314	0.351	1.928
10	1224	1277	1255	0.314	0.351	2.531

6.10 Visual Assessment of Contouring

Contouring is the appearance of steps or bands where only a continuous or smooth gradient is expected. Contouring is a function of many variables and it is important to look at a series of test patterns with shallow gradations to simulate naturally occurring gradations in images. Examples include horizons, particularly at sunset or sunrise, and the natural falloff around high intensity spotlights, particularly if diffused by atmosphere or lens filtration. These test pattern ramps need to have a step width of no less than 4 pixels with an increment of one code value per step and need to be placed on a background equal to the minimum value in the ramp, so that the eye is adapted for maximum sensitivity.

The assessment of this artifact is visual. Look at each image or sequence of images from a normal viewing distance and under normal operating conditions and determine if any contouring (step in luminance) or color deviation from the neutral gray can be seen.

Dynamic fades to black are widely used in real world content. The SMPTE ST 431 documents do not offer any specific test patterns for a dynamic fade test, but a ramp that starts at what is described above, then slowly decreases in code values would suffice. In use the observer would watch the dynamic fade and judge it for any non-neutral colors in the fade series of images.

6.11 Measurement of the Transfer Function Exponent

The transfer function exponent controls the projected image contrast, which is an important part of the overall quality of the image. The tolerance around the transfer function exponent is designed to allow some variation in the system without seriously degrading image quality. This section describes how to measure that transfer function exponent. The decoding equation for luminance, Equation 5-5, can be rewritten as

$$\log(Y) = 2.6 * \log(Y') - 2.6\log(4095) + 2.6 * \log(52.37/L) = 2.6 * \log(Y') - K \qquad (6\text{-}1)$$

The value of K is unimportant in this test. Therefore if a series of white to gray frames, for example the colors defined in Table 6-7, are projected and the luminance values are measured for each frame, a plot of log(Y) vs log(Y') should give a straight line with a slope of 2.6. Because the *X'Y'Z'* values define tristimulus values above the theatre black, the theatre black luminance must be subtracted from each measured luminance before taking the log of the luminance. Table 6-9 shows the nominal value for this best fit slope and the tolerances, in both percentages as specified in SMPTE RP 431-2 and in actual numbers, around the slope for review rooms and for theatres.

Table 6-9 – Best Fit Slope of the Transfer Function Exponent and Tolerances for Review Rooms and Theatres

Image Parameters	Nominal Value (Reference Projector)	Tolerances (Review Rooms)	Tolerances (Theatres)
Exponent	2.6	± 2%	± 5%
Exponent	2.6	2.548 to 2.652	2.47 to 2.73

6.12 Measurement of the Color Gamut (Color Primaries)

In an additive display, the color gamut is determined by the chromaticity coordinates and luminance values of the three primaries, the white, and the black. The white and the theatre black were described above. The minimum set of color primaries are shown in Table 6-10. In practice, a projector may have a larger color gamut by using alternate primaries as long as the projector with its primaries can produce the chromaticity coordinates and luminance values from the code values in Table 6-10 within the color accuracy tolerances specified in Section 6.13. It is recommended that the measurement of the chromaticity coordinates and luminance values be made from the center of the screen when a full-field frame of the color primary code values is displayed by the projector.

Table 6-10 – RGB Primary Code Values, Luminance Values, and Chromaticity Coordinates

	Code Values			Chromaticity Coordinates		Luminance
Primary	**X'**	**Y'**	**Z'**	**x**	**y**	**Y,** cd/m²
Red	2901	2171	100	0.6800	0.3200	10.06
Green	2417	3493	1222	0.2650	0.6900	34.64
Blue	2014	1416	3816	0.1500	0.0600	3.31

6.13 Specification of the Color Accuracy of any Displayed Colors

Within the minimum color gamut specified for the Reference Projector, all colors need to be accurately reproduced. A discussion of delta E*ab is given in Appendix L. In theory this applies to all colors, but in practice it would be impossible to display and measure all possible colors that can be encoded by the DCDM color encoding equations and displayed by a Reference Projector. Therefore Table 6-11 gives a set of colors that can be used to verify the color accuracy of a system. It is felt that if these colors are within the tolerance limits, then all colors are most likely within the tolerances. The neutral colors 6 through 10 in Table 6-7 may also be used as tests of the color accuracy of any projector in its environment.

Table 6-11 – Color Accuracy Color Patch Code Values, Luminance Values, and Chromaticity Coordinates

	Input Code Values			Output Chromaticity Coordinates		Output Luminance
Patch	**X'**	**Y'**	**Z'**	**x**	**y**	**Y,** cd/m²
Red-1	2901	2171	100	0.6800	0.3200	10.06
Green-1	2417	3493	1222	0.2650	0.6900	34.64
Blue-1	2014	1416	3816	0.1500	0.0600	3.31
Cyan-1	2911	3618	3890	0.2048	0.3602	37.95
Magenta-1	3289	2421	3814	0.3424	0.1544	13.35
Yellow-1	3494	3853	1221	0.4248	0.5476	44.70
Red-2	2738	2171	1233	0.5980	0.3269	10.06
Green-2	2767	3493	2325	0.2884	0.5282	34.64
Blue-2	1800	1416	3203	0.1664	0.0891	3.31
Cyan-2	3085	3590	3756	0.2409	0.3572	37.19
Magenta-2	3062	2421	3497	0.3382	0.1838	13.35
Yellow-2	3461	3777	2065	0.3973	0.4989	42.44

7 Conversion of Reference Projector R'G'B' Code Values to DCDM Code Values and then to Linear Projector Code Values

There are two conversions that are most important in the entire D-Cinema color workflow as shown in Figure 4-1: (1) There are the DSM code values that must be transformed into the DCDM *X'Y'Z'* code values and (2) There are the DCDM *X'Y'Z'* code values that must be transformed into the Projector RGB values. The DSM to *X'Y'Z'* transform is dealt with in Sections 7-1 - 7.4, Section 9, and Annex K. The *X'Y'Z'* to Projector RGB transform is dealt with in Sections 7.1 – 7.4, Annex J, and Annex K.

7.1 Background and Theory

Although the *X'Y'Z'* DCDM encoding is a non-linear encoding, it is based on the XYZ linear, additive, color encoding system defined by the CIE in 1931. Television is also a non-linear R'G'B' encoding that is based on an RGB linear, additive, imaging system. The mathematics of dealing with conversions between different additive display devices, whether real devices, imaginary devices, or theoretical encoding devices, is the same. The concepts involved are not difficult to grasp, but the math can be confusing due to the number of calculations needed to calculate the different transforms. Although the calculations described in SMPTE RP 176 and RP 177 are explicitly for television systems, the calculations apply equally well to the transformations between the DCDM encoding and any real, additive, display device. Therefore, those calculations will be reviewed here and a specific numerical example will be worked. Although these equations apply to a theoretical additive display device, most additive display devices follow these equations very closely.

There are two laws of colorimetry upon which the DCDM encoding is based and which are the starting points for all of the following calculations:

1. If two lights have the same CIE 1931 tristimulus values in the same viewing environment, the two lights will match in appearance.

2. When one light with CIE tristimulus values XYZ_1 is added to a second light with CIE tristimulus values XYZ_2, the tristimulus values for the combination of these two lights is $XYZ_1 + XYZ_2$.

There are two other points that must be made in order to understand the following equations:

1. In all of these equations, the XYZ and RGB values are normalized values. This means that the Y value is scaled to a range of 0 to 1 and the X and Z values are scaled with the same normalizing constant as the Y normalizing constant. Although the Y value is limited to a range from 0 to 1, the X and Z values may have upper limits higher or lower than 1. The RGB values range in value from 0 to 1 and can be thought of as the fractions of the full-on primaries in a particular color. In many applications, the normalized values are needed. In other applications, the absolute values are needed. The conversion from the normalized to the absolute values is a multiplication operation – multiplication of the normalized values by the appropriate constant. Therefore, although the following equations make use of the normalized XYZ and RGB values, it is left to the user to determine whether normalized or absolute values are needed in a particular piece of equipment.

2. It is assumed that the light output of the display device modeled with these equations is directly proportional to the RGB values. There are cases in which this is not true. For example, a television with a power supply too small for the television may be able to produce a small very bright red or green or blue pixel or area of pixels on a black background, but when the entire television screen is white, the power supply may not be able to produce a white that is as bright as the sum of the red alone plus the green alone plus the blue alone. In this case, the equipment has failed, not the equations.

7.2 Derivation of the RGB-to-XYZ and XYZ-to-RGB Matrices, General Equations

The same basic equations can be used to describe all linear, additive, color display devices. SMPTE RP 176 and RP 177, which are written for television systems, apply equally well to digital projection systems. Therefore, the calculations described in those RPs will be summarized here to show how they apply to the digital projection systems. This section will show how to use the equations and the information that defines the Reference Projector to do the calculations. More details on the calculations are provided in Annex K and in SMPTE RP 176 and SMPTE RP 177.

There are two general equations that describe the relationship between the XYZ tristimulus values and the RGB device values.

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{pmatrix} * \begin{pmatrix} R \\ G \\ B \end{pmatrix} = NPM * \begin{pmatrix} R \\ G \\ B \end{pmatrix} \qquad (7\text{-}1)$$

where XYZ are the normalized CIE tristimulus values, R, G, B sub-scripts refer to the Red, Green, and Blue primaries, and RGB are the normalized linear RGB values or the normalized linear amounts of each of the primaries. NPM is the normalized primary matrix.

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = NPM^{-1} * \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \qquad (7\text{-}2)$$

Equation 7-1 shows how to go from the RGB values to the XYZ tristimulus values and Equation 7-2 shows how to go from the XYZ tristimulus values to the RGB values. The relationship between normalized XYZ and absolute XYZ values for the Reference Projector is shown in Equation 7-3. The value 48 comes from the definition of the white point as 48 cd/m^2.

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{Normalized} = \left(\frac{1}{48} \right) * \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{Absolute} \qquad (7\text{-}3)$$

From Table 6-10, which gives the xyY values of the Reference Projector primaries, the equations in Annex J that show how to convert xyY to XYZ, and Equation 7-3, the normalized primary XYZ values can be calculated. These are shown in Table 7-1.

Table 7-1 – Absolute and Normalized XYZ values of the Reference Projector Primaries

	Absolute XYZ Values			Chromaticity Coordinates		Luminance
Primary	**X**	**Y**	**Z**	**x**	**y**	**Y,** cd/m²
Red	21.37	10.06	0.00	0.6800	0.3200	10.06
Green	13.30	34.64	2.26	0.2650	0.6900	34.64
Blue	8.28	3.31	43.59	0.1500	0.0600	3.31
	Normalized XYZ Values			**Chromaticity Coordinates**		**Luminance**
Primary	**X**	**Y**	**Z**	**x**	**y**	**Y,** cd/m²
Red	0.4453	0.2096	0.0001	0.6800	0.3200	10.06
Green	0.2770	0.7216	0.0470	0.2650	0.6900	34.64
Blue	0.1724	0.0690	0.9082	0.1500	0.0600	3.31

7.3 Derivation of the RGB-to-XYZ and XYZ-to-RGB Matrices, Reference Projector

The NPM matrix, using the normalized XYZ data in Table 7-1 and Equation 7-1, is

$$NPM = \begin{pmatrix} 0.4453 & 0.2770 & 0.1724 \\ 0.2096 & 0.7216 & 0.0690 \\ 0.0001 & 0.0470 & 0.9082 \end{pmatrix} \qquad (7\text{-}4)$$

The problem is that this matrix is not correct. It was calculated from the data in Table 7-1, some of which were taken from the data in Table 6-10. Table 6-10 came from Table A-4 in SMPTE RP 431-2, which was intended to be used to test the color accuracy of any projector and its environment. The numbers in Tables 6-10 and 7-1 are given to a precision of four significant digits for all the xyY values except the Y value of the blue primary, which is given to three significant digits. It can be seen that there is a round-off error because the sum of the luminances of the three primaries is 48.01 cd/m^2 and this sum should equal the luminance of the white, which is 48.00 cd/m^2. A much longer, but more accurate, method of calculating the NPM matrix is given in SMPTE RP 177 and shown in Appendix K. Using the calculation method shown in Appendix K, the correct NPM for the Reference Projector is

$$NPM = \begin{pmatrix} 0.4452 & 0.2771 & 0.1723 \\ 0.2095 & 0.7216 & 0.0689 \\ 0.0000 & 0.0471 & 0.9074 \end{pmatrix} \qquad (7\text{-}5)$$

SMPTE RP 177 suggests that the NPM should be calculated to 10 significant digits. Therefore using the method in Appendix K and calculating to 10 significant digits, the NPM for the Reference Projector RGB to XYZ transform matrix (the same matrix as shown in SMPTE RP 431-2 Annex C) is

$$NPM = \begin{pmatrix} 0.4451698156 & 0.2771344092 & 0.1722826698 \\ 0.2094916779 & 0.7215952542 & 0.0689130679 \\ 0.0000000000 & 0.0470605601 & 0.9073553944 \end{pmatrix} \qquad (7\text{-}6)$$

The main reason for the differences in the calculated NPM matrices, Equations 7-4 and 7-5, is the precision of the luminance values for each of the primaries. Table 7-2 shows these differences in the luminance values.

Table 7-2 – Luminance Values of the Reference Projector Primaries

	From Table 7-1	**Higher Precision**
Primary	**Y,** cd/m²	**Y,** cd/m²
Red	10.06	10.05560054
Green	34.64	34.63657220
Blue	3.31	3.30782726

For color accuracy purposes, the luminance values in SMPTE RP 431-2 are more precise than anyone will be able to measure. The Reference Projector primaries and white point are specified in a Recommended Practice and are not subject to measurement error. The NPM is more appropriately calculated from the standardized values and done with the 10 significant digits as recommended in SMPTE RP 177. Note, however, that all the NPM matrices calculated here would result in a maximum color error considerably less than any of the tolerances in any of the SMPTE Digital Cinema Standards and Recommended Practices. In addition, any NPM for any actual projector will be calculated based on measured data that will be less precise than any of these calculations. The purpose in going through this discussion was to show how simple round-off errors would lead to noticeable differences in the calculated NPM matrix.

From Figure 4-1, it can be seen that the matrix that is needed inside the projector is not the NPM shown above, but the inverse of the NPM. The reason for this is that in Figure 4-1, inside the projector, the transform that is needed is the XYZ to RGB transform, not the RGB to XYZ transform. The inverse of the NPM is

$$NPM^{-1} = \begin{pmatrix} 2.7253940305 & -1.0180030062 & -0.4401631952 \\ -0.7951680258 & 1.6897320548 & 0.0226471906 \\ 0.0412418914 & -0.0876390192 & 1.1009293786 \end{pmatrix} \qquad (7\text{-}7)$$

These matrices are the same matrices that are shown in Annex C of SMPTE RP 431-2 except for the fact that they are shown to 10 digits to the right of the decimal point here.

Combining Equations 7-1 and 7-6 gives the equation

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0.4451698156 & 0.2771344092 & 0.1722826698 \\ 0.2094916779 & 0.7215952542 & 0.0689130679 \\ 0.0000000000 & 0.0470605601 & 0.9073553944 \end{pmatrix} * \begin{pmatrix} R \\ G \\ B \end{pmatrix} \qquad (7\text{-}8)$$

Likewise, combining Equations 7-2 and 7-7 gives the equation

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} 2.7253940305 & -1.0180030062 & -0.4401631952 \\ -0.7951680258 & 1.6897320548 & 0.0226471906 \\ 0.0412418914 & -0.0876390192 & 1.1009293786 \end{pmatrix} * \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \qquad (7\text{-}9)$$

These two equations relate the linear XYZ values to the linear Reference Projector RGB values and are therefore very useful for many of the calculations that must be done to create digital projection content. If a digital projector has a white point or primaries that are not exactly the same as the Reference Projector white point and primaries, these matrices must be recalculated as described in Appendix J and the new matrices must be used in place of these Reference Projector matrices.

Annex F shows that inside the Reference Projector, the linear RGB values need to be a minimum of 16 bits to avoid contouring and to carry all of the information that is contained in the 12-bit *X'Y'Z'* code values. It was calculated that if the matrix in Equation 7-9 is rounded to four digits to the right of the decimal point, the maximum linear RGB error will be less than 10 code values, if Equation 7-9 is rounded to five digits to the right of the decimal point, the maximum linear RGB error will be less than 0.5 code values, and if Equation 7-9 is rounded to six digits to the right of the decimal point, the maximum linear RGB error will be less than 0.03 code values. Therefore, the use of five or more digits to the right of the decimal point in Equation 7-9 will carry all the information in the *X'Y'Z'* code values into the linear RGB values and even the use of four digits will most likely produce no visible artifacts or loss of information. SMPTE RP 431-2 shows the matrix to four digits to the right of the decimal for both Equations 7-8 and 7-9.

7.4 Explanation of Annex C in SMPTE RP 431-2, Reference Projector (conversion example for R'G'B' to XYZ to *X'Y'Z'*)

SMPTE RP 431-2 deals with the Reference Projector and its environment. Informative Annex C in SMPTE RP 431-2 describes the processing path from R'G'B' code values to XYZ to *X'Y'Z'* code values. This section gives a more detailed description of the assumptions behind that transform and a more detailed description of the transform itself. In this section, all references to Annex C are to Annex C in SMPTE RP 431-2.

There are five assumptions that are being made in Annex C. The first assumption is that content is being created with some device that outputs RGB code values that range from 0 to 4095 and sends those RGB code values to an additive, three-primary display device. These code values are called R'G'B' in Annex C. In Annex C it is assumed that this additive, three-primary display device is a digital projector. As long as the digital projector processes those RGB code values in a consistent and smooth way, variations in RGB will make smooth variations in displayed color. Therefore, this is a reasonable way by which one could make digital images. The second assumption is that the digital projector has a processing path that has at least these two steps in this order: (1) A 1d lut that converts input RGB values into internal RGB values and (2) A 3x3 matrix that converts these internal RGB values into another set of internal RGB values. The third assumption is that the user can either populate the 1d lut and 3x3 matrix with the user's own numbers or the user can determine the numbers that are in the 1d lut and 3x3 matrix. Either case will work, but it will be shown that the case in which the user can define the numbers is more useful. The fourth assumption is that the RGB values after the 3x3 matrix are linearly related to the intensity of the three primaries. The fifth assumption is that the digital projector primaries have xy chromaticity coordinates as shown in Table 6-10 and the digital projector white point has xy chromaticity coordinates as shown in Table 6-2. This means the digital projector primaries and white point exactly match the Reference Projector primaries and white point.

In Annex C the code values that are sent to the digital projector are called R'G'B'. It is stated that the relationship between the input R'G'B' code values and the linear RGB values is

$$R = \left(\frac{R'}{4095} \right)^{2.6} \qquad (7\text{-}10)$$

and similar equations relating G’ to G and B’ to B. The 4095 in the denominator of Equation 7.10 indicates that the R’G’B’ code values are 12-bit values. In the general case, the R’G’B’ code values do not need to be 12-bit values, but because the Reference Projector in SMPTE RP 431-2 expects 12-bit numbers, this is a reasonable normalization of the input code values. This equation is implemented in the digital projector by a 1d lut as stated in the second and third assumptions. Figure F-1 and Table F-1 show that in order to avoid contouring in the most critical scenes, the linear RGB values must be defined to a bit depth of at least 16 bits.The second assumption also calls for a 3x3 matrix. In this case the RGB values will be proportional to the intensities of the primaries only if that 3x3 matrix is a unity matrix. It is not standard practice to set up a digital projector with a unity matrix following the 1d lut that implements the gamma 2.6 function, but in this case, the matrix must be a unity matrix. The net result of assumption four, which says that the RGB values are proportional to the intensities of the primaries of the projector, and assumption five, which says that the primaries and white point of the digital projector match the primaries and white point of the Reference Projector, is that Equation 7.8 can be used to calculate the XYZ values of the image resulting from sending the R’G’B’ code values to the digital projector.

But the calculation of the XYZ values for each pixel of an image is not the end of the calculation of the DCDM *X’Y’Z’* code values. To calculate the *X’Y’Z’* code values, Equations 5-1, 5-2, and 5-3 must be used. In Annex C of SMPTE RP 431-2, as is done in SMPTE 428-1, the symbol $CV_{X'}$ is used in place of X’.

The above paragraphs explain how to determine the *X’Y’Z’* code values that represent the content that was prepared under the assumptions listed above. This may not be the way that all people will want to create their content, but it is a reasonable way to create content and is a way that at least some people will create content. There is one clear reason for creating content in this way. The R’G’B’ starting code values are converted inside the projector into linear RGB values that represent the relative intensity of the primaries where 0 means that primary is off and 1 means that primary is full-on. Therefore, all content will be within the gamut of the Reference Projector and no gamut mapping of the content in a projector that meets the specifications set out in SMPTE RP 431-2 will be needed. If content is created in *X’Y’Z’* code values, it is not clear from the code values themselves if the encoded color is inside or outside the color gamut of the Reference Projector. This is the reason this series of equations and calculations was described in Annex C of SMPTE RP 431-2.

Annex C of SMPTE RP 431-2 did not stop at the calculation of the *X’Y’Z’* code values from the R’G’B’ code values. Annex C also described the minimum processing that must be present in the digital projector to assure that the image seen on the screen is the exact image that the creator of the image intended the viewer to see on the screen. In this case, the code values sent to the projector are not the R’G’B’ code values, but the *X’Y’Z’* code values. The second through the fifth assumptions still hold true for the digital projector. The same 1d lut that took the input R’G’B’ code values to linear RGB values will be used to take the input *X’Y’Z’* code values to linear XYZ values. In this case, the linear XYZ values must be converted into linear RGB values that are proportional to the intensities of the primaries. Therefore, Equation 7-9 shows the processing that must be done and the 3x3 matrix in that equation must be put into the digital projector in place of the unity 3x3 matrix that was used previously. The output linear RGB values will be proportional to the intensities of the primaries and will then produce on the screen the image defined by the input *X’Y’Z’* code values.

It is often easier to follow a set of calculations if one sees actual numbers instead of only variables. Therefore, the following tables show the calculations for a few sets of code values through the processing described above.

Table 7-3 contains a set of colors and their input R’G’B’ code values.

Table 7-3 – R'G'B' Code Values that Define Several Colors

Color	R'	G'	B'
White	4095	4095	4095
Gray	2000	2000	2000
Green Primary	0	4095	0
Reddish	3000	1000	2000
Bluish	1000	2000	3000

Table 7-4 shows the RGB values after Equation 7-10.

Table 7-4 – RGB Code Values Calculated from the R'G'B' Code Values

Color	R	G	B
White	1.0000	1.0000	1.0000
Gray	0.1552	0.1552	0.1552
Green Primary	0.0000	1.0000	0.0000
Reddish	0.4453	0.0256	0.1552
Bluish	0.0256	0.1552	0.4453

Table 7-5 shows the XYZ tristimulus values and the xyz chromaticity coordinates after Equations 7-8 and I-1.

Table 7-5 – XYZ and xyz Values Calculated from the RGB Code Values

Color	X	Y	Z	x	y	z
White	0.8946	1.0000	0.9544	0.3140	0.3510	0.3350
Gray	0.1388	0.1552	0.1481	0.3140	0.3510	0.3350
Green Primary	0.2771	0.7216	0.0471	0.2650	0.6900	0.0450
Reddish	0.2321	0.1224	0.1420	0.4674	0.2466	0.2860
Bluish	0.1311	0.1480	0.4114	0.1899	0.2144	0.5957

Table 7-6 shows the *X'Y'Z'* DCDM 12-bit code values after Equations 5-1, 5-2, and 5-3.

Table 7-6 – DCDM *X'Y'Z'* Code Values

Color	X'	Y'	Z'
White	3794	3960	3890
Gray	1853	1934	1900
Green Primary	2417	3493	1222
Reddish	2258	1766	1869
Bluish	1813	1899	2814

Table 7-7 shows the XYZ tristimulus values and the xyz chromaticity coordinates after Equations 5-4, 5-5, 5-6, and I-1.

Table 7-7 – XYZ and xyz Values Calculated from the *X'Y'Z'* Code Values

Color	X	Y	Z	x	y	z
White	0.8946	1.0000	0.9547	0.3140	0.3510	0.3351
Gray	0.1388	0.1552	0.1482	0.3140	0.3509	0.3351
Green Primary	0.2770	0.7216	0.0470	0.2649	0.6901	0.0450
Reddish	0.2321	0.1225	0.1420	0.4674	0.2467	0.2859
Bluish	0.1312	0.1480	0.4114	0.1900	0.2143	0.5958

Table 7-8 shows the RGB values after Equation 7-9. These RGB values are slightly different from the RGB values in Table 7-4 due to the rounding operation in the calculation of the *X'Y'Z'* values when Equations 5-1, 5-2,and 5-3 were used. In a projector the values below 0 or above 1 would be clipped to 0 and 1 respectively. The remaining differences, at most 0.0003, would not be visible.

Table 7-8 – RGB Code Values Calculated from the R'G'B' Code Values

Color	R	G	B
White	1.0000	0.9999	1.0003
Gray	0.1552	0.1551	0.1552
Green Primary	-0.0003	1.0001	0.0000
Reddish	0.4454	0.0257	0.1551
Bluish	0.0258	0.1550	0.4453

8 Gamut Mapping and the Value of the Mastering Projector Metadata

There are a number of reasons an encoded color may fall outside the Reference Projector Gamut Boundary (the letters RPGB will be used in this section). Figure C-1 shows the maximum gamuts, in chromaticity coordinate space, of the Reference Projector, film, the spectral locus, and the XYZ space. Clearly some film colors fall outside the RPGB. As another example, if one were to use a projector with primaries outside the RPGB, then such a projector would have colors that fall outside the RPGB. There is the possibility that there will be encoded image colors that fall outside the RPGB. If this happens there will need to be some strategy that substitutes colors that a projector can produce for colors that the projector cannot produce. This process is called gamut mapping.

Figure C-1 shows that there are some film colors that fall outside the RPGB. In this section, one of those colors, a cyan color shown in Figure 8-1, will be used to give an example of how out-of-gamut colors might be handled. This film cyan color was defined by a set of Cineon code values, written to intermediate film, printed to print film, projected using a film projector, and the colorimetry of the color was measured off the screen. Therefore, this is a color that has been produced by the film system, not a theoretical color. Table 8-1 summarizes the calculations for this cyan color through the system. That table shows that this cyan color can be encoded by legal DCDM code values. This encoded cyan color is the color that is desired.

Table 8-1 shows that the Reference Projector normalized R value, R_{RP}, is negative. This means the Reference Projector cannot produce this color because the limit on what colors the Reference Projector can produce is the set of colors in which the normalized RGB values are all greater than or equal to 0 and less than or equal to 1. This result is expected because Figure 8-1 shows that this cyan color is inside the film gamut, but outside the RPGB.

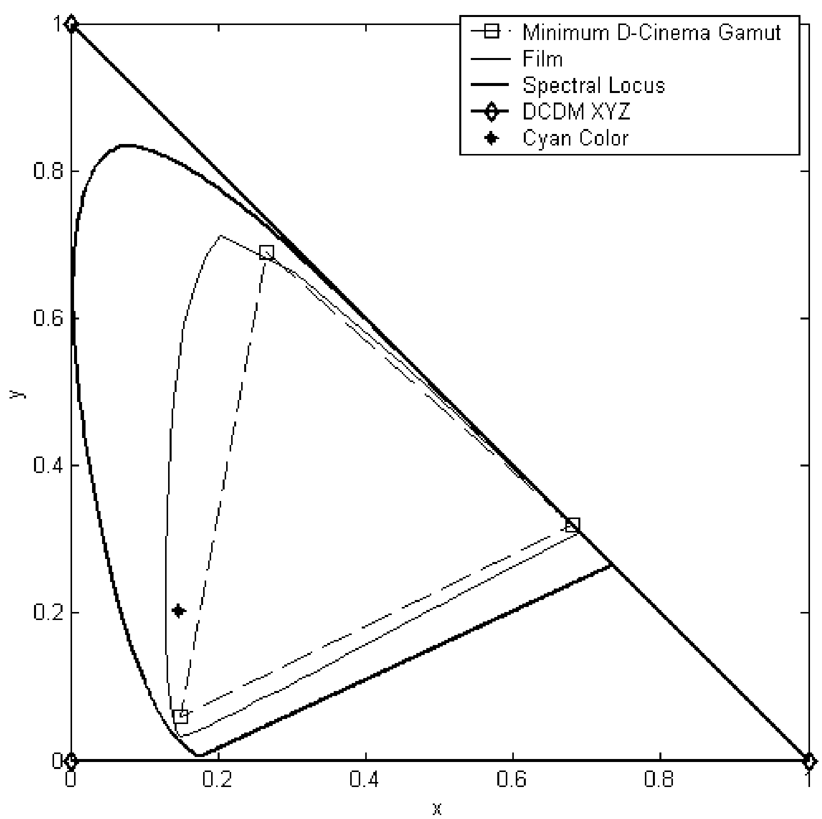

Figure 8-1 – Cyan Color Compared to the Film and Reference Projector Color Gamuts

If the Reference Projector cannot produce this encoded cyan color, it must produce some other color. This process by which one color, which a device cannot produce, is replaced by another color, which the device can produce, is known as Gamut Mapping. All image display systems must have some gamut mapping strategy. Even film has a gamut mapping strategy, but it is done in chemistry and it is not as obvious as the gamut mapping in a digital system. No recommendation on the gamut mapping strategy that should be followed will be made here. That is an implementation decision that is not a part of any of the D-Cinema standards. The references in the Bibliography describe a large number of gamut mapping strategies. By describing a very simple gamut mapping strategy, the basic principles behind different strategies will be demonstrated. In addition, how the information in the DCDM file might be used to implement a gamut mapping strategy can be explained.

Table 8-1 – Following a Cyan Color through Gamut Mapping

What the Numbers Are	Numbers		
Film XYZ	2.799	3.822	12.303
Film xyz	0.1479	0.2020	0.6501
DCDM *X'Y'Z'* Values	1327	1496	2346
Reference Projector Absolute XYZ Values	2.797	3.820	12.305
Reference Projector Normalized RGB Values, R_{RP}, G_{RP}, B_{RP}	-0.035	0.094	0.278
Gamut Mapping by Clipping, RGB Values, R_{RP}, G_{RP}, B_{RP}	0.000	0.094	0.278
Gamut Mapping by Clipping, XYZ Values	3.546	4.172	12.305
Gamut Mapping by Clipping, xyz Values	0.1770	0.2084	0.6145

The easiest gamut mapping strategy is to clip all Reference Projector Normalized RGB Values less than zero to zero and all Reference Projector Normalized RGB Values greater than one to one. The problem with this simple clip strategy is that it usually leads to hue shifts in the color produced on the screen and people are quite sensitive to hue shifts. If a color goes a little darker or lighter or it goes a little less saturated (gamut mapping usually does not make a color go more saturated), the color change is usually less objectionable than if the color changes hue. Certainly there are some hue shifts that are acceptable, but in general people try to avoid anything more than a small hue shift. So simply clipping the code values is usually not a preferred gamut mapping strategy. Table 8-1 and Figure 8-2 show the effect of clipping of this cyan color. Figure 8-2 has been greatly expanded in the region near the cyan color so that the shift in chromaticity due to clipping can more easily be seen. The clipped cyan color lies on a line connecting the chromaticity coordinates of the original cyan color and the Reference Projector red primary. This line is shown as the dotted line on Figure 8-2.

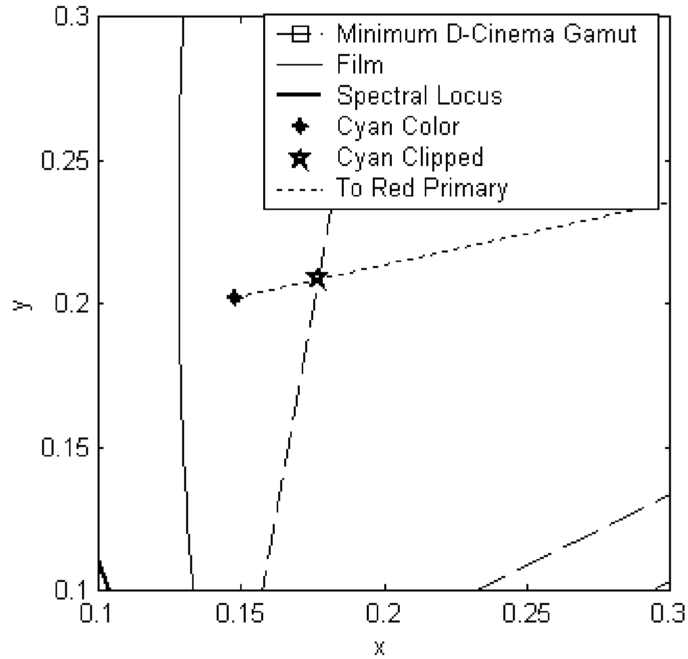

Figure 8-2 – Clipping the Cyan Color Code Values in the Reference Projector

Another problem with the simple clip strategy for gamut mapping can be seen in Figure 8-2. There are a number of possible colors lying on the line connecting the original cyan color and the gamut mapped cyan color that would all be gamut mapped to the same cyan color. In an image, the result is that a series of colors that vary slightly, as in a saturation series, will be mapped to the same color. In the image, this will look like a uniform blob of color and is not attractive. Therefore, another simple gamut mapping strategy is to map the color that is farthest from the RPGB to the RPGB and colors that are between the farthest color and the RPGB are mapped to colors slightly inside the RPGB. This gives a compressed saturation scale to the mapped colors, but at least there is some discrimination among the colors and the end result is more pleasing. Figure 8-3 shows a possible gamut mapping strategy that implements these thoughts. In Figure 8-2 the encoded cyan color is 0.030 chromaticity coordinate units away from the RPGB. Assume this was the cyan color that was farthest from the RPGB. Then in Figure 8-3, the encoded cyan color was moved 0.030 xy units to put it right on the RPGB. In addition, a color that was 0.020 xy units outside the RPGB was moved 0.0225 xy units, so it will fall 0.0025 xy units inside the RPGB. A color that was originally right on the RPGB was moved 0.0075 xy units. In all cases in this example, the movement is toward the red primary. Finally, any color more than 0.010 xy units inside the RPGB will not be moved at all.

This strategy to move colors, even some that are inside the gamut boundary so that not all colors fall at the same point, can be applied to all possible hue angles. It is more common to move the colors toward the neural axis (the white point chromaticity coordinates) than toward the chromaticity coordinates of a primary, but the principle is the same. In defining this strategy it is useful to know how far out of gamut any color might be. In particular, it is most helpful if the color that is the greatest distance from the gamut boundary is known. For example, if the maximum distance of the encoded cyan from the gamut boundary had been 0.060 xy units instead of 0.030 xy units, Figure 8-3 would have been drawn a bit differently. In this case, possibly even colors as far as 0.020 inside the gamut boundary would have been moved. The point is that as original colors fall farther from the gamut boundary more colors inside the gamut will be moved. If no colors fall outside the gamut boundary, then no colors need to be moved. Therefore, it would be useful to know the limits of the colors that may fall outside the gamut of the projector that is displaying the images. The encoded color is the color that is desired and that the digital projector should make. But in the case in which the encoded color falls outside of the gamut of the digital projector in the theatre, the digital projector in the theatre has to gamut map some of the colors in order to display them.

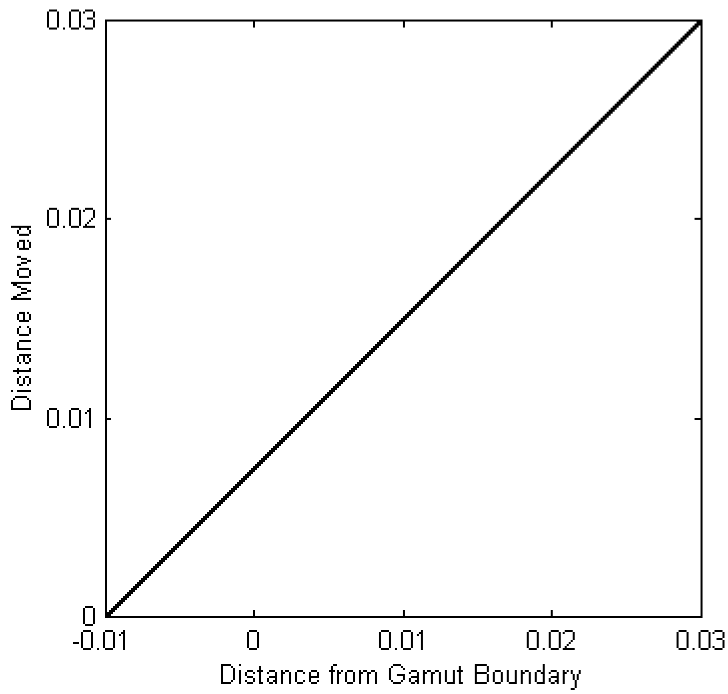

Figure 8-3 – A Gamut Mapping Strategy to Preserve Color Discrimination

This simple example has demonstrated a principle of most gamut mapping strategies: In order to preserve color discrimination, some of the colors that are inside the RPGB will be moved farther inside the RPGB. In general, the distance the colors that were inside the RPGB were moved is proportional to the maximum distance that the color farthest outside the RPGB had to be moved to get to the RPGB. A reasonable estimate of the gamut of the encoded colors is useful in designing the gamut mapping strategy because it will minimize the color shifts from the encoded colors to the gamut-mapped colors. Most gamut mapping strategies move the in-gamut colors toward the neutral axis. Excessively large shifts desaturate the colors and produce low color images.

The XYZ space encloses all possible encoded colors, but is an excessively large color space. Using the XYZ gamut boundary as an estimate of the most saturated colors leads to shifts of some colors that are much larger than necessary. It is possible to compute the digital projector RGB values from the DCDM *X'Y'Z'* values for every pixel in a production and find the one pixel that is the greatest distance outside the RPGB. However, this will be a very time-consuming calculation and is not practical. If however, the chromaticity coordinates of the mastering projector primaries were known, it would be relatively easy to compare those chromaticity coordinates to the chromaticity coordinates of the primaries of the digital projector in the theatre. If the mastering projector primaries are on or inside the gamut of the theatre digital projector, no gamut mapping strategy is needed. If however, the chromaticity coordinates of the mastering projector primaries are far outside the gamut of the theatre projector, a considerable amount of gamut mapping may be needed. Thus even the knowledge of the location of the mastering projector primaries can greatly help in the definition of the gamut mapping strategy.

9 An Example of Color Processing Through the Entire System

The DSM has not been standardized because there are a great number of ways in which the color in the DSM can be defined and modified. The creation of the DSM for any content and the transform to convert the DSM to the DCDM is an implementation issue and therefore may never be standardized. Based on the nature of the data in the DSM, the user will need to calculate the specific transform or transforms for each situation. However in order to show how the color processing may move through the entire digital cinema system, it is necessary to start with a color defined in the DSM and track it through to the display of the color using a digital projector in a theatre. This section will show the equations and work a few numerical examples of colors starting in the DSM and going through to projection onto a screen in a theatre.

9.1 Specification of Color in the DSM

There are numerous ways the color can be created in the DSM. As examples of how a DSM could be produced, these five methods that could be used will be described in greater detail below:

1. Pixel-by-pixel define a set of code values, send those code values to a Reference Projector, look at the color produced, and modify the code values until the desired color is produced.

2. Start with an image defined by code values, modify the code values, send those code values to a Reference Projector, look at the color produced, and modify the code values until the desired image is produced.

3. Start with an image defined by code values, modify the code values, send those code values to a display device (not a Reference Projector), look at the color produced, modify the code values until the desired image is produced, and convert the colorimetry of the image on the display device to X'Y'Z' code values.

4. Use an electronic camera that captures the CIE XYZ values of each pixel of an original scene, convert the XYZ to *X'Y'Z'*, and send the *X'Y'Z'* code values to a Reference Projector.

5. Start with an image defined by film printing density (SMPTE RP 180) code values, modify the code values, use a Printing Density-to-*X'Y'Z'* transform, send those *X'Y'Z'* code values to a Reference Projector, look at the image produced, and modify the printing density code values until the desired image is produced.

These are not the only methods by which an image could be produced in the DSM, but they will show a variety of ways and the calculations that are associated with each method. The variety of the ways described will show why it is not advisable to standardize the workflow to make the DSM. There are too many different ways different people want to work and it serves no useful purpose to standardize how everyone must work. This section will also serve to show how the standards and recommended practices that have been written are sufficient to describe the processing of the color to produce the desired look in the final display of the images. In addition, the encoding of the image in the DSM may either already be standardized by existing standards or new standards could be written if it is found to be desirable to encode the DSM images using another encoding method or file format.

The first example, certainly the most direct method to encode colors in the DSM, is to define pixel-by-pixel a set of three 12-bit code values, send them to a Reference Projector, and see what color appears on the screen. If the color displayed is not the desired color, change the code values until the desired color does appear. This laborious trial-and-error process could be used to create one image and eventually the motion content defining an entire movie. Or a section of an image could be modified pixel-by-pixel in this way until the desired image had been created. No knowledge of any encoding or decoding equations is required. This example demonstrates that there is a process by which the DSM is defined in terms of the *X'Y'Z'* code values and those code values can be transferred directly to the DCDM.

The second example is similar to the first example, but starts with an existing image instead of building up the image pixel-by-pixel. The process defined in the previous paragraph is very similar to what a colorist does to modify the color and the look of an image. Instead of starting with a blank screen, a colorist starts with a digital or analog image, but can make modifications to the image by moving knobs or levers or trackballs without knowing anything about the equations or relationships behind those movements. If the movements adjust digital code values, the final image has already been defined in terms of the encoding color space of the display device. However, someone had to design that system so that the movements did make reasonable adjustments to the colors displayed and that person had to have some knowledge of the encoding of the colors. Figure 4-1 showed a processing path that included the steps of [DSM] ➔ [DSM to XYZ transform] ➔ [XYZ to *X'Y'Z'* transform]. If the code values sent to a digital projector were the R'G'B' code values described in Section 7.4, then the processing from these R'G'B' code values to XYZ and to *X'Y'Z'* has been described in Section 7.4. However, if the code values sent to a digital projector were *X'Y'Z'* code values, it can be seen that the DSM is itself defined in terms of *X'Y'Z'* and no additional conversion steps are needed.

The third example involves the transfer of the colorimetry displayed on one device to the DCDM *X'Y'Z'* code values so that the same colorimetry can be displayed by the Reference Projector. This process by which colors can be encoded in the DSM is very similar to that described in the preceding paragraph and in Section 7.4. In this process, assume the code values in the DSM represent R'G'B' code values that will be sent to a display device. The characteristics of this display device have intentionally been chosen so that they do not match the characteristics of any existing device. The purpose here is to show how an image displayed on any device can be analysed and encoded in the *X'Y'Z'* code values so that the exact same image can be displayed on a Reference Projector. The following assumptions will be made about this display device: (1) The display device accepts 10-bit code values. (2) The display device has primaries and white point, shown in Table 9-1, that are similar to, but slightly different from the primaries and white point shown in the Opto-electronic conversion table in Part 1 of Recommendation ITU-R BT.709-5. (3) The display device gamma has been determined to be 2.34. One would determine the display device gamma value using a process very similar to the method described in Section 6.11. A series of code values would be sent to the display device, the luminance of the display device would be measured, and a plot of log(Luminance) vs log(Code Value) would be plotted, The slope of the best fit straight line is the gamma value. If there is significant deviation from a straight line, the display device may not be following a simple gamma function and a more complex model for the display device may be needed. For this example, it will be assumed that the display device does follow a simple gamma function and the gamma value is 2.34. (4) The display device white luminance has been set to 48.00 cd/m^2.

Figure 9-1 shows that the display device primaries are all inside the triangle formed on a chromaticity diagram by the Reference Projector primaries. From Table 9-1 it can be seen that the red and blue display device primaries are at higher luminance than the red and blue primaries of the Reference Projector. The Reference Projector values were given in Tables 6-2 and 6-10. From this information alone it can be stated that the display device white point is outside the color gamut of the Reference Projector, but it cannot be stated whether any of the primaries are outside the color gamut of the Reference Projector. The sample calculations below will show that the blue primary and a ridge of colors from the blue primary to the white point of the display device are outside the color gamut of the Reference Projector.

The chromaticity coordinates of the white point and the primaries of the display device in Table 9-1 were arbitrarily chosen. The luminance of the white point was set to 48.00 cd/m^2 so that it matched the luminance of the Reference Projector white point. The normalized XYZ values of the display device white point came from vector W in Equation K-9. The normalized XYZ values of the display device primaries came from the columns of matrix NPM in Equation K-13. The absolute XYZ values came from multiplying the normalized XYZ values by 48, the luminance of the white point.

Table 9-1 – Absolute and Normalized XYZ values of the Display Device White Point and Primaries

	Absolute XYZ Values			Chromaticity Coordinates		Luminance
Color	**X**	**Y**	**Z**	**x**	**y**	**Y,** cd/m²
White Point	45.97	48.00	51.05	0.3170	0.3310	48.00
Red Primary	20.93	10.47	0.81	0.6500	0.3250	10.47
Green Primary	15.97	33.32	5.78	0.2900	0.6050	33.32
Blue Primary	9.06	4.21	44.46	0.1570	0.0730	4.21
	Normalized XYZ Values			**Chromaticity Coordinates**		**Luminance**
Color	**X**	**Y**	**Z**	**x**	**y**	**Y,** cd/m²
White Point	0.9577	1.0000	1.0634	0.3170	0.3310	48.00
Red Primary	0.4361	0.2181	0.0168	0.6500	0.3250	10.47
Green Primary	0.3327	0.6941	0.1205	0.2900	0.6050	33.32
Blue Primary	0.1888	0.0878	0.9262	0.1570	0.0730	4.21

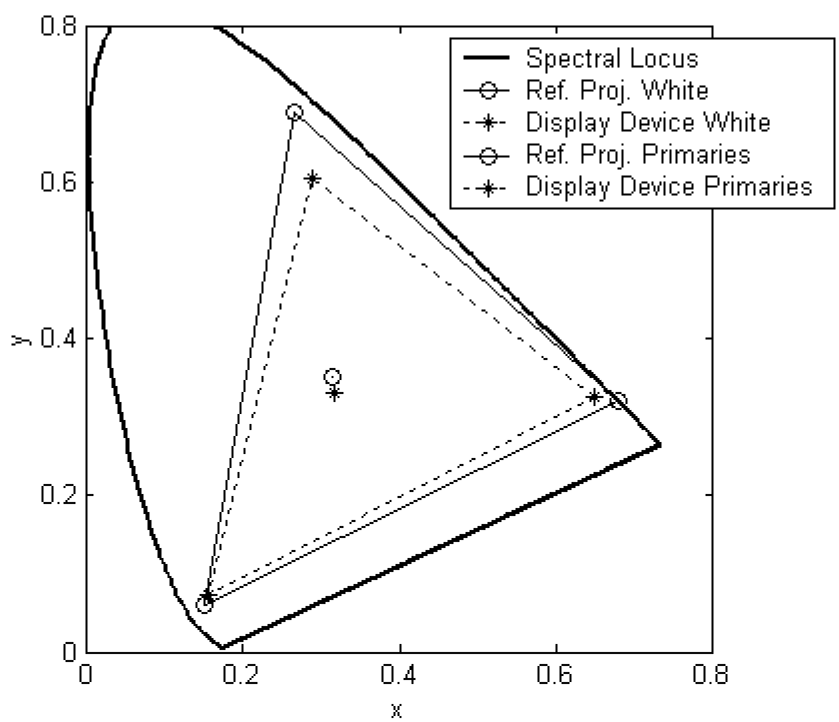

Figure 9-1 – White Point and Primaries of the Display Device and the Reference Projector

In Annex K, the NPM for this system was calculated. The equation that relates the linear RGB values with the linear XYZ values displayed on this display device are given by Equation 9-1, which is copied from Equation K-14.

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0.4361343357 & 0.3327206339 & 0.1888489579 \\ 0.2180671678 & 0.6941240810 & 0.0878087511 \\ 0.0167743975 & 0.1204678157 & 0.9262018955 \end{pmatrix} * \begin{pmatrix} R \\ G \\ B \end{pmatrix} \quad (9\text{-}1)$$

The objective here is (1) To create content in R'G'B' code values in the DSM that when displayed on the display device described above has the desired look and (2) To encode that content in DCDM *X'Y'Z'* code values such that the image displayed on a Reference Projector will display the exact same colorimetry. Even though the primaries of this display device are inside the color gamut of the Reference Projector, the white point of the display device is outside the color gamut of the Reference Projector and a few near white colors on the display device will be outside the color gamut of the Reference Projector. This will be shown in the color patches that are used as examples of how to do the calculations.

Table 9-2 shows a set of R'G'B' colors that will be tracked through the system to the corresponding *X'Y'Z'* code values and then to the corresponding linear RGB Reference Projector values.

Table 9-2 – R'G'B' Code Values that Define Several Colors

Color	R'	G'	B'
White	1023	1023	1023
Light Gray	973	973	973
Blue Primary	0	0	1023
Blue Primary 2	0	0	1014
Blue 1	200	200	1023
Blue 2	500	500	1023
Blue 3	800	800	1023
Reddish	800	200	400
Greenish	150	550	90

The gamma of the display device has been defined as 2.34, therefore the linear RGB values are related to the 10-bit R'G'B' values by Equation 9-2

$$RGB = \left(\frac{R'G'B'}{1023} \right)^{2.6} \quad (9\text{-}2)$$

Table 9-3 shows the RGB values from the R'G'B' values in Table 9-2 and Equation 9-2.

Table 9-3 – RGB Code Values Calculated from the R'G'B' Code Values

Color	R'	G'	B'
White	1.0000	1.0000	1.0000
Light Gray	0.8894	0.8894	0.8894
Blue Primary	0.0000	0.0000	1.0000
Blue Primary 2	0.0000	0.0000	0.9795
Blue 1	0.0219	0.0219	1.0000
Blue 2	0.1873	0.1873	1.0000
Blue 3	0.5625	0.5625	1.0000
Reddish	0.5625	0.0219	0.1111
Greenish	0.0112	0.2341	0.0034

Table 9-4 shows the XYZ tristimulus values and the xyz chromaticity coordinates from the RGB values in Table 9-3, Equation 9-1, and Equations J-1. These represent the XYZ values on the display device and the XYZ values that are desired on the projector.

Table 9-4 – XYZ and xyz Values Calculated from the RGB Code Values

Color	X	Y	Z	x	y	z
White	0.9577	1.0000	1.0634	0.9577	1.0000	1.0634
Light Gray	0.8517	0.8894	0.9458	0.8517	0.8894	0.9458
Blue Primary	0.1888	0.0878	0.9262	0.1888	0.0878	0.9262
Blue Primary 2	0.1850	0.0860	0.9072	0.1850	0.0860	0.9072
Blue 1	0.2057	0.1078	0.9292	0.2057	0.1078	0.9292
Blue 2	0.3328	0.2586	0.9519	0.3328	0.2586	0.9519
Blue 3	0.6213	0.6009	1.0034	0.6213	0.6009	1.0034
Reddish	0.2736	0.1476	0.1150	0.2736	0.1476	0.1150
Greenish	0.0834	0.1652	0.0315	0.0834	0.1652	0.0315

Table 9-5 shows the *X'Y'Z'* DCDM 12-bit code values from the XYZ values in Table 9-4, Equation 5-1, Equation 5-2, and Equation 5-3. These represent the *X'Y'Z'* values that would be sent to the projector.

Table 9-5 – DCDM *X’Y’Z’* Code Values

Color	X’	Y’	Z’
White	3895	3960	4055
Light Gray	3723	3785	3876
Blue Primary	2086	1554	3845
Blue Primary 2	2069	1541	3815
Blue 1	2156	1681	3850
Blue 2	2594	2354	3886
Blue 3	3298	3256	3965
Reddish	2406	1897	1723
Greenish	1523	1981	1048

Table 9-6 shows the XYZ tristimulus values and the xyz chromaticity coordinates from the *X’Y’Z’* values in Table 9-5, Equation 5-4, Equation 5-5, Equation 5-6, and Equations J-1. These are the XYZ values that would be computed inside the projector.

Table 9-6 – XYZ and xyz Values Calculated from the *X’Y’Z’* Code Values

Color	X	Y	Z	x	y	z
White	0.9579	1.0000	1.0635	0.3170	0.3310	0.3520
Light Gray	0.8517	0.8891	0.9458	0.3170	0.3309	0.3520
Blue Primary	0.1889	0.0879	0.9262	0.1570	0.0730	0.7700
Blue Primary 2	0.1849	0.0860	0.9075	0.1569	0.0729	0.7701
Blue 1	0.2058	0.1078	0.9293	0.1656	0.0867	0.7477
Blue 2	0.3329	0.2586	0.9521	0.2157	0.1675	0.6168
Blue 3	0.6215	0.6011	1.0033	0.2792	0.2701	0.4507
Reddish	0.2737	0.1476	0.1149	0.5105	0.2752	0.2143
Greenish	0.0834	0.1652	0.0315	0.2977	0.5897	0.1126

Table 9-7 shows the RGB values from the XYZ values in Table 9-6 and Equation 7-9. These are the linear RGB values inside the Reference Projector needed to produce the XYZ values on the screen that are shown in Table 9-6.

Table 9-7 – Reference Projector RGB Values Needed to Match the XYZ Values in Table 9-6

Color	R	G	B
White	1.1244	0.9521	1.1228
Light Gray	0.9999	0.8465	0.9984
Blue Primary	0.0177	0.0192	1.0198
Blue Primary 2	0.0170	0.0188	0.9992
Blue 1	0.0421	0.0395	1.0222
Blue 2	0.2249	0.1939	1.0393
Blue 3	0.6403	0.5443	1.0775
Reddish	0.5453	0.0343	0.1249
Greenish	0.0452	0.2135	0.0237

The above tables show the results of the calculations that are needed to find the DCDM *X'Y'Z'* code values that will, when sent to a Reference Projector, produce the same colors on the screen that were on the display device. There are a few interesting observations that can be made about this set of calculations. If one or more of the Reference Projector RGB values in Table 9-7 are greater than 1 or less than 0, that color is outside the Reference Projector color gamut. Even though the primaries of the display device are inside the primaries of the Reference Projector, the fact that the white point of the display device is different from the white point of the Reference Projector means that there are some colors that the display device can produce that are outside the Reference Projector color gamut. The white point was clearly outside the Reference Projector color gamut. From Tables 9-7 and 9-2 it can be seen that only neutrals defined by code values less than 974 (on the 10-bit display device code value scale) are inside the Reference Projector color gamut. Although the blue primary is inside the triangle formed by the primaries of the Reference Projector, the luminance of the display device blue primary is higher than the luminance of the Reference Projector blue primary. The RGB values in Table 9-7 show that the blue primary is outside the Reference Projector color gamut. Only when the B' code value is decreased to 1014, with the R' and G' code values at 0, does the color fall inside the Reference Projector color gamut. Colors Blue Primary, Blue 1, Blue 2, Blue 3, and White form a series in which the blue primary is at full intensity and the red and green primaries are at varying intensity levels. It can be seen from Table 9-7 that all of these colors are outside the Reference Projector color gamut. Therefore, there is a ridge of colors from the display device blue primary to the display device white point that are outside the Reference Projector color gamut. This is mentioned here to point out that it is not always obvious from knowledge of the location of the primaries and white point of a display device to know which colors are inside or outside the Reference Projector color gamut. Note, however, that all of the colors in this example were within the encoding gamut of the DCDM *X'Y'Z'* code values as shown in Table 9-5.

The fourth example of how to encode colors in the DSM is to use an electronic camera that captures the original scene colorimetry, the XYZ tristimulus values of each pixel of the image. A slight modification of this approach is an electronic camera that captures the scene with a set of sensitivities such that a simple mathematical operation will convert the captured signal to scene colorimetry. In either case, this method uses the XYZ color space as the DSM color space. Therefore, in Figure 4-1, the step [DSM] ➔ [DSM to XYZ transform] is not needed. The method by which the XYZ is converted to *X'Y'Z'* code values is defined by Equations 5-1 to 5-3. There may need to be some work on the images because if original scene colorimetry is displayed on a screen, the look is not particularly pleasing. But if someone knows how to convert from XYZ to a space in which the images are modified, the inverse transform will put the modified images back to XYZ. Then Equations 5-1 to 5-3 can be used to get to *X'Y'Z'*.

9.2 Conversion from the Film Printing Density DSM Color Encoding to X'Y'Z'

The content known as the StEM material was originally shot on film, the film was scanned, and the printing density code values (SMPTE RP 180) were converted to *X'Y'Z'* code values using a 3d look-up table (3d lut). Modifications in the color of the content were made by changing the code values and allowing the processing with the 3d lut to convert the modified code values to *X'Y'Z'* code values. This method or modifications of this method are in common use for the production of digital content today and will be described in greater detail below. This process does require all the steps shown in Figure 4-1 in going from the DSM to *X'Y'Z'*.

For this example, assume an original scene was captured on film, that film was scanned, and the image is defined in terms of printing density code values. Therefore, the DSM encoding color space is printing density code values. It will be assumed here that the goal of the digital cinema system is to produce on the screen the exact same image as the film image produced from those code values. Therefore, for the digital cinema encoding of the image, the user needs to produce a Printing Density-to-*X'Y'Z'* transform that models this film path. The steps needed to produce a film image from printing density code values are (1) Write onto intermediate film with a film writer which has been sent the code values. (2) Print that intermediate negative onto print film. (3) Project with a film projector the print film. One method to produce this Printing Density-to-*X'Y'Z'* transform is as follows. One starts with a grid of code values. The process described above from step 1 through step 3 is run. The XYZ values of the color patches defined by the code values are measured off the screen. Finally the XYZ values are converted to *X'Y'Z'* code values using Equations 5-1, 5-2, and 5-3. From this an algorithm that transforms printing density code values to the corresponding *X'Y'Z'* DCDM code values can be constructed. A common transform is a 3d lut, but other mathematical transforms could be used. The algorithm that will be used to do the transform is primarily a question of available hardware to do the processing at the speed needed and trade-offs in the accuracy of the transform. Note that Figure 4-1 shows the output of the DSM going through a DSM to XYZ Transform and then through an XYZ to *X'Y'Z'* Transform. The process above did involve those steps, but in the final implementation there could be a 3d lut (a form of transform) that goes directly from the printing density code values (the DSM encoding) to the *X'Y'Z'* code values. Therefore, although Figure 4-1 shows the steps that the numbers need to pass through, not all of the steps in Figure 4-1 must be executed in the final implementation.

There is another slight modification of the above process that one can use to determine the transform to go from printing density code values to *X'Y'Z'* values. In the example above, once the print film had been produced, it was stated that the print film could be projected and the XYZ values measured off the screen. In practice this is a difficult measurement to make. Therefore, an easier method is to measure the Status A densities of the patches on the print film and to determine a transform from Status A densities to *X'Y'Z'* values. In this way, the transform from printing density to *X'Y'Z'* is the concatenation of two transforms, the transform from printing density to Status A and the transform from Status A to *X'Y'Z'*. The final result will be the same.

There is one implementation issue that will be mentioned. The paragraph above described how to produce *X'Y'Z'* code values from printing density code values once the final image had been produced. However, nothing has been said about how an image is modified so that the desired look is achieved. In particular the color space in which the image modifications are made is important for efficiency. One color space is the printing density code value space. This allows the Printing Density-to-*X'Y'Z'* transform to be fixed and people have been making image modifications in the printing density space for a number of years. The disadvantage of working in the printing density code value space is that when complete, the printing density code values are not the scanned code values and one may want to save or archive the original scanned code values. This may or may not require the archival of the adjusted printing density code values. This is an implementation issue and no recommendation is made here. Once the code values are transformed to the *X'Y'Z'* color space, the image modifications could be made in *X'Y'Z'* space. But the *X'Y'Z'* values do not align with the red, green, blue directions in which image modifications are usually made, so it is not recommended that modifications be made in *X'Y'Z'* space. The process by which the *X'Y'Z'* code values are converted to linear RGB values inside the projector was described in Section 7.4. The same procedure would be followed once the *X'Y'Z'* values have been determined from the printing density values.

Whatever process is followed to determine the Printing Density-to-*X'Y'Z'* transform, it must be remembered that the film writer has variability, the processing of the intermediate film has variability, the printing process has variability, the processing of the print film has variability, the film projector has variability, and the measurement of whatever is measured has variability. Therefore, there may need to be frequent up-dates to the transform. If the transform has to be frequently up-dated, the process must allow these up-dates at a reasonable cost.

Annex A (Informative)
Bibliography

Note: All references in this document to other SMPTE documents use the current numbering style (e.g. SMPTE ST 268:2003) although, during a transitional phase, the document as published (printed or PDF) may bear an older designation (such as SMPTE 268M-2003). Documents with the same root number (e.g. 268) and publication year (e.g. 2003) are functionally identical.

Standards

At the time of publication, the editions of the standards indicated below were valid. All standards are subject to revision, and parties to agreements based on this standard are encouraged to investigate the possibility of applying the most recent edition of the standards indicated below.

Recommendation ITU-R BT.709-5, Parameter Values for the HDTV Standards for Production and International Programme Exchange

SMPTE RP 176-1993, Derivation of Reference Signals for Television Camera Color Evaluation

SMPTE RP 177-1993, Derivation of Basic Television Color Equations

SMPTE RP 180-1999, Spectral Conditions Defining Printing Density in Motion-Picture Negative and Intermediate Films

SMPTE ST 268:2003, File Format for Digital Moving-Picture Exchange (DPX), Version 2.0

SMPTE ST 428-1:2006, D-Cinema Distribution Master (DCDM) — Image Characteristics

SMPTE ST 431-1:2006, D-Cinema Quality — Screen Luminance Level, Chromaticity and Uniformity

SMPTE RP 431-2-2007, D-Cinema Quality — Reference Projector and Environment

Colorimetry, Color Science, and Color Management

CIE Publication 15.2 (1986), Colorimetry, Second Edition, 1986

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CIE Publication 17.4 (1987), International Lighting Vocabulary, 1987

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Wyszecki, G. and Stiles, W. S., Color Science, Concepts and Methods, Quantitative Data and Formulae, 2nd Edition. John Wiley & Sons (1982)

DCI Specification

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Human Contrast Sensitivity

Barten, P. G. J., Contrast Sensitivity of the Human Eye and Its Effects on Image Quality. Bellingham, Washington USA: SPIE Optical Engineering Press; (1999)

Cowan, M., Kennel, G., Maier, T., and Walker, B., Contrast Sensitivity Experiment to Determine the Bit Depth for Digital Cinema, SMPTE Motion Imaging Journal, **113**, 281-292 (2004)

Image State Diagrams

Giorgianni, E. G., Madden, T. E., and Spaulding, K. E., “Color Management for Digital Imaging Systems,” in CRC Digital Color Imaging Handbook, Ed. G. Sharma, CRC Press, New York, 239-268 (2003)

ISO 22028-1:2004 Photography and graphic technology—Extended colour encodings for digital image storage, manipulation and interchange — Part 1: Architecture and requirements

Gamut Mapping Strategies

The following website has a very large list of references to published gamut mapping strategies:
http://www.colour.org/tc8-03/survey/survey_index.html

Morovic J. and Luo M. R., The Fundamentals of Gamut Mapping: A Survey, Journal of Imaging Science and Technology, **45**, 283-290(2001)

Matrix Algebra

Any bookstore will have a number of books on matrix algebra or linear algebra as the subject is more commonly called.

Silva, J., The Role of Transform Matrices in Digital Cinema, SMPTE Motion Imaging Journal, **114**, 402-414 (2005)

Annex B (Informative)
Encoding Schemes Considered

B.1 The Image State Diagram

In order to understand the various encoding schemes considered it is easiest to start with an Image State Diagram, Figure B-1. There are three image states in this diagram: The Scene Referred Encoding, the Input Referred Encoding, and the Output Referred Encoding. Scene Referred Encoding means the encoding of the colorimetry of an original scene. Input Referred Encoding means the encoding of the image that was formed from the capture of an original scene. Output Referred Encoding means the encoding of the colorimetry of an image as the creator of the image intended it to be displayed. In all of these color encoding systems the encoding involves the specification of each color by a set of one or more numbers – it is a numerical encoding system. In general there must be transforms or calculations to move from one encoding scheme to another encoding scheme in this diagram.

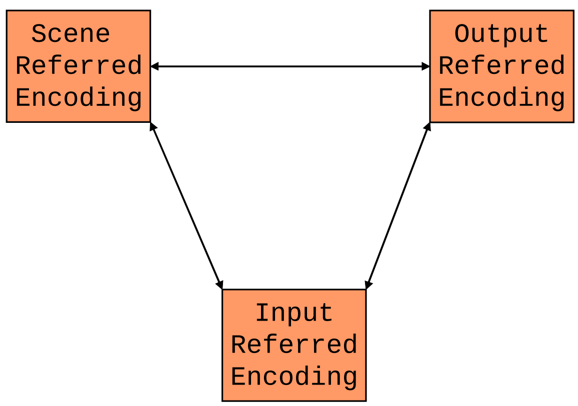

Figure B-1 – An Image State Diagram

Scene Referred Encoding was rejected for the DCDM. If one were to start with the Scene Referred Encoding, as is common with the digital capture of an original scene, there needs to be a conversion of that scene encoding to the Output Referred Encoding. The simplest would be a unity transform, but if the exact same colorimetry appears in the output image that was present in the original scene, the resulting output image will not be of optimum quality. This is particularly true in the display of projected images in a dark theatre. Therefore, some change in the image must be made in going from Scene Referred Encoding to Output Referred Encoding. Although this could be done, it was felt that this is an indirect way of encoding the D-Cinema image and Scene Referred Encoding was rejected.

Input Referred Encoding was also rejected for the DCDM. If the original image is captured on film and scanned into the Input Referred Encoding, some transform must be applied to the Input Referred Encoding to put it into the Output Referred Encoding. In the film system, the analogous transform is the printing of the camera negative onto a print film with the proper color and density balance. Therefore, as was the case with the Scene Referred Encoding, an Input Referred Encoding does not uniquely define the desired projected image in a theatre and a transform to go from the Input Referred Encoding to the desired Output Referred Encoding would need to be specified along with the image.

The Output Referred Encoding can uniquely define the projected image in a theatre. In order to do this, there are two elements that must be specified: (1) An encoding of the colors that are to be displayed and (2) The environment in which the image is displayed. Equations 5-1 to 5-3, which come from SMPTE ST 428-1, define the encoding of the colors that are to be displayed. Equations 5-4 to 5-6, which come from SMPTE RP 431-2, define the decoding of the colors that are to be displayed. Output Referred Encoding is simple and complete and it was decided to use this encoding for the DCDM. The colors that are to be displayed on the screen are completely defined when the DCDM file is made. Therefore, the expression has arisen that the color has been “baked in” at the time of the creation of the DCDM file.

Note also that any technology improvements in the future will be able to use and understand the DCDM file and produce on the screen the exact colors that were defined in the DCDM file as long as the color gamut of the future device is the same as or larger than the color gamut of the mastering device.

B.2 Output Referred Encoding Schemes Considered

A number of Output Referred Encoding schemes were considered.

The most efficient encoding scheme proposed was a suggestion to associate each code value with a defined color. For example, code value 0 might be associated with black of a defined luminance and chromaticity. Then code value 1 would be associated with another color, slightly different from black, with a defined luminance and chromaticity. The advantage of such a system is that it is 100% efficient: the number of code values needed equals the number of colors that will be encoded. . The disadvantage is that there must be a look-up table to define the relationship between each code value and the associated colorimetry. In addition, in such a scheme there is no concept of red, green, and blue as there is in the projector that will produce the images. Therefore, this scheme was rejected.

The most commonly discussed scheme and the one that was adopted is a scheme based on the concept of three primaries where the code values represent the intensities of these primaries. The major debates then centered on (1) the location of the primaries, (2) the relationship between the code values and the intensities of the primaries, (3) the range in the intensities of the primaries, (4) the intensity difference between adjacent code values, and (5) the encoding of the absolute colorimetry reflected from the screen or encoding of the colorimetry reflected from the screen relative to the theatre black. Once these five parameters have been defined, the minimum bit depth the code values must have will be defined.

Annex C (Informative)
Location of the Encoding Primaries

Although there are many ways a color gamut can be displayed, the most common method used in the discussions of the location of the primaries for D-Cinema was the CIE xy chromaticity diagram. This diagram and the transform of this diagram, the CIE u'v' chromaticity diagram, have been commonly used when describing three primary additive systems due to the fact that all the chromaticities that can be displayed by such a system fall within a triangle formed by drawing straight lines connecting the chromaticity points of each of the primaries. In addition, any chromaticities falling outside this triangle cannot be displayed by this system. But not all chromaticities within the prism formed by the primaries from the minimum luminance to the maximum luminance can be displayed by such a system. Therefore, the shape of a color gamut in this space is not a prism, but is a multifaceted solid. However, it is still useful to use the CIE xy chromaticity diagram to compare color gamuts of different systems and this is what was done in the selection of the encoding primaries.

There were many suggestions for the encoding primaries for the DCDM. Figure C-1 shows some of the encoding primary sets that were considered.

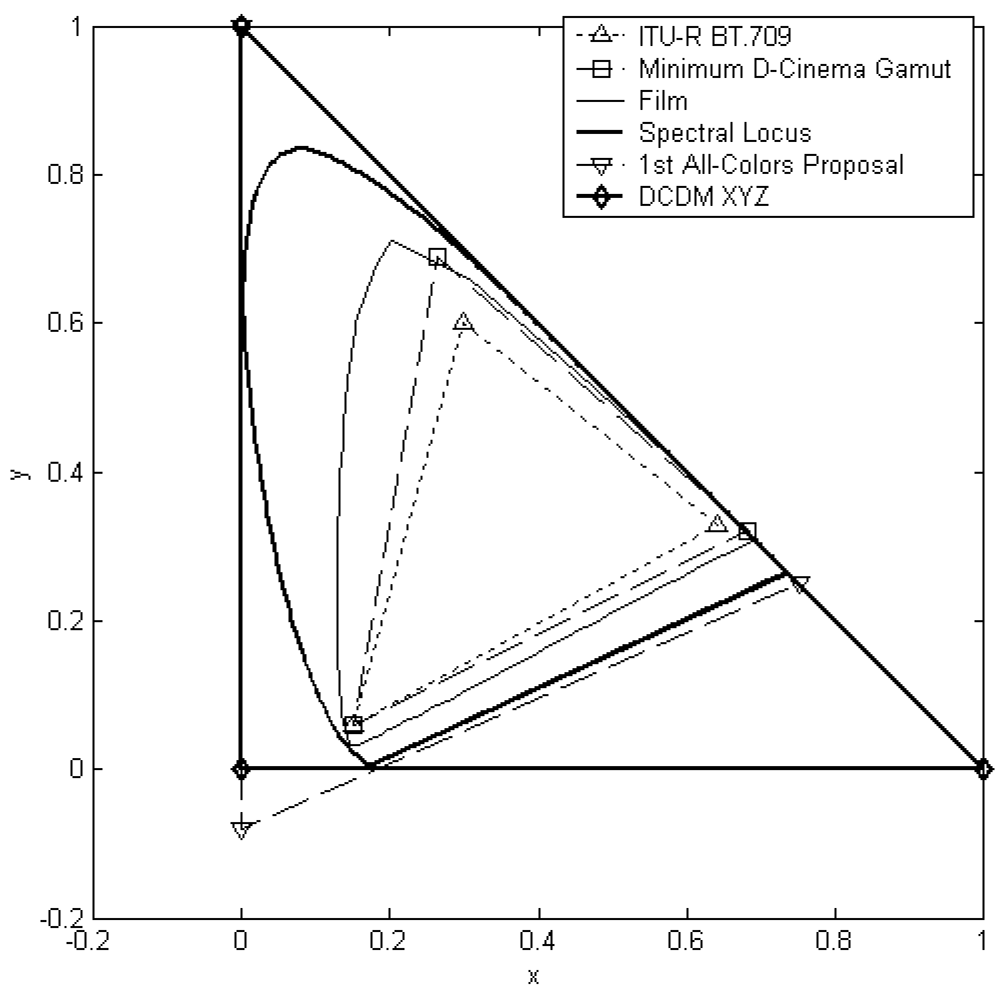

Figure C-1 – Primary Sets that were Considered for the Encoding of Colors in the DCDM

The advantages of the ITU-R BT.709-5 primary set (from the Opto-electronic table in Part 1 of that Recommendation), shown in Figure C-1 as the ITU-R BT.709 triangle, are that the conversion from DCDM to the ITU-R BT.709 primaries would be relatively easy and the compression of these code values is known to work well. The disadvantage is that this represents the smallest color gamut considered. In fact the color gamut is smaller than the color gamut of commercially available, cinema-grade projectors when the discussion of these standards was started in the year 2000. Therefore this set of primaries was rejected.

The Minimum Digital Cinema Gamut primary set, shown in Figure C-1, is the set of primaries that existed in the year 2000 in the DLP Cinema™ projector using filtered Xenon light. The advantage of this color gamut is that the encoding primaries are the actual primaries in a real projector and therefore the conversion of the DCDM code values to the internal projector code values is very easy. There were two disadvantages with this primary set. First, there was a desire to be able to encode in the DCDM all film colors, some of which are colors outside the color gamut of this set of primaries. Second, any advances in expanding the color gamut of a projector, such as the use of laser primaries, would not be seen due to this limited encoding color gamut.

There were several proposals, not shown in Figure C-1, that located the primaries outside the triangle labeled Minimum D-Cinema Gamut, but did not enclose the entire spectral locus. The advantages of these primary sets are that they enclose (or very nearly enclose) the film gamut and that they enclose a possible set of laser primaries. Disadvantages of these primary sets were that one (sometimes two) of the primaries fall outside the spectral locus, that the efficiency of the encoding, defined as the ratio of code values that represent real colors to all possible code values, is below 100%, and that for the added complexity, it did not enclose all possible colors.

The first All-Colors primary set, shown in Figure C-1, represented an attempt to define a set of primaries that enclosed the spectral locus. The obvious advantage of this set is that it does enclose the spectral locus and therefore will enclose the gamut of any real projector. The disadvantages are that all three primaries fall outside the spectral locus and that the efficiency of such a primary set was considerably lower than the efficiency of any of the previous sets considered. However, the fact that this primary set did enclose the spectral locus and hence all possible colors was very attractive to many people and this proposal was considered for quite a long time. The final decision came down to this set of primaries and the XYZ primary set described in the next paragraph.

The DCDM XYZ primary set, which is shown in Figure C-1, places the primaries at the same chromaticity coordinates as the CIE XYZ system. Although this system is mathematically exactly the same as all the previous systems that commonly use the letters RGB to describe the primaries, this proposal uses the letters XYZ to indicate the CIE XYZ system as the basis for the encoding. The DCDM XYZ primary set represents the logical extension of all of the previous primary set proposals. There are a number of advantages to this primary set. This set encloses the spectral colors and therefore all possible colors that can be seen and might be encoded. This set separates luminance into the Y channel, which corresponds to the G channel, and the X and Z channels contribute color, but no luminance. The disadvantages are that the primaries are all imaginary primaries outside the spectral locus, that this primary set was quite inefficient (but it will be shown in the section on bit depth that efficiency is not a critical consideration), and that there was little experience with working with an image encoded in XYZ as opposed to RGB. After the CIE XYZ primaries were proposed, a number of experiments have been done which have shown that XYZ images can be compressed and that compression in this color space is at least as effective as RGB. In addition it has been found that it is as easy to work with XYZ images as it is to work with RGB images in terms of transforming from one primary space to another primary space. Therefore, the final decision was to use the XYZ primaries as the DCDM primaries.

Annex D (Informative)
Reason for the Constant 2.6

One area that has been extensively studied in the field of visual perception is the question, “What is the minimum change in luminance that a person can see?” Although this may seem like a simple question, there are many variables that can alter the threshold of visibility of a pattern. For example, the type of pattern used will change the visibility of any luminance changes and the absolute luminance from which the change is made will change the visibility of the luminance changes. It has been found that the eye is not a good detector of absolute luminance changes, but is an excellent detector of relative luminance changes represented by the change in luminance divided by the average luminance. In the vision experiments designed to answer this question, it is common to use sinusoidal waves and to analyze the observer’s response relative to the modulation, m, defined by the equation

$$m = \frac{L_{high} - L_{low}}{(L_{high} + L_{low})} = \frac{\Delta L}{2 * L_{average}} \qquad \text{(D-1)}$$

where L_{high} and L_{low} are the maximum and minimum luminances in the sine wave, ΔL is the difference between L_{high} and L_{low}, and $L_{average}$ is the average of L_{high} and L_{low}. In any encoding scheme if the modulation of that encoding scheme, as calculated from the change in luminance encoded by a one code value change, is smaller than the Human Visual Modulation Threshold (HVMT), then that encoding scheme is capable of encoding all the information that a person can possibly see and that encoding scheme will not introduce image artifacts due to the encoding. Barten has derived an equation that predicts the HVMT of sine waves as a function of a large number of variables. It is this equation that was used to compare the HVMT and the modulation of any proposed encoding scheme. This HVMT as a function of luminance is shown in Figure D-1. The luminance range of interest for the projection of motion pictures in a theatre is from about 50 cd/m^2 to about 0.01 cd/m^2, a 5,000:1 luminance range. There is no simple equation that describes this curve.

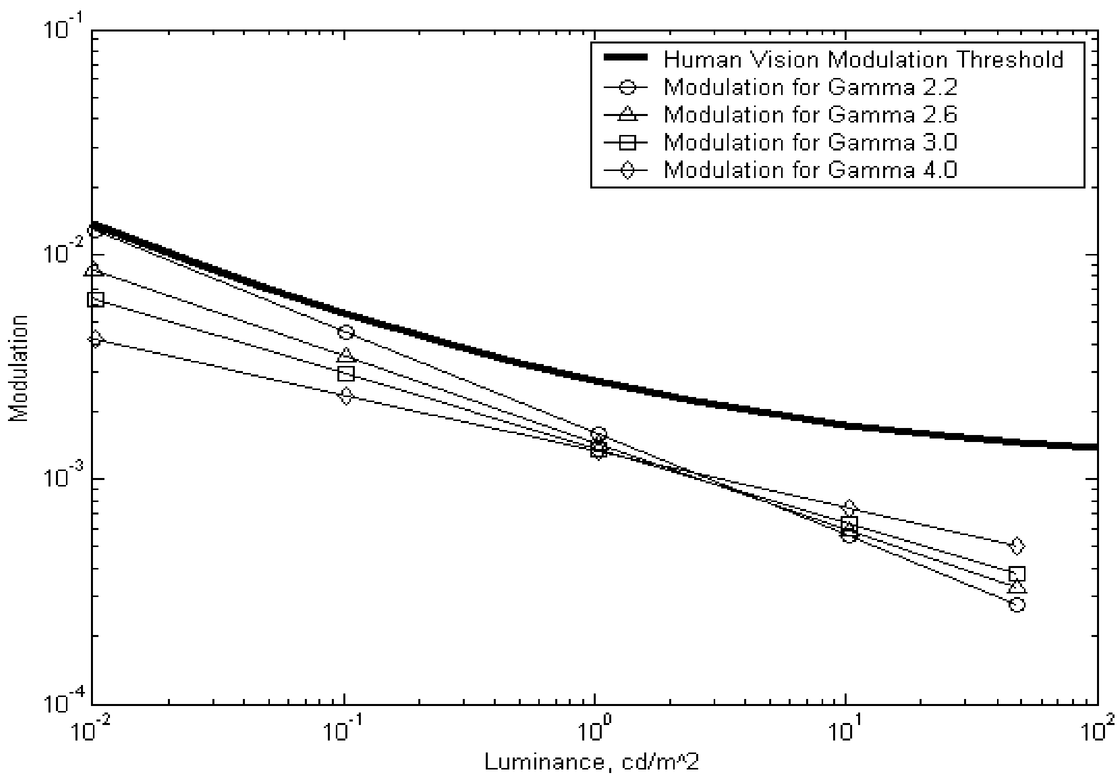

Figure D-1 – Modulation Thresholds for Human Vision and Equations with Various Gamma Values

The HVMT curve in Figure D-1 is the minimum modulation that can be seen under ideal conditions and with the pattern to which people are most sensitive. The minimum modulation corresponds to the maximum amount of information that needs to be encoded. A person is most sensitive to a set of sine waves of the frequency at which the person has the highest sensitivity (between 1 and 5 cycles per degree depending on the average luminance of the sine waves) and sufficiently wide field of view to have a large number of sine waves (a field of view with 15 or more sine waves). For less demanding patterns, the modulation threshold moves upward. For example, for one edge, as would occur in the artifact known as contouring, the modulation threshold is roughly 10 times the HVMT shown in Figure D-1. The HVMT curve was used as the basis for all encoding decisions so that all visible information in an image would be encoded.

There were a number of proposals for the general form of the encoding and decoding equations. The most efficient equation would be an equation that matches as closely as possible the shape of the human visual modulation threshold curve in Figure D-1. It was decided to use an encoding equation of the form

$$CV = CV_{\max} * \left(\frac{L}{P}\right)^{1/m} \qquad \text{(D-2)}$$

and a decoding equation of the form

$$L = P * \left(\frac{CV}{CV_{\max}}\right)^{n} \qquad \text{(D-3)}$$

In these equations P is a normalizing constant and CV_{max} is

$$CV_{\max} = 2^{b} - 1 \qquad \text{(D-4)}$$

where b is the bit depth of the encoding.

In the general case, the encoding exponent is 1/m and the decoding exponent is n. In some systems, m and n are not equal. However, with an output referred encoding in which the final color is “baked in” to the DCDM code values, the exponent in the decoding equation has to be the inverse of the exponent in the encoding equation. This means m must equal n and the Greek letter gamma, γ, is used as the symbol. Therefore, the encoding exponent is 1/γ and the decoding exponent is γ.

Once the decision was made to use the general equations D-2 and D-3, the next step was a decision on the value of gamma. However, the choice of gamma is also somewhat dependent on the choice of P and CV_{max}. Annex E gives the reasons for choosing 4095 as the value of CV_{max} and Annex G gives the reasons for choosing 52.37 as the value of P. From Equation 5-2 it can be calculated that the code value, Y’, that encodes the maximum luminance, 48 cd/m^2, is 3960. The code value 3960 is dependent on the gamma value. Therefore, in the following explanation of the choice of 2.6 as the value for gamma, CV_{max}, will be held at 4095 and P will be allowed to vary in order to keep 3960 as the code value that encodes 48 cd/m^2. The general decoding equation then becomes

$$L = P * \left(\frac{CV}{4095}\right)^{\gamma} \qquad \text{(D-5)}$$

From Equation D-5, for any value of gamma, the value of P can be calculated. With all the parameters in Equation D-5 defined, for all code values from 0 to 4095, the encoded luminance, L, can be calculated. The modulation for all one-code value changes can be then calculated from these calculated luminance values and Equation D-1. This set of calculations was done for gamma values of 2.2, 2.6, 3.0, and 4.0. The results of those calculations are shown in Figure D-1. It can be seen in that figure that the gamma value of 2.2 has a modulation at low luminance values that is only slightly below the HVMT. Any gamma value less than 2.2 would be above the HVMT at these low luminance values. This set the lower limit for the gamma value at 2.2. As the gamma value increases, the modulation curve for any gamma value moves away from the HVMT curve at low luminance values and toward the HVMT curve at high luminance values. Therefore, in theory any gamma value greater than 2.2 could be used.

Table D-1 gives the code values that encode various luminance values for a number of gamma values. It can be seen that as the gamma value increases, given that the code value 3960 has been defined to encode the luminance 48 cd/m^2, the code value to encode any given luminance value also increases. The most important luminance range is from 0.01 to 48 cd/m^2 and the code value that encodes the 0.01 cd/m^2 is of considerable interest. Code values lower than this code value are essentially wasted code values because these values are below what a projector can ever be expected to display.

Table D-1 – Code Values that Encode Various Luminance Values for several Gamma Values

	Gamma Values			
Luminance	2.2	2.6	3.0	4.0
0.01	85	153	237	479
0.1	242	372	510	852
1.0	690	903	1100	1515
10	1967	2190	2370	2695
48	3960	3960	3960	3960

From the information in Figure D-1 and Table D-1, one can make a choice of the optimum gamma value to use. There is obviously no exact gamma value that is perfect. Each gamma value offers trade-offs. From Table D-1, a gamma value of 4.0 clearly allocates too many, almost 500, code values to luminance values that will never be used. Thus a gamma value of 4.0 can be rejected. The gamma value of 3.0, with 237 code values that will never be used, seems like an upper limit on the gamma value. From Figure D-1, a gamma value below 2.2 crosses over the HVMT curve. Therefore the range of reasonable gamma values seems to lie between 2.2 and 3.0. The trade-off is between efficient use of the code values and allocation of more code values to encode the higher luminance values or to encode the lower luminance values. In the end, the gamma value 2.6 was chosen. In hindsight, it is clear that gamma values near 2.6 are equally valid, but this seemed like a good compromise at the time and it is the gamma value chosen. The fact that many full-length feature movies have been encoded and displayed with this gamma value of 2.6 with no problems related to the gamma value seems to justify this choice.

It is important to note that the selection of the value 2.6 has nothing to do with the physics or electronics of any display device. The decision was made based on the ability to encode the luminance values at a modulation that will not limit the quality of the encoded images. Although the emphasis has been on a 5,000:1 luminance range, the gamma value of 2.6 will not be a limiting factor in image quality even if a future projector were to reach a luminance range of 1,000,000:1.

Annex E (Informative)
Reason for the Constant 4095

Just as the HVMT curve was used to choose the general form of the encoding and decoding equations and to choose the gamma value in those equations as explained in Annex D, that HVMT curve was used to determine the bit depth of the encoding. From the general decoding equation, Equation D-3, the luminance that corresponds to each code value can be calculated. A P value of 48 cd/m^2 was initially used because it had been decided that the luminance of the white would be 48 cd/m^2, but the final answer on bit depth is only weakly dependent on the value of P as is explained in Annex G. The variable CV_{max} is directly related to the bit depth of the encoding as shown by Equation D-4. It was decided to consider only even numbers of bits for the encoding. Given this, it was relatively easy to calculate the luminance for every code value for a specific bit depth. The minimum ΔL is the change in luminance when the code value is changed by one and the modulation of a specific bit depth encoding can be calculated for all luminance values using Equation D-1. Figure E-1 shows the calculated HVMT curve for the most demanding pattern and the curves for 8-bit, 10-bit, 12-bit, and 14-bit encoding. This is the lowest HVMT that can be calculated for viewing images in a dark theatre. In Figure E-1, patterns above or to the right of the HVMT curve can be seen and patterns below or to the left of the curve cannot be seen. This curve has been calculated for the most demanding sine wave patterns and thus represents the limiting case. There are a number of factors that can make a pattern invisible even though it may lie above the HVMT curve. For example, noise or grain in an image will shift the threshold curve up and to the right. Computer generated imagery can be produced with no noise and therefore represents this limiting case. Based on Figure E-1, it appears that 10-bit encoding (or lower) has too few bits and 12-bit encoding (or higher) has more bits than are needed to avoid any bit depth related loss of information in an image or any image artifacts.

Figure E-1 is based on calculations only. Certainly there are good experiments behind the HVMT curve, but that curve is dependent on a large number of variables and what has been calculated and used in the development of the DCDM encoding has been a limiting case scenario. There was a considerable reluctance to accept the 12-bit encoding answer without doing some verification experiments in a theatre setting with D-Cinema projection. Therefore, an experiment was designed and run to determine if people could see patterns encoded with a bit depth of 10 and how that compared with patterns encoded with a bit depth of 12. Those results have been described in detail in the SMPTE Journal (see Annex A Bibliography) and will only be summarized here.

Using a digital projector, square wave patterns were projected onto the screen in a dark theatre. The square waves were projected at different average luminances and at different modulations. The observers were seated at different distances from the screen and were asked to identify the orientation of the square waves, which were oriented either vertically or horizontally. From an analysis of the observers' responses, the modulation threshold for each observer was determined. The observers were volunteers from the SMPTE DC28 meetings, studio employees, cinematographers, and a few film school students. The observer's average results matched the results predicted by calculations very well as shown in Figure E-2.

In Figure E-2 the calculated threshold varies as a function of distance due to the varying field of view and the varying frequency of the square waves as seen by the observer. Even though the observers farthest from the screen consistently had a lower modulation threshold than calculated, the results are in excellent agreement with the calculations. This gives strong support to the validity of the use of the HVMT curve for determining the bit depth needed in the DCDM encoding.

The results in Figure E-2 show the averages of groups of observers, but do not give any information on the distribution of the results around each average. Table E-1 shows the percentage of observers who correctly identified the orientation of the square waves at the 50% confidence level as a function of the luminance and bit depth.

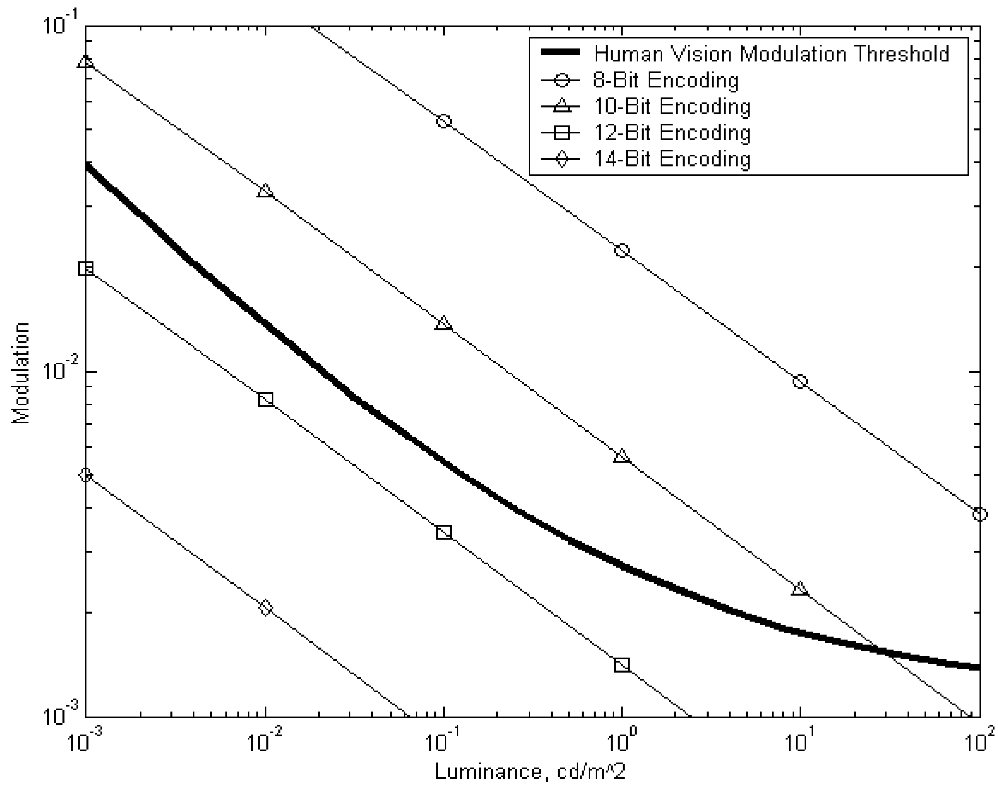

Figure E-1 – Visability of 8-, 10-, 12-, and 14-Bit Encoding

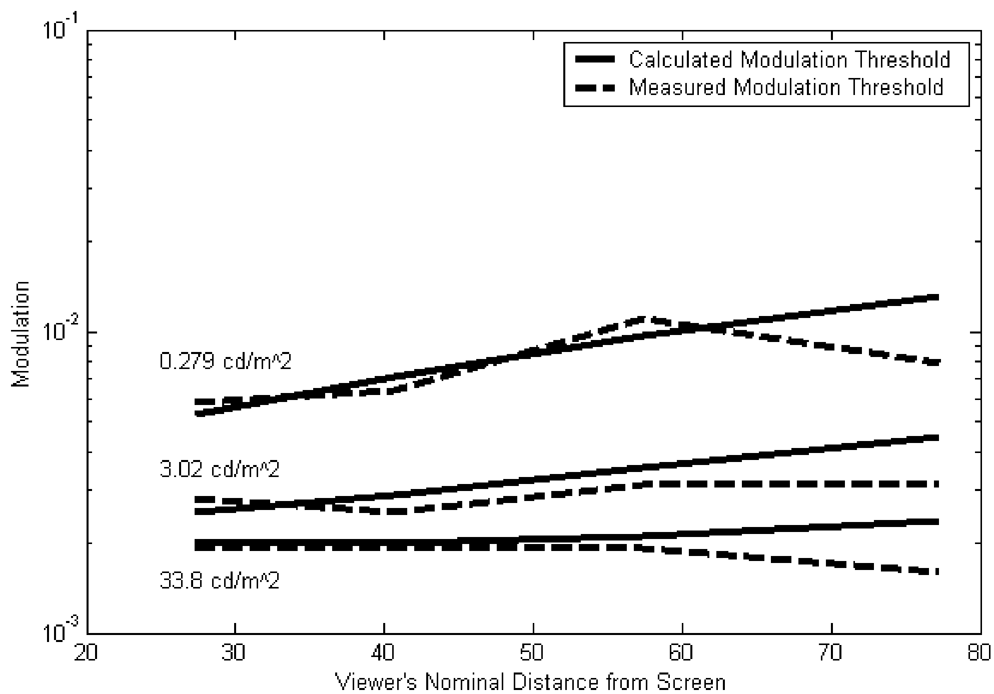

Figure E-2 – Comparison of the Modulation Thresholds Determined in the Theatre and the Calculated Modulation Thresholds

Table E-1 – Percentage of Observers Who Will Correctly Identify the Orientation of the Square Waves in a Pattern the Same as was Used in the Experiment if the DCDM is Encoded using 10, 11, and 12 Bits

Luminance	Bit Depth		
cd/m^2	10 bits	11 bits	12 bits
0.279	80%	47%	4%
3.02	92%	46%	9%
33.8	62%	4%	4%

Table E-1 shows that with 10-bit or 11-bit encoding a sizeable number of the observers could see the square waves, but with 12-bit encoding only a few observers could see the square waves. The visibility of the square waves is an indication of whether observers will see the information in an image. The objective was to have a one DCDM code value change encode slightly less information that a person can see. If people cannot see a one code value change, the images will display no artifacts due to the bit depth of the encoding.

Therefore, both the calculations and the experiment that was conducted in a theatre with a digital projector indicated that 12 bits were needed to encode all information that a person can see and that there would be no contouring artifacts. Based on these results, the DCDM was defined with 12 bits per channel.

The above calculations and experiment demonstrate that 12 bits are needed to encode the luminance channel. Whether the luminance is carried in the Y' channel as is done in the DCDM encoding or in three RGB channels, the neutral scale must be encoded with 12 bits. Early in the discussions of the encoding primaries, there was considerable attention paid to the efficiency of the encoding, which varied as a function of the primaries chosen. The *X'Y'Z'* encoding is a particularly inefficient encoding, which means there are a very large number of sets of *X'Y'Z'* values that lie outside the spectral locus and outside any practical set of real primaries. However, it is now clear that the discussion of encoding efficiency was a distraction because 12-bits per channel are needed for the encoding of the neutral scale. The best estimates of the number of colors that a person can differentiate are 2 million to 10 million. 12-bit encoding allows the encoding of roughly 64 billion colors. Therefore, with a 12-bit encoding system, the encoding efficiency has to be at best about 0.003%. If 12-bit encoding of the neutral scale is sufficient to encode all the visual information a person can see in luminance, there is a need for only 4096 encoded luminances along the neutral scale. Clearly, more efficient encoding algorithms, which would allow much smaller bit depths, must exist, but because it is desired to have an RGB type of encoding with equal (or roughly equal) RGB code values along the neutral scale, these smaller bit depth encoding algorithms have been rejected.

Annex F (Informative)
Minimum Linear RGB Bit Depth Needed in the Reference Projector

Section 7 described how to calculate the linear RGB values from the DCDM *X'Y'Z'* values. Appendix E shows that the *X'Y'Z'* code values must be encoded as 12-bit numbers. Although not a part of any standard or recommended practice, it is reasonable to ask how many bits are needed to encode the linear RGB values in the Reference Projector to likewise carry all the information a person can see and avoid all possibility of producing the contouring artifact. Equation D-1 can be rearranged to show the ΔL at the threshold of visibility.

$$\Delta L = 2 * m * L_{average} \qquad \text{(F-1)}$$

The HVMT in Figure E-1 can be plotted as the Human Vision Delta Luminance Threshold (HVDLT) as shown in Figure F-1. With the gamma (1 / 2.6) encoding, the encoded delta luminance for each code value change is different and increases as the code values increase. However, with linear encoding, the delta luminance for each code value change is the same independent of the code value. Therefore, the delta luminance for linear encoding depends on the number of code values in the encoding as shown by Equation F-2:

$$\Delta L_{Linear} = 48 / \left(2^{n} - 1\right) \qquad \text{(F-2)}$$

where ΔL_{Linear} is the change in luminance when the code values are increased by 1, n is the bit depth for the linear encoding, and the 48 comes from the fact that the maximum luminance of the white is 48 cd/m^2. The ΔL_{Linear} is shown in Figure F-1 for bit depths of 14-bits, 15-bits, 16-bits, and 17-bits. Figure F-1 also shows the minimum luminances that define a 2000:1 contrast ratio and a 4000:1 contrast ratio. From Figure F-1, for a 4000:1 contrast ratio it appears that more than 17 bits are needed for the linear encoding and more than 16 bits are needed for the 2000:1 contrast ratio. However, from Figure E-1 it can be seen that the 12-bit gamma (1 / 2.6) encoding falls below the HVMT line. It is likely that 17 bits would be adequate for linear encoding of a 4000:1 contrast ratio and 16 bits would be adequate for linear encoding of a 2000:1 contrast ratio. Table F-1 shows the results of the calculation of the maximum contrast ratios that can be encoded by linear encoding with 14-bits, 15-bits, 16-bits, and 17-bits. The HVDLT curve shows the encoding that is needed to encode the maximum amount of information a person can see and the 10 * HVDLT curve shows the encoding that is needed to avoid the contouring artifact. From this even 14-bits will avoid the contouring artifact.

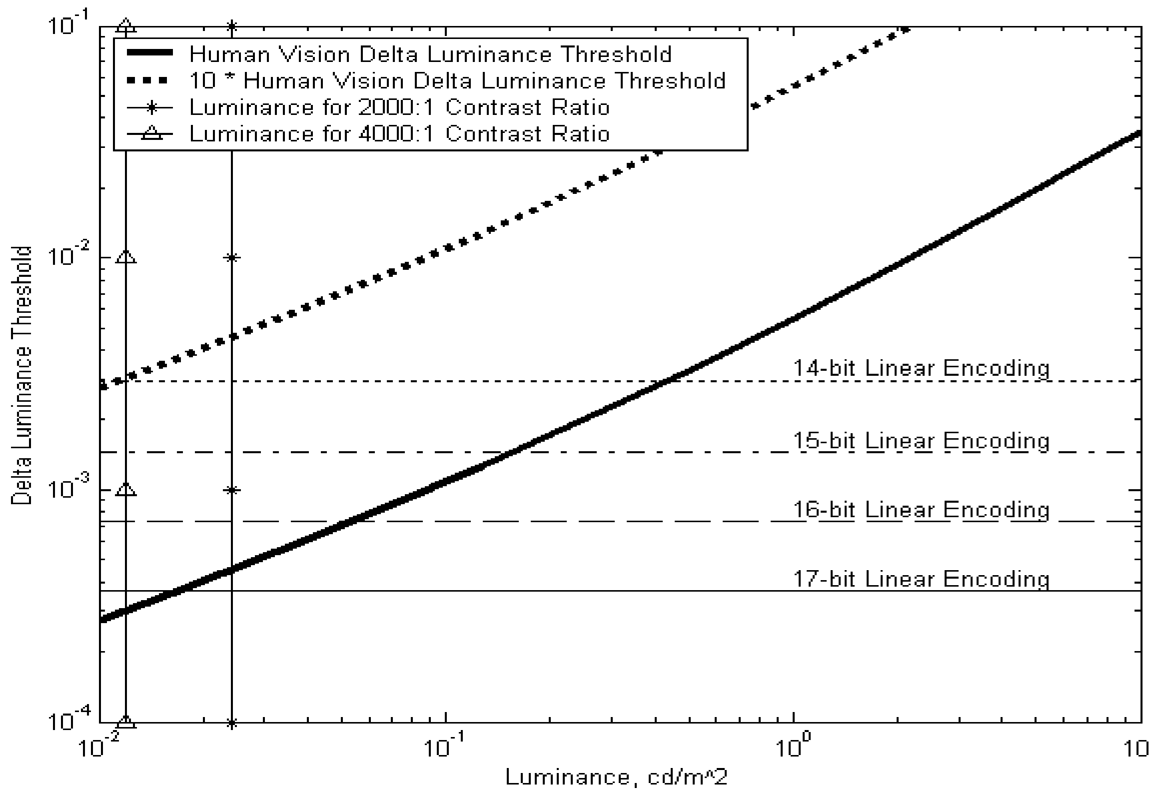

Figure F-1 – Comparison of the Delta Luminance Thresholds for the Human Visual System and Various Linear Encoding Bit Depths

Table F-1 – Contrast Ratios with Different Bit Depths for Linear Encoding

Bit Depth	ΔL_{Linear}, cd/m^2	Luminance of HVDLT Corresponding to ΔL_{Linear}	Contrast Ratio Based on HVDLT	Contrast Ratio Based on 10 * HVDLT
14	0.00293	0.403	119:1	4350:1
15	0.00146	0.144	333:1	14250:1
16	0.00073	0.049	977:1	48920:1
17	0.00037	0.016	3003:1	176000:1

Annex G (Informative)
Reason for the Constant 52.37

In Equations 5-1 to 5-6, it would seem that the constant that normalizes the XYZ variables should be the maximum luminance that can be encoded. Early in the development of the DCDM standard this was 41.11 cd/m^2, but was then increased to 48.00 cd/m^2. Therefore the value of 52.37 in the equations may seem a bit strange. The SMPTE D-Cinema standards specify a maximum luminance of 48.00 cd/m^2, a normalizing constant of 52.37, so the maximum Y' code value that is allowed is 3960. However, because there is no limit on the X' and Z' values, the maximum X' and Z' values are 4095. Some implementations or hardware, due to reserved code values, may set a lower maximum code value on X' and Z', but the reason for allowing them to have higher values than Y' still holds. The reason for the use of the 52.37 is that the gamut of the encoding space is increased and in particular there are more color temperatures along the CIE D-Illuminant line on a chromaticity diagram that can be encoded at the maximum luminance, 48.00 cd/m^2. The result of this is that there are more white points to which a projector can be set in the case that one wanted to set up a projector with its white point at a point other than the white point of the Reference Projector. The following calculations and plots will make this clearer.

If Equations 5-1 to 5-6 use a value of 48.00 as the normalizing constant, a luminance of 48.00 will be encoded any time the Y' code value is 4095. The encoding white point, which will be discussed in the section below and which is defined as the point where the code values are equal and at their maximum values, will be [4095 4095 4095]. The notation [X' Y' Z'] will be used here to indicate the *X'Y'Z'* code values for one color. The XYZ values corresponding to this color are [48 48 48]. The xyz chromaticity coordinates corresponding to this color are [0.3333 0.3333 0.3333]. One of the encoding gamut boundaries at the maximum luminance and in the direction from the white point toward yellow (maximum values of X and Y) is defined by the set of values [4095 4095 B] where B is less than 4095. Likewise, another encoding gamut boundary at the maximum luminance and in the direction from the white point toward cyan (maximum values of Y and Z) is defined by the set of values [R 4095 4095] where R is less than 4095. Figure G-1 shows the plane of maximum luminance that can be encoded using 48.00 as the normalizing constant. Figure G-2 shows a very enlarged version of the same plot so that the area around the most common white points can be more clearly seen. In these figures, the area that can be encoded with real colors is above the dark red and blue lines and below the dark black line. Therefore it can be seen that with this normalizing constant, D55, the Equal Energy Point, and the Reference Projector white point can be encoded, but D61 and D65 cannot be encoded at 48 cd/m^2.

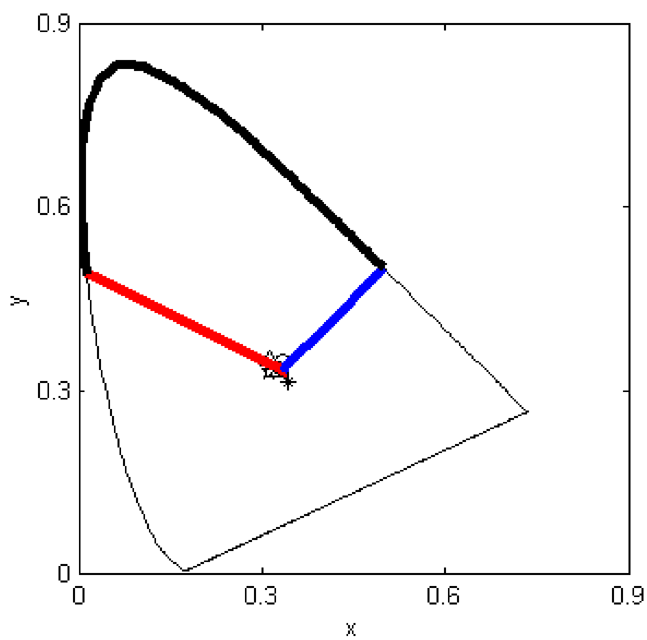

Figure G-1 – Encoded Gamut Boundary at a Luminance of 48 cd/m^2 and with a Normalizing Constant of 48.00

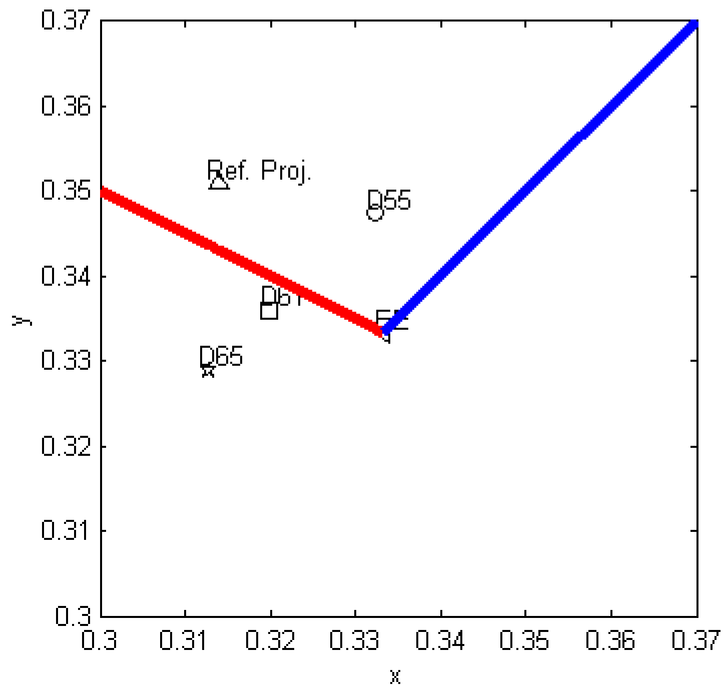

Figure G-2 – Encoded Gamut Boundary at a Luminance of 48 cd/m² and with a Normalizing Constant of 48.00

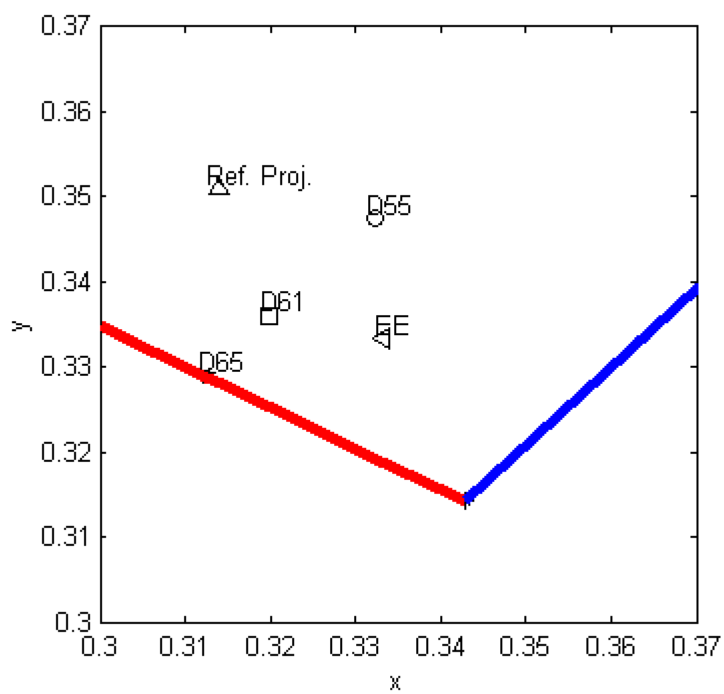

Figure G-3 – Encoded Gamut Boundary at a Luminance of 48 cd/m² and with a Normalizing Constant of 52.37

In order to provide headroom for possible changes in white point preference, it was decided to change the normalization factor to allow the encoding of D65 at the maximum luminance of 48 cd/m^2. Using Equations D-2 and D-3 with 12-bit encoding, limiting the maximum luminance to 48 cd/m^2, and enclosing D65 in the encoded gamut, leads to the normalizing constant of 52.37. With this normalizing constant the gamut on the 48 cd/m^2 plane is shown in Figure G-3. It can be seen that the D65 point is the point that forces the 52.37 constant, not the D55 point and not the Equal Energy point. The point where the red and blue lines meet in Figure G-3 is at chromaticity coordinates [0.3429 0.3143].

As is shown in Figure G-4, the use of 52.37 as the normalizing constant has no significant effect on the visibility of contouring. The modulation when the encoding equation has the normalizing constant 52.37 is not significantly different from the modulation when the encoding equation has the normalizing constant 48.00. Therefore, the normalizing constant 52.37 has been adopted.

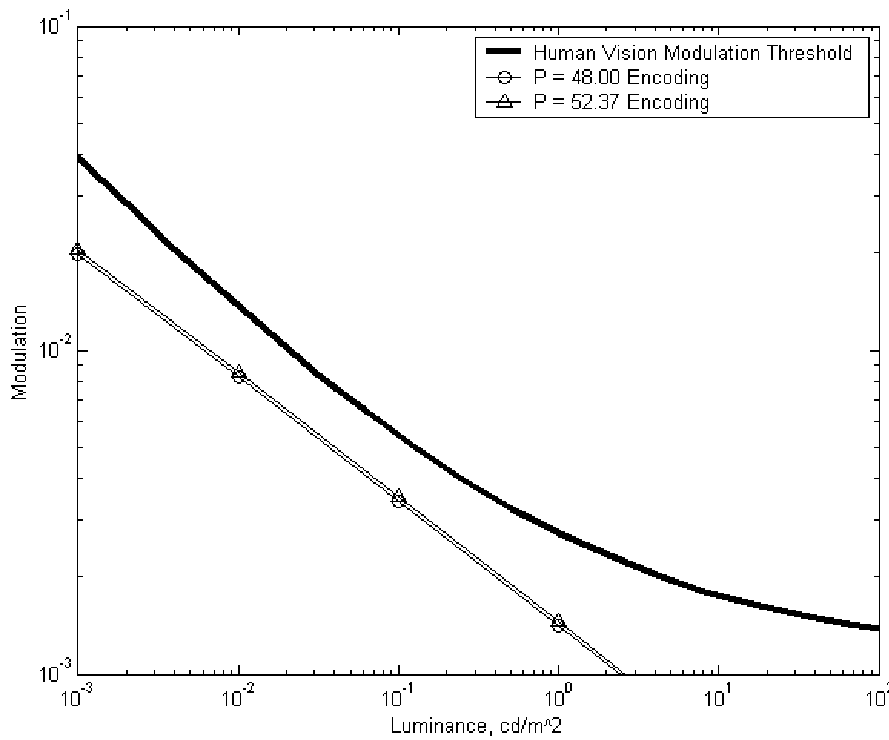

Figure G-4 – Encoding Modulation for a Normalizing Constant of 48.00 and 52.37 in the Encoding Equation

It was stated earlier that the use of the 52.37 normalizing constant allows the use of more white points for an actual projector. Table G-1 shows the *X'Y'Z'* code values and the xyz chromaticity coordinates of a variety of D-illuminants. The fact that no *X'Y'Z'* code values go above 4095 shows that these are all legal white points in terms of encoding of the content at the white point luminance of 48 cd/m^2.

Table G-1 – xyz and *X'Y'Z'* Values for Several D-illuminants

Color	x	y	z	X'	Y'	Z'
D55	0.3324	0.3474	0.3202	3893	3960	3838
D60	0.3217	0.3378	0.3405	3886	3960	3972
D61	0.3198	0.3360	0.3442	3885	3960	3997
D65	0.3127	0.3290	0.3583	3883	3960	4092

Using the technique described in Annex K, the NPM and inverse NPM matrices can be calculated for the above D-illuminant white points assuming the primaries in all these cases are the same primaries as are defined for the Reference Projector. Those matrices in the appropriate equations are given below. As explained in Section 7.3, the specification of the matrices to 5 digits to the right of the decimal will eliminate the possibility of color errors due to the precision of the matrix. Therefore these equations show the matrices with that precision.

Reference Projector Primaries, D55 White Point

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0.52709 & 0.26321 & 0.16652 \\ 0.24804 & 0.68535 & 0.06661 \\ 0.00000 & 0.04470 & 0.87701 \end{pmatrix} * \begin{pmatrix} R \\ G \\ B \end{pmatrix} \quad \text{(G-1)}$$

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} 2.30183 & -0.85979 & -0.37176 \\ -0.83722 & 1.77909 & 0.02384 \\ 0.04267 & -0.09067 & 1.13903 \end{pmatrix} * \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \quad \text{(G-2)}$$

Reference Projector Primaries, D60 White Point

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0.50474 & 0.26474 & 0.18286 \\ 0.23752 & 0.68933 & 0.07314 \\ 0.00000 & 0.04496 & 0.96304 \end{pmatrix} * \begin{pmatrix} R \\ G \\ B \end{pmatrix} \quad \text{(G-3)}$$

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} 2.40374 & -0.89786 & -0.38821 \\ -0.83238 & 1.76881 & 0.02371 \\ 0.03886 & -0.08257 & 1.03728 \end{pmatrix} * \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \quad \text{(G-4)}$$

Reference Projector Primaries, D61 White Point

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0.50085 & 0.26497 & 0.18596 \\ 0.23570 & 0.68992 & 0.07439 \\ 0.00000 & 0.04499 & 0.97941 \end{pmatrix} * \begin{pmatrix} R \\ G \\ B \end{pmatrix} \quad \text{(G-5)}$$

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} 2.42239 & -0.90482 & -0.39123 \\ -0.83167 & 1.76731 & 0.02369 \\ 0.03821 & -0.08119 & 1.01993 \end{pmatrix} * \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \quad \text{(G-6)}$$

Reference Projector Primaries, D65 White Point

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0.48657 & 0.26567 & 0.19822 \\ 0.22897 & 0.69174 & 0.07929 \\ 0.00000 & 0.04511 & 1.04394 \end{pmatrix} * \begin{pmatrix} R \\ G \\ B \end{pmatrix} \quad \text{(G-7)}$$

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} 2.49350 & -0.93138 & -0.40271 \\ -0.82949 & 1.76266 & 0.02362 \\ 0.03585 & -0.07617 & 0.95688 \end{pmatrix} * \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \quad \text{(G-8)}$$

For completeness, here are the matrices for the Reference Projector Primaries and the [0.3140 0.3510] White Point. These are Equations 7-8 and 7-9 shown to 5 digits to the right of the decimal.

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0.44517 & 0.27713 & 0.17228 \\ 0.20949 & 0.72160 & 0.06891 \\ 0.00000 & 0.04706 & 0.90736 \end{pmatrix} * \begin{pmatrix} R \\ G \\ B \end{pmatrix} \quad \text{(G-9)}$$

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} 2.72539 & -1.01800 & -0.44016 \\ -0.79517 & 1.68973 & 0.02265 \\ 0.04124 & -0.08764 & 1.10093 \end{pmatrix} * \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \quad \text{(G-10)}$$

Annex H (Informative)
Encoding White Points Considered

The white point of an additive imaging system is commonly defined as the color (as defined by the chromaticity coordinates and luminance) that results when the system is sent the maximum RGB code values that the system can accept. In some cases, the maximum code values are not the maximum as determined from the bit depth of the digital encoding, but are somewhat less than this maximum. However, it is common to define the white point as coming from equal RGB code values. With this definition of the encoding white point of a system and from Equations 5-1 to 5-6, the encoding white point for the DCDM system is the Equal Energy Point and the xy chromaticity coordinates of this point are [0.3333 0.3333]. The Equal Energy Point is shown on Figures G-2 and G-3 as the point labeled EE. The entire encoded neutral scale, defined as the scale of grays from white to black with equal code values, falls at this same set of chromaticity coordinates.

In SMPTE RP 431-2, the Reference Projector white point is defined as having chromaticity coordinates [0.314 0.351] and is shown in Figures G-2 and G-3 as the point labeled Ref. Proj. Clearly the white point for a properly set-up and calibrated digital projector does not have to be the same as the encoding white point. There was considerable discussion of what encoding white point to use, but the final decision, based on the argument that it simplified the hardware in a projector, was to use the Equal Energy Point. There will always have to be a conversion from the encoding code values based on the encoding primaries, which define a device independent system, to the projector code values based on the projector primaries, which define a device dependent system. Thus the encoding white point and the projector white point do not have to be the same. The adaptive white point, set by the scene color balance which is set for artistic and esthetic reasons, does not need to correspond to either the encoding white point or the projector white point.

In summary, there are three important points to remember concerning white in the DCDM system. (1) The encoding white is determined from the encoding and decoding Equations 5-1 to 5-6. Those equations define the relationship between colorimetry and the encoding code values. In the DCDM system, the xyY values of the encoding white are [0.3333 0.3333 48.00]. (2) The projector white is defined by the proper set-up and calibration of a specific projector. The Reference Projector white has xyY values of [0.314 0.351 48.00]. (3) The adaptive white for any particular scene is determined by the person creating the image and can be set at any xy chromaticity coordinates.

If the projector is properly set up and the primaries and set-up white point of that projector are known, the conversion between the encoding code values and the internal projector code values is relatively easy. The process by which this conversion is done was described in Section 7, Section 9, and Annex K.

Annex I (Informative)
Encoding of Colorimetry above Theatre Black

In a dark theatre there will be some light reflected onto the screen and back to the audience due to the lights required by building and safety codes. In addition, if the code values [b b b] are sent to the projector, some light will fall on the screen from the projector even though code values [b b b] define no light. This light, the light from the safety lights plus the light from the projector when the code values [b b b] are sent, bounced off the screen will be called ‘theatre black’. This is the blackest black that can be measured off the screen in that theatre with the projector turned on. In a dark theatre the theatre black will not alter the white point because the white light out of the projector is so much brighter than the theatre black. The ratio of the white luminance to the theatre black luminance is called the contrast ratio. If the chromaticity coordinates and luminance of the theatre black were the same in all theatres over all time, there would not be a problem. However, review rooms typically have a lower theatre black luminance than theatres open to the public. Also, one advance that has already been made in digital projectors is the increase in the contrast ratio. The higher the contrast ratio, given the defined white point, the lower the luminance of the theatre black.

If the encoding of the colorimetry in the DCDM were to represent the absolute colorimetry of the light reflected by the screen, then the encoding would represent both the light from the projector plus the theatre black. In absolute colorimetry encoding, the code value 0 would represent absolutely no light reflected from the screen.

If the encoding of the colorimetry in the DCDM were to represent the relative colorimetry of the light reflected by the screen, where relative colorimetry means the colorimetry of the light that is above the theatre black, then the encoding represents the light emitted by the projector when code values greater than [b b b] are sent to the projector and reflected by the screen. Although this may sound like an encoding of the light emitted by the projector, it is not the light emitted by the projector because the screen has to be involved also – the light is measured off the screen. Therefore, with relative colorimetry the light must be measured with a meter pointed at the screen, not pointed directly at the projector. Also, code values [b b b] represent theatre black reflected from the screen and theatre black represents some light reflected from the screen.

In the limiting case in which the theatre black XYZ values are [0 0 0], the absolute colorimetry and relative colorimetry are identical and it would not matter whether the DCDM were defined in terms of absolute or relative colorimetry. However, this is never the case. Also, if the theatre black were the same in all theatres and at all time, there would be a simple transform from absolute colorimetry to relative colorimetry. The most common case is that the theatre black in one theatre, for example the review room, has lower XYZ values than the theatre black in another theatre, for example an exhibition theatre. The question then is, “Which encoding, absolute colorimetry or relative colorimetry, gives the best overall quality when the same DCDM file is projected in a large number of different theatres?” The answer to this question will determine the encoding to use in the DCDM.

Consider two theatres with digital projectors that are each calibrated to the white point luminance of 48 cd/m^2. Assume that a first theatre has a 2000:1 contrast ratio, which means the theatre black luminance is 0.024 cd/m^2, that a second theatre is the mastering theatre and has a contrast ratio of 2000:1, and that a third theatre has a 1000:1 contrast ratio, which means the theatre black luminance is 0.048 cd/m^2. Figure I-1 shows the luminance that would be measured off the screen in both the relative colorimetry and absolute colorimetry encoding cases given a series of patches arbitrarily numbered 0, 1, 2, 3, etc.

In Figure I-1, the heavy black line shows the measured luminance for the first theatre and for the mastering theatre, the 2000:1 contrast ratio theatres. Because these two theatres have the same contrast ratios, it does not matter if the encoding is absolute colorimetry or relative colorimetry; the results are the same for the two theatres.

In this example, the third theatre, with the 1000:1 contrast ratio, will display two different sets of luminance values for these patches depending on whether absolute colorimetry or relative colorimetry encoding is chosen.

If absolute colorimetry encoding is chosen, the luminance values of these patches will be as shown by the dotted line. The dotted line is hidden by the heavy black line for patches 3 to 16, but is a horizontal line for patches 0 to 3. Absolute colorimetry encoding demands that the system display those luminance values it is able to display at the proper luminance values as far into the black as it can go (patches 3 to 16) and then the other patches (patches 0 to 3) are all displayed at the 0.048 cd/m^2 luminance. The net result is that although in the 2000:1 contrast ratio theatre, patches 0, 1, 2, and 3 were reproduced at different luminance values, in the 1000:1 contrast ratio theatre, with absolute colorimetry encoding these patches are all displayed at the same luminance. Therefore these blacks are crushed in the 1000:1 contrast ratio theatre.

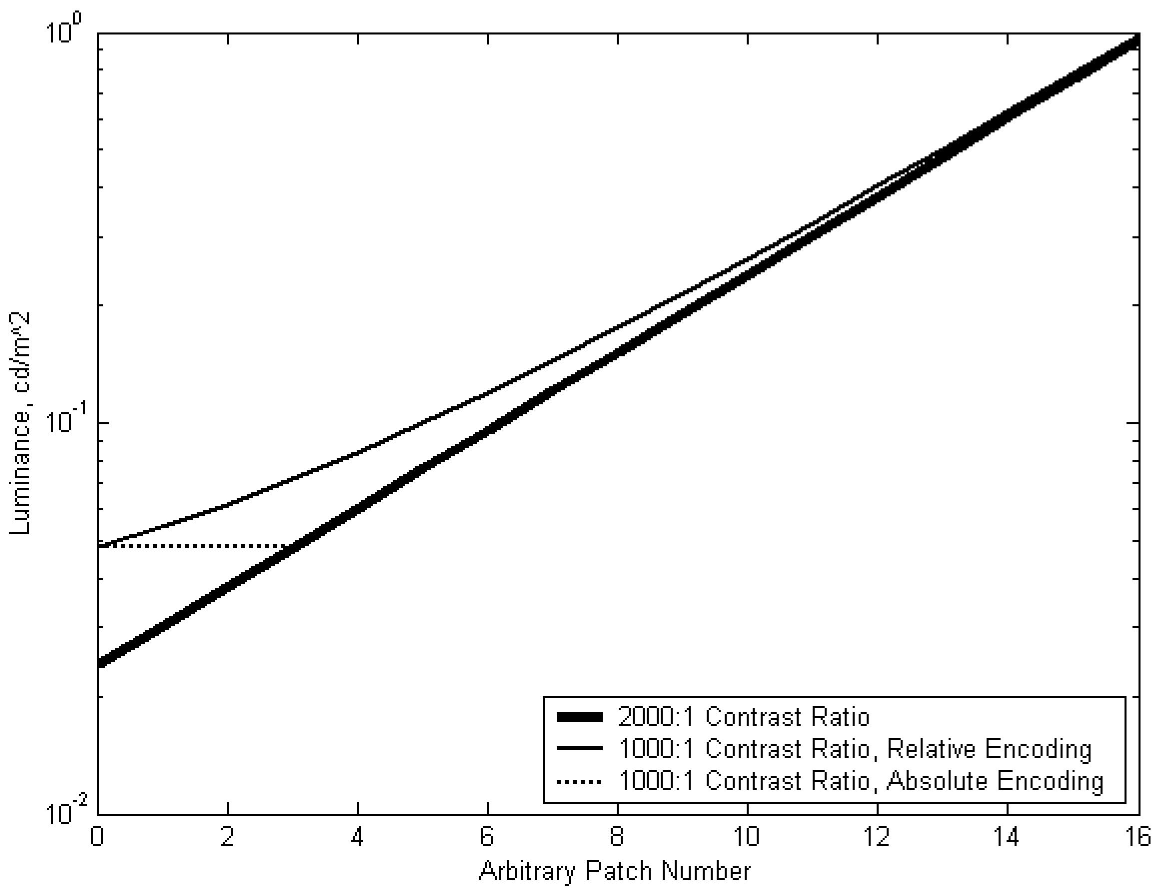

Figure I-1 – Effect of Differing Theatre Contrast Ratios on the Low Luminances that can be Displayed

If relative colorimetry encoding is chosen, the luminance values of these patches will be as shown by the thin line in Figure I-1. Both absolute colorimetry and relative colorimetry encoding display patches 14 and higher patch numbers as the same (or indistinguishably the same), but the relative colorimetry encoding displays patches 0 through 13 at higher luminance levels than the absolute colorimetry encoding displayed the patches. However, with relative colorimetry encoding the benefit is that all of the patches 0 through 13 are displayed at different luminance values. These patches will appear lighter and lower contrast with the relative colorimetry encoding than they would appear with the absolute colorimetry encoding. However, with the relative colorimetry encoding none of the patches will appear to be crushed. This effect was verified in an experiment using a digital projector. This, then, is the important trade-off between relative colorimetry and absolute colorimetry encoding.

If we analyze what is done today with the projection of a film print, we can see that the result is the same as relative colorimetry encoding. When the film prints are made, all the film prints are made (in theory) exactly the same. Therefore, the light reflected from the screen with any film print is the sum of the light from the theatre black and the light that was modulated by the film print. If the theatre black was higher in one theatre, the blacks are higher, the contrast in the blacks is lower, but if two black patches have different film densities, they are displayed on the screen at two different luminance values.

There is one other problem that can show up with absolute colorimetry encoding that does not occur with relative colorimetry encoding. With relative colorimetry encoding, the code values represent levels of light above the minimum light reflected off the screen in the theatre. Therefore, every code value produces some level of light that is projected onto the screen. There are no “hidden” or “unseen” code values. But with absolute colorimetry encoding, every triad of code values defines a color that is supposed to be displayed on the screen. However, if the encoded color is outside the gamut of colors that a particular projector can produce on a screen, for example the color is darker than the theatre black, than that color will be displayed as the theatre black. So assume an image is being mastered by a system with a particular contrast ratio. With absolute colorimetry encoding, there will be some code value triads that define a color that cannot be accurately displayed because those colors are darker than the contrast ratio of the system. It is possible that some of these code value triads will be placed into the digital file because in the mastering operation, the colors displayed were theatre black and that was an acceptable color for that image element. If at some time in the future a system with a larger contrast ratio is used to display this image, the color defined by these code value triads may be displayed properly and not as theatre black. There is the strong possibility that the color produced is not the desired color because the encoded color was not seen in mastering,. Therefore, color errors can occur with absolute colorimetry encoding if the theatre projector has a higher contrast ratio than the mastering projector.

In summary, the difference between absolute colorimetry encoding and relative colorimetry encoding shows up when two conditions are met: (1) The mastering projector has a different contrast ratio than a theatre projector and (2) There is some content that is above the theatre black of one projector, but below the theatre black of the other projector. The use of absolute colorimetry encoding means the contrast in the black region is maintained to the lowest luminance the lower contrast ratio projector is able to produce, then all darker blacks in the DCDM file are reproduced at the same luminance – hence some blacks are crushed. Conversely, the relative colorimetry encoding lowers the contrast in the black region, but maintains some differentiation in luminance for all blacks in the DCDM file – hence no blacks are crushed. In addition, in the special case in which the mastering projector has a smaller contrast ratio than the theatre projector, there is the strong possibility that there will be colors displayed in the theatre that were not seen in the mastering theatre. This can lead to undesirable color errors in the image.

It was decided to use relative colorimetry encoding for the encoding of the colorimetry for the DCDM file for a number of reasons. Film, which is a form of relative colorimetry encoding, gives good images in theatres with varying theatre black levels. Absolute colorimetry encoding will lead to crushed blacks and it is known that crushed blacks, with their loss of detail, decreases the quality of an image. There is the strong possibility that absolute colorimetry encoding will introduce color errors into the DCDM file if the file is projected with a system with larger contrast ratio than the mastering system. Therefore the DCDM code values represent the colorimetry above the theatre black.

Annex J (Informative)
Conversions among xyY, XYZ, and *X'Y'Z'*

Equations 5-1 to 5-6 defined the relationship between XYZ tristimulus values and the DCDM *X'Y'Z'* code values. However, it is much more common for a measuring instrument to give chromaticity coordinates, x and y, and luminance, Y, than for an instrument to give the XYZ values. An instrument gives absolute luminance values in cd/m^2, not relative Y values as are used in the encoding and decoding equations 5-1 to 5-6. Therefore Tables 6-7, 6-8, and 6-11, which were copied from SMPTE 431-2, define the colorimetry in xyY values, not XYZ values. The equations relating the chromaticity coordinates x, y, and z to the tristimulus values X, Y, and Z are:

$$x = \frac{X}{X+Y+Z} \qquad y = \frac{Y}{X+Y+Z} \qquad z = \frac{Z}{X+Y+Z} \tag{J-1}$$

The equations relating x, y, and Y to X, Y, and Z are:

$$X = \left(\frac{x}{y}\right) * Y \qquad Y = Y \qquad z = 1 - x - y \qquad Z = \left(\frac{z}{y}\right) * Y \tag{J-2}$$

As a specific, worked example of how to calculate the *X'Y'Z'* values from the xyY values, the calculation for the white point, step number 10 in Table 6-7 will be shown in detail.

The xyY values for the white as defined by SMPTE 431-1 are [0.314 0.351 48.00].

From the equations above, the absolute XYZ values are:

$$X = \left(\frac{x}{y}\right) * Y = \left(\frac{0.314}{0.351}\right) * 48.00 = 42.940 \tag{J-3}$$

$$Y = Y = 48.00 \tag{J-4}$$

$$z = 1 - x - y = 1 - 0.314 - 0.351 = 0.335 \qquad Z = \left(\frac{z}{y}\right) * Y = \left(\frac{0.335}{0.351}\right) * 48.00 = 45.812 \tag{J-5}$$

The Y of the white is 48 cd/m^2, so the normalizing factor to give normalized XYZ values is 48. Therefore the normalized XYZ values are:

$$X = X / 48 = 42.940 / 48 = 0.894583 \tag{J-6}$$

$$Y = Y / 48 = 48 / 48 = 1.000000 \tag{J-7}$$

$$Z = Z / 48 = 45.812 / 48 = 0.954417 \tag{J-8}$$

$$X' = INT\left(4095 * \left(\frac{L * X}{52.37}\right)^{1/2.6}\right) = INT\left(4095 * \left(\frac{48 * 0.894583}{52.37}\right)^{1/2.6}\right) = 3794 \tag{J-9}$$

$$Y' = INT\left(4095 * \left(\frac{L * Y}{52.37}\right)^{1/2.6}\right) = INT\left(4095 * \left(\frac{48 * 1.000000}{52.37}\right)^{1/2.6}\right) = 3960 \quad \text{(J-10)}$$

$$Z' = INT\left(4095 * \left(\frac{L * Z}{52.37}\right)^{1/2.6}\right) = INT\left(4095 * \left(\frac{48 * 0.954417}{52.37}\right)^{1/2.6}\right) = 3890 \quad \text{(J-11)}$$

Annex K (Informative)
Calculation of the NPM Using the Method in SMPTE RP 177

SMPTE RP 177 gives the specifics on how to calculate the NPM. What follows is a summary of the equations and calculations in SMPTE RP 177.

The calculations start with the CIE x, y chromaticity coordinates of the reference white and of the Red, Green, and Blue primaries. The z chromaticity coordinate for the reference white and each of the RGB primaries is also needed:

$$z = 1 - (x + y) \tag{K-1}$$

Form the following P matrix and W column vector from the [x y z] chromaticity coordinates of the Red, Green, and Blue primaries and reference white:

$$P = \begin{pmatrix} x_R & x_G & x_B \\ y_R & y_G & y_B \\ z_R & z_G & z_B \end{pmatrix} \tag{K-2}$$

$$W = \begin{pmatrix} x_W / y_W \\ 1 \\ z_W / y_W \end{pmatrix} \tag{K-3}$$

where the R, G, and B subscripts refer to the Red, Green, and Blue primaries and the W subscript refers to the reference white.

The W vector, representing the reference white, has been normalized so that white has a luminance factor of 1.0, i.e. Y = 1.0.

Compute the elements of a vector by multiplying the W vector by the inverse of the P matrix. The notation P^{-1} indicates the matrix inversion operation. These C_R, C_G, and C_B elements are normalization factors that normalize the intensities of the Red, Green, and Blue primaries such that unit amounts of each primary combine to produce the white point chromaticities with a luminance factor of 1:

$$\begin{pmatrix} C_R \\ C_G \\ C_B \end{pmatrix} = P^{-1} * W \tag{K-4}$$

Form the diagonal matrix from the vector elements C_R, C_G, and C_B:

$$C = \begin{pmatrix} C_R & 0 & 0 \\ 0 & C_G & 0 \\ 0 & 0 & C_B \end{pmatrix} \tag{K-5}$$

Compute the final normalized primary matrix NPM as the product of the P and C matrices:

$$NPM = \begin{pmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{pmatrix} = P * C \qquad \text{(K-6)}$$

This matrix, NPM, is the normalized primary matrix and relates linear RGB signals to CIE XYZ tristimulus values as follows:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{pmatrix} * \begin{pmatrix} R \\ G \\ B \end{pmatrix} = NPM * \begin{pmatrix} R \\ G \\ B \end{pmatrix} \qquad \text{(K-7)}$$

Equation K-7 is the same equation as Equation 7-1.

As an example of a numerically worked calculation, assume the chromaticity coordinates of the white point and primaries defined in Table 9-1. These chromaticity coordinates do not define any known display device, but are shown here as an example of the calculations using actual numbers. Although the matrices in Equations K-8 through K-12 are shown to four digits to the right of the decimal point, the calculations were performed at the maximum precision that the computer system allowed. Then Equations K-13 and K-14 are shown to 10 digits to the right of the decimal point as recommended by SMPTE RP 177.

Table K-1 – Chromaticity Coordinates for the White Point and Primaries of the Monitor

Color	x	y	z
White Point	0.3170	0.3310	0.3520
Red Primary	0.6500	0.3250	0.0250
Green Primary	0.2900	0.6050	0.1050
Blue Primary	0.1570	0.0730	0.7700

Equation K-2 becomes

$$P = \begin{pmatrix} 0.6500 & 0.2900 & 0.1570 \\ 0.3250 & 0.6050 & 0.0730 \\ 0.0250 & 0.1050 & 0.7700 \end{pmatrix} \qquad \text{(K-8)}$$

Equation K-3 becomes

$$W = \begin{pmatrix} 0.3170/0.3310 \\ 1 \\ 0.3520/0.3310 \end{pmatrix} = \begin{pmatrix} 0.9577 \\ 1 \\ 1.0634 \end{pmatrix} \qquad \text{(K-9)}$$

Equation K-4 requires the inverse of the P matrix. Here is that inverse matrix

$$P^{-1} = \begin{pmatrix} 2.0029 & -0.9041 & -0.3227 \\ -1.0860 & 2.1707 & 0.0156 \\ 0.0831 & -0.2667 & 1.3070 \end{pmatrix} \quad \text{(K-10)}$$

Equation K-4 becomes

$$\begin{pmatrix} C_R \\ C_G \\ C_B \end{pmatrix} = P^{-1} * W = \begin{pmatrix} 2.0029 & -0.9041 & -0.3227 \\ -1.0860 & 2.1707 & 0.0156 \\ 0.0831 & -0.2667 & 1.3070 \end{pmatrix} * \begin{pmatrix} 0.9577 \\ 1.0000 \\ 1.0634 \end{pmatrix} = \begin{pmatrix} 0.6710 \\ 1.1473 \\ 1.2029 \end{pmatrix} \quad \text{(K-11)}$$

Equation K-6, the equation that calculates the NPM, becomes

$$NPM = \begin{pmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{pmatrix} = P * C = \begin{pmatrix} 0.6500 & 0.2900 & 0.1570 \\ 0.3250 & 0.6050 & 0.0730 \\ 0.0250 & 0.1050 & 0.7700 \end{pmatrix} * \begin{pmatrix} 0.6710 & 0.0000 & 0.0000 \\ 0.0000 & 1.1473 & 0.0000 \\ 0.0000 & 0.0000 & 1.2029 \end{pmatrix} \quad \text{(K-12)}$$

$$NPM = \begin{pmatrix} 0.4361343357 & 0.3327206339 & 0.1888489579 \\ 0.2180671678 & 0.6941240810 & 0.0878087511 \\ 0.0167743975 & 0.1204678157 & 0.9262018955 \end{pmatrix} \quad \text{(K-13)}$$

Equation K-7 becomes

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0.4361343357 & 0.3327206339 & 0.1888489579 \\ 0.2180671678 & 0.6941240810 & 0.0878087511 \\ 0.0167743975 & 0.1204678157 & 0.9262018955 \end{pmatrix} * \begin{pmatrix} R \\ G \\ B \end{pmatrix} \quad \text{(K-14)}$$

SMPTE RP 177 also describes the equations to transform between primary sets. It is stated that the input data consists of the normalized primary matrices for a source system (NPM_S) and for a destination system (NPM_D). Note that although the RP says this is a transform between primary sets, the NPM matrices contain information from both the primaries and the white point of each system. The equations are equally valid for transforms between (1) different primaries with the same white points, (2) the same primaries with different white points, and (3) different primaries with different white points. There may be instances in which it is desired to calculate the linear RGB values for a projector using primaries or a white point different from the Reference Projector primaries and white point. Thus the calculation of this conversion matrix will be shown here.

Given the normalized primary matrices for the source (NPM_S) and the destination (NPM_D) systems, the following equations relate CIE tristimulus values to the linear RGB signals in both source and destination systems:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = NPM_S * \begin{pmatrix} R_S \\ G_S \\ B_S \end{pmatrix} \quad \text{(K-15a)}$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = NPM_D * \begin{pmatrix} R_D \\ G_D \\ B_D \end{pmatrix} \quad \text{(K-15b)}$$

The inverse relationships, predicting RGB from XYZ, may also be written:

$$\begin{pmatrix} R_S \\ G_S \\ B_S \end{pmatrix} = NPM_S^{-1} * \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \quad \text{(K-16a)}$$

$$\begin{pmatrix} R_D \\ G_D \\ B_D \end{pmatrix} = NPM_D^{-1} * \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \quad \text{(K-16b)}$$

Again, the superscript -1 notation on the NPM matrices indicates matrix inversion.

This is how to determine a matrix that transforms RGB signals from the source system into appropriate RGB signals for the destination system. Equation J-17a shows how to predict XYZ values from the source RGB signal values. Equation J-17b predicts the destination RGB signals from the XYZ values.

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = NPM_S * \begin{pmatrix} R_S \\ G_S \\ B_S \end{pmatrix} \quad \text{(K-17a)}$$

$$\begin{pmatrix} R_D \\ G_D \\ B_D \end{pmatrix} = NPM_D^{-1} * \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \quad \text{(K-17b)}$$

The XYZ values are the same for the source and the destination systems when the color displayed is the same, so the XYZ vector on the right side of Equation K-17b can be replaced with the entire right side of Equation K-17a

$$\begin{pmatrix} R_D \\ G_D \\ B_D \end{pmatrix} = NPM_D^{-1} * NPM_S * \begin{pmatrix} R_S \\ G_S \\ B_S \end{pmatrix} \quad \text{(K-18)}$$

The desired transformation matrix TRA is the product of NPM_D inverse and NPM_S:

$$TRA = NPM_D^{-1} * NPM_S \qquad \text{(K-19)}$$

and

$$\begin{pmatrix} R_D \\ G_D \\ B_D \end{pmatrix} = TRA * \begin{pmatrix} R_S \\ G_S \\ B_S \end{pmatrix} \qquad \text{(K-20)}$$

The recommendation in SMPTE RP 177 is to use 10 significant digits in the matrices and round the RGB or XYZ values to four significant digits after computing them to 10 significant digits. Although the use of 10 significant digits in the matrices will eliminate round-off errors, matrices calculated from measurements will not have 10 significant digits of accuracy.

Although the above derivation of the TRA matrix is mathematically correct, it is based on the assumption that if the XYZ values of two images match, the images themselves will match. This is only true if the viewing conditions are exactly the same. This will be true if the two images are digital cinema images projected onto a screen in an environment that meets all the applicable SMPTE Standards and Recommended Practices. However, if the environments are not the same, the images will not visually match even though the XYZ values may match. For example, if two theatres have significantly different theatre black luminance values, the images may look different. Likewise, the environment for viewing Digital Cinema images is different from the environment for viewing television images and we cannot expect that the conversion of Reference Projector linear RGB values to television linear RGB values using these equations will produce images that will match when each image is displayed in its environment.

Annex L (Informative)
Description of CIELab Space and Delta E*ab

L.1 Calculations of L*a*b* and Delta E*ab in CIELab Space

There are a number of different color difference equations that could be used. The delta E*ab in this space is based on the L*a*b* equations, which are derived from the XYZ tristimulus values. The equations relating these quantities are

$$L^* = 116 * f(Y/Yn) - 16 \quad \text{(L-1)}$$

$$a^* = 500 * [f(X/Xn) - f(Y/Yn)] \quad \text{(L-2)}$$

$$b^* = 200 * [f(Y/Yn) - f(Z/Zn)] \quad \text{(L-3)}$$

where

$$f(X/Xn) = (X/Xn)^{1/3} \quad \text{if } (X/Xn) > 0.008856 \quad \text{(L-4)}$$

$$f(X/Xn) = \frac{1}{3}\left(\frac{29}{6}\right)^2 \left(X/_{Xn}\right) + \left(\frac{4}{29}\right) \quad \text{if } (X/Xn) \le 0.008856 \quad \text{(L-5)}$$

$$f(Y/Yn) = (Y/Yn)^{1/3} \quad \text{if } (Y/Yn) > 0.008856 \quad \text{(L-6)}$$

$$f(Y/Yn) = \frac{1}{3}\left(\frac{29}{6}\right)^2 \left(Y/_{Yn}\right) + \left(\frac{4}{29}\right) \quad \text{if } (Y/Yn) \le 0.008856 \quad \text{(L-7)}$$

$$f(Z/Zn) = (Z/Zn)^{1/3} \quad \text{if } (Z/Zn) > 0.008856 \quad \text{(L-8)}$$

$$f(Z/Zn) = \frac{1}{3}\left(\frac{29}{6}\right)^2 \left(Z/_{Zn}\right) + \left(\frac{4}{29}\right) \quad \text{if } (Z/Zn) \le 0.008856 \quad \text{(L-9)}$$

and where XYZ are the tristimulus values of the color patch and Xn, Yn, Zn are the tristimulus values of the white. In the case of Digital Cinema, the white absolute Xn, Yn, Zn tristimulus values are given by Equations J-3, J-4, and J-5 and are 42.940, 48.000, and 45.812 and the normalized values are 0.894583, 1.000000, and 0.954417. In the above equations either absolute or normalized values can be used because all of the functions are ratios of tristimulus values.

The difference between two color stimuli, delta E*ab, is calculated as the Euclidean distance between the points in the L*a*b* color space

$$deltaE^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \quad \text{(L-10)}$$

where for color 0 and color 1

$$\Delta L^* = L^*_1 - L^*_0 \quad \text{(L-11)}$$

$$\Delta a^* = a^*_1 - a^*_0 \quad \text{(L-12)}$$

$$\Delta b^{*} = b_{1}^{*} - b_{0}^{*} \qquad \text{(L-13)}$$

Many instruments that measure XYZ values will also calculate the delta E*ab for two colors given the XYZ values of the white.

A large number of points at, for example, delta E*ab = 4 could be calculated around each primary. The results of this calculation are shown in Figure L-1. In addition Figure L-1 shows the delta E*ab = 4 circle of a light gray with chromaticity coordinates equal to the chromaticity coordinates of the white point and at a luminance of 40.00 cd/m^2. In the calculations in Figure L-1 it was assumed that the luminance values were the same for all the patches, so the calculated figures are the maximum sizes that can be shown on these figures.

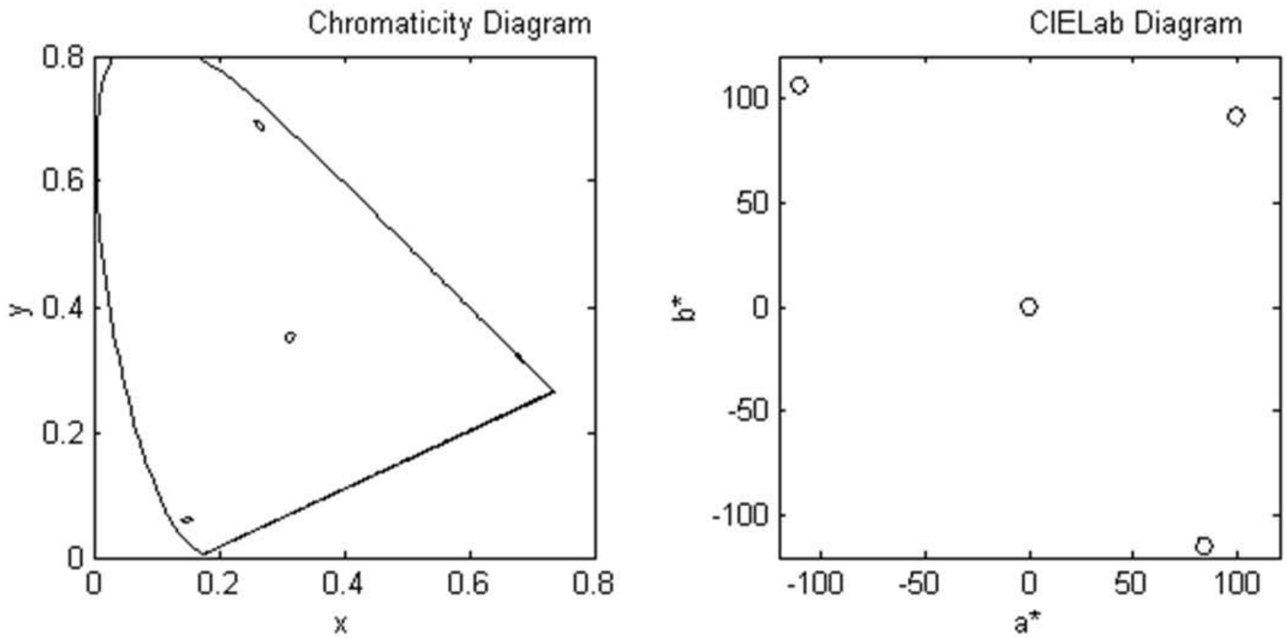

Figure L-1 – Delta E*ab=4 Figures around the Primaries and a Light Gray on the Chromaticity Diagram and on the a*b* Diagram of CIELab Space

Figure L-1 shows ΔE*ab = 4 around the red, green, and blue primaries of the reference projector and a light gray assuming no luminance change when calculating the figure. The figure on the red primary is adjacent to the spectral locus and is so small as to be almost invisible. On the a*b* diagram, the circle in the upper left corner corresponds to the green primary, the circle in the upper right corner corresponds to the red primary, the circle in the lower right corner corresponds to the blue primary, and the circle in the center of the diagram corresponds to the light gray. Although a CIELab color difference of ΔE*ab = 4 defines a circle on the a*b* diagram (assuming no luminance change) and all the circles on the a*b* diagram are the same size, the figures on the chromaticity diagram are not circles and they are not the same size.

L.2 Discussion of the CIELab Color Space

Although one can implement the color tolerances specified in SMPTE RP 431-2 without any more knowledge of CIELab space than is given in Annexes J and L, there are a number of properties of the CIELab space that are useful to know in order to understand the tolerances and the measurement of the tolerances better. The delta E*ab was chosen as the tolerance specification because it is defined in the CIELab color space. The most useful property of this space is that it is what is termed a “uniform” color space. By “uniform” color space is meant that equal Euclidean distances in this space are perceived to be equal color differences. Certainly a red does not look like a green, but if two red colors differ by 2 delta E*ab units and two green colors differ by 2 delta E*ab units, the prediction is that the two color differences will be judged to be equal. This is a very useful property when a color tolerance is being defined in terms of Euclidean distances. The chromaticity space is not as uniform as the CIELab space, hence in Figure L-1 on the a*b* diagram the tolerance circles appear to be all the same size, which they are, whereas on the xy chromaticity diagram the tolerance figures appear as varying sized figures.

The Munsell color space is the most uniform color space. - It was defined by having many people make many judgements of color differences using color patches. One problem with the Munsell space is that it was based on judgements of color patches and it is not based on any mathematical equations. The CIELab space is a mathematical approximation, based on XYZ tristimulus values and Equations L-1 to L-13, of the Munsell space. But the equations that define the CIELab space do not exactly describe the Munsell space. Therefore the CIELab space is not perfectly uniform, but is sufficiently uniform for most uses. There is a general rule of thumb that says that when comparing two color patches, which are placed near each other, which are near neutral in color, and which are in the environment specified for judging colors in the Munsell color system, a delta E*ab = 1 is at or near the threshold of visibility of the color difference for most people. If any of these conditions is changed, for example the environment is changed or the colors are very colorful instead of being near neutral or the colors are presented sequentially at very low frequency, not simultaneously, the threshold of visibility of the color difference increases. This means that for any of these different conditions, in order for a person to see the color difference, the delta E*ab will increase. Conversely, for any of these different conditions, a pair of color patches with a given delta E*ab will appear to be less different than if they were in the environment specified for judging colors in the Munsell color system. For the case in which the two colors are highly colored, the threshold of the visibility of the color difference increases to a delta E*ab of about 2. The result of this is that because the illuminance levels in a theatre are much lower than were used to define the Munsell space and because the color differences are between colors in one theatre using one projector and colors in another theatre using another projector, this delta E*ab of 4 is visually a very tight tolerance. In fact, few, if any, people will be able to detect the color difference between two colors from the same code values in two different theatres if both theatres and projectors are set up to these tolerances.

Figure L-2 shows several other differences between the CIELab space and the chromaticity space. In Figure L-1 the tolerance figures were calculated for the primaries at the luminance values of each primary and for the light gray at a luminance value of 40.00 cd/m^2. In Figure L-2, the tolerance figures were calculated at four different sets of luminance values. The first set was exactly the same as for Figure L-1. In the second set the luminance values were reduced to 10% of their values in the first set. In the third set the luminance values were reduced to 1% of their values in the first set. In the fourth set the luminance values were reduced to 0.5% of their values in the first set. This is equivalent to a density series centered on the same xy chromaticity coordinates. In color science terms, this is a saturation series, same xy values, but different Y values.

The tolerance figures in the chromaticity diagram and on the a*b* diagram in Figure L-2 show a number of interesting differences. On the a*b* diagram there are only 13 tolerance figures shown instead of the 16 expected and shown on the chromaticity diagram. The four tolerance figures around the light gray are all identical in shape and location, so only show up as one circle instead of 4 different circles. On the a*b* diagram, a tolerance figure around a neutral will be identical in shape and location independent of the luminance of the central gray. In the chromaticity diagram the location of the central gray is the same independent of luminance, but the size and shape of the tolerance figure changes: as the luminance decreases, the size of the tolerance figure increases. In the a*b* diagram for each primary there are four circles for the four levels of luminance around each primary. The four circles for each primary are not all centered at the same a*b* values, but instead fall on a line from the a*b* values of the primary at its highest luminance to the neutral axis. The circle corresponding to the 0.5% luminance patch is the closest to the neutral axis. In the chromaticity diagram, the reference point of the tolerance figures is located at the same xy chromaticity coordinates independent of the luminance value. However, although all of the tolerance figures were circles of radius 4 in the a*b* diagram, the tolerance figures in the xy diagram increase in size with decreasing luminance. It is obvious from the xy diagram that parts of some of the tolerance figures fall outside the spectral locus, a region where real colors cannot fall. The fact that there are some mathematical colors defined by the tolerance figures that fall outside the spectral locus is not evident from the CIELab figure. No tolerance figures for luminance values lower than 0.5%, which corresponds to a 200:1 contrast ratio, are shown because the tolerance figures for different colors on the chromaticity diagram overlap. The conclusion from this is that although the delta E*ab tolerance specification for low luminance colors appears valid on the a*b* diagram, the xy diagram shows that some of the specified colors are outside the spectral locus. Both diagrams show that as the luminance values go down, the tolerance figures begin to overlap. This indicates that at low luminance values, the delta E*ab tolerance is probably not appropriate for assessment of the color errors produced by a system.

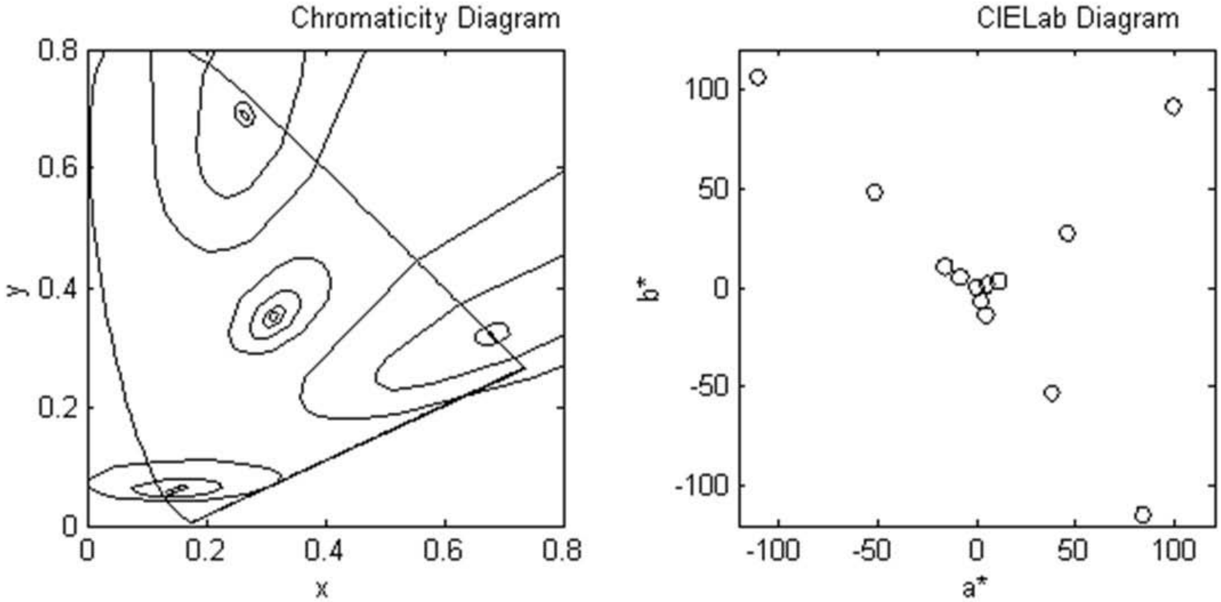

Figure L-2 – Delta E*ab=4 Figures around the Primaries and a Light Gray at Different Luminance Values on the Chromaticity Diagram and on the a*b* Diagram of CIELab Space

Annex M (Informative)
Explanation of Annex B in SMPTE ST 428-1

Annex B in SMPTE ST 428-1 shows that there are 135 code values of headroom at the high end of the 12-bit DCDM encoding scale, 45 code values of headroom at the bottom end of the encoding scale for a 2000:1 contrast ratio projector, and 35 code values of headroom at the bottom end of the encoding scale for a 4000:1 contrast ratio projector. This section shows how those calculations were made.

For the high end of the encoding scale, the maximum luminance required of a projector as defined in SMPTE 431-1 is 48 cd/m^2 and the white point at this luminance has chromaticity coordinates [0.314 0.351]. Annex J went through the calculations from these xyY values to the DCDM *X'Y'Z'* values. The *X'Y'Z'* values are [3794 3960 3890]. The maximum 12-bit code value is 4095 and therefore the headroom between 3960 and 4095 is 135 code values.

The reasoning behind the headroom at the bottom end of the encoding scale is different. There is no restriction that prevents the code values 0, 1, 2, etc. from being used. Therefore, technically there is no headroom on the bottom end. However, there is a practical amount of headroom. If the white luminance is 48 cd/m^2, the minimum luminance for a 2000:1 contrast ratio projector is 0.024 cd/m^2. Figure E-1 shows that at a luminance of 0.024 cd/m^2, the modulation threshold is about 0.010. The equation for modulation, Equation D-1, can be rearranged to give

$$\Delta L = 2 * m * L_{average} \qquad \text{(M-1)}$$

If $L_{average}$ is set to the minimum luminance, 0.024 cd/m^2, Equation M-1 becomes

$$\Delta L = 2 * 0.01 * 0.024 = 0.00048 \qquad \text{(M-2)}$$

The DCDM encoding is based on the idea of XYZ values above the theatre black. Using Equation 6-2, the DCDM code value for a luminance of 0.00048 cd/m^2 is 45. This means that given an image of uniform black of 0.024 cd/m^2, 50% of observers will not be able to see a series of sine waves in luminance if the highest luminance portion of the sine waves were defined by a Y' code value of 45. A similar calculation using a 4000:1 contrast ratio produced the code value 35 for the luminance of the highest luminance portion of the sine wave. The calculation of these values assumes that the observer is viewing the sine waves under ideal viewing conditions. Under any other conditions, the modulation threshold will be larger and the code value will be higher. In particular the presence of higher luminance scene elements will make the sine waves defined by the minimum and maximum code values less visible. In order for an observer to see the sine waves, the modulation of the sine waves will need to be larger and the calculated code value will be larger. The conclusion, then, is that in only one scene, a background of Y' code value 0 and sine waves of the optimum frequency and with a peak luminance defined by a Y' code value 45 will even 50% of the observers be able to see the sine waves. In any other scene the peak Y' code value will need to be higher, and most likely considerably higher, than 45. Therefore, it is concluded that there are at least 45 code values of headroom at the bottom end of the encoding scale for a 2000:1 contrast ratio projector.

Appendix N (Informative)
Glossary and Acronyms

Although two of the references, Measuring Colour by Hunt and Digital Color Management by Giorgianni and Madden, have excellent glossaries, to make it easier to understand this guideline, many words are defined here. The International Lighting Vocabulary has the most complete list of words.

achromatic: A color that is perceived to have no hue. White, gray, and black are achromatic colors.

adaptive white: A color that an observer, adapted to a set of viewing conditions, would judge to be white.

ambient light: The light reflected from the screen in a theatre due to sources such as exit signs and foot lights, but not due to the projection mechanism.

calibration: The process by which a device or system is brought into the condition whereby a defined input produces a defined output.

characterization: The process by which the output of a device or system is measured given a defined input to that device or system.

checkerboard contrast: The intra-frame contrast in which the black and white patches in an image are arranged in alternating pattern. In this case, the white luminance is measured as the sum of the white luminance of each white patch and the black luminance is measured as the sum of the black luminance of each black patch as long as the number of white and black patches is the same.

chromatic: A color that is not white, gray, or black. This is the set of colors that are not achromatic. Chromatic colors have hue.

chromaticity coordinates: The ratio of each X, Y, and Z tristimulus value to the sum of the tristimulus values. See Annex I for the calculations of the x, y, and z chromaticity coordinates. Also the u', v' coordinates that result from a linear operation on the xyz chromaticity coordinates. The u', v' chromaticity coordinates are mentioned, but not used, in this guideline.

chromaticity diagram: A plot of the x and y chromaticity coordinates in which the x coordinate is plotted on the abscissa and the y coordinate is plotted on the ordinate. There is a similar u', v' chromaticity diagram, but it is not used in this guideline.

CIE: Commission Internationale de l'Eclairage, an international organization that is responsible for photometry and colorimetry.

CIE Standard Colorimetric Observer: An observer with spectral sensitivities that exactly match the CIE 1931 color matching functions.

CIE tristimulus values: The X, Y, and Z values determined by the data and equations defined in 1931 by the CIE for the Standard Colorimetric Observer.

CIELab color space: A 3-dimensional color space defined by the coordinates L*, a*, and b*. The equations that define L*a*b* are given in Annex K. The most useful property of the CIELab space is that for a pair of colors in this space the perceived color difference between the two colors is proportional the Euclidean distance between the colors.

clip: A gamut mapping strategy in which code values less than the minimum allowed are encoded as the minimum allowed and code values greater than the maximum allowed are encoded as the maximum allowed.

code value: A number that carries color information and either comes from or goes to an imaging device.

code value b: The code value b means the minimum code value that a particular D-Cinema system allows. This designates the minimum luminance from the projector, which is black. In some cases b would be 0, but in other cases, b may be some other, higher code value. In practice, values as high as 100 will most likely not produce any more light than a value of 0.

color appearance: What a color looks like to an observer. Color appearance depends in many factors including absolute luminance, surround luminance, adaptation of the observer, etc. Color appearance differs from color measurements in that the same measured color will change its appearance as the environment in which the color is observed changes.

color decoding: The definition of a relationship between color information and numbers. Decoding is the conversion of the numbers, also called code values, into color information.

color encoding: The definition of a relationship between color information and numbers. Encoding is the conversion of the color information into the numbers, also called the code values**.**

color gamut: The limits of the colors that can be displayed by a system. Also the limits of the colors that belong to a set of colors that are mathematically defined.

color processing: Mathematical manipulations that are applied to code values.

colorimetry: The area of color science that deals with the measurement and specification of color stimuli. Also the science of color measurement.

contouring: An image artefact in which there is the appearance of steps or bands where only a continuous or smooth gradient is expected.

contrast: The numerical value of the white luminance divided by the black luminance.

contrast sensitivity: The inverse of the modulation threshold. See modulation and modulation threshold.

D-Cinema: An abbreviation for digital cinema.

DCDM: Digital Cinema Distribution Master

density (optical density): The logarithm, base 10, of the ratio of the light transmitted by a perfectly transmitting material divided by the light transmitted by a given material or light reflected by a perfectly reflecting material divided by the light reflected by a given material. The light can either be appropriately filtered or the light can be weighted by the appropriate weighting function.

delta E*ab: The Euclidean distance between the two colors in the CIELab color space.

digital cinema: A projector in a theatre that accepts the code values defined by SMPTE standards and recommended practices and that projects images on a screen that are of theatrical quality.

Digital Cinema Distribution Master (DCDM): An uncompressed digital representation of a set of images that make up the motion content that will be sent to the digital cinema.

digital cinema system: All of the hardware and software that is needed to create, encode, transport, and display digital cinema images.

digital image: An image defined by code values.

Digital Source Master (DSM): A digital representation of a set of images that make up the motion content and from which many distribution elements are created, for example, the Film Distribution Master, the Digital Cinema Distribution Master, the Home Video Master, the Airline Version Master, the Broadcast Master, etc.

DPX: Digital Moving Picture Exchange file format for files with the extension .dpx. In this use the code values in the file are scanner code values and the code values generally represent film printing densities. See SMPTE 268M and SMPTE RP 180.

DSM: Digital Source Master

exhibition projector: A working projector for digital cinema that is capable of operating within the tolerances defined by the SMPTE 431 documents.

exhibition theatre: A theatre in which the paying public can view images projected onto a screen.

gamut mapping: A process by which one color, which a device cannot produce, is replaced by another color, which the device can produce.

gray scale: The series of achromatic colors from the lowest luminance to the highest luminance.

HVDLT: Human Vision Delta Luminance Threshold. This is the minimum change in luminance that a group of people can correctly identify 50% of the time. See also HVMT from which this is derived.

HVMT: Human Visual Modulation Threshold. This is the minimum modulation that a group of people can correctly identify 50% of the time.

Image State Diagram: A diagram showing the various states in which an encoded image can exist. There are three states, the Scene Referred State, the Output Referred State, and the Input Referred State. An image can be transformed between any two states.

INT: A mathematical operator that rounds numbers to integer values. Numbers with fractional parts less than 0.50 are rounded down to the nearest integer and fractional parts equal to or greater than 0.50 are rounded up to the next integer.

intra-frame contrast: The ratio of the luminance of the white divided by the luminance of the black, normalized to a denominator of 1,when the white and black that are measured are projected onto the screen in the same image. This is usually expressed as number:1, for example 2000:1. See also checkerboard contrast.

luminance: A measure of the energy being reflected or emitted by a surface and in which the energy is weighted by the CIE V_λ, also called the CIE y-bar color matching function. Luminance is an approximate correlate of brightness. The Y value in the set of CIE XYZ tristimulus values is the luminance.

luminance factor: The ratio of the luminance of a sample divided by the luminance of a perfectly reflecting or transmitting object when both are illuminated identically.

lut: A look-up table. A lut is a common way of processing information quickly on a computer. In operation, the input value is the entry to the table from which the output value is extracted.

modulation: For a given pattern varying in luminance, the modulation is the ratio of the difference between the high luminance and the low modulation divided by the sum of the two luminance levels. See Equation D-1.

modulation threshold: The modulation of the pattern that can be correctly identified by a group of people 50% of the time.

nd lut: A lut in which the number of input values is n. The number of output values does not have to be equal to n. The most common types of luts are a 1d lut and a 3d lut. See also lut.

normalize: The mathematical operation in which one value is divided by its maximum (or maximum possible) value so that the resulting maximum (or maximum possible) value is 1. Also the mathematical operation in which all values in a set of values are divided by their sum so that the sum of the values is 1.

normalized primary matrix (NPM): A 3x3 matrix that converts from the linear RGB values, which represent the fractions of each additive primary needed to define a color, and the XYZ tristimulus values of the resulting color. The matrix is said to be normalized because the sum of the second row of the matrix is 1.

NPM: Normalized Primary Matrix

primary: A color from which other colors are made by addition or subtraction. The Reference Projector primaries are red, green, and blue and all other colors are made by addition of light from each of these primaries. The DCDM encoding primaries are X, Y, and Z, which are imaginary primaries, and by which all other colors are defined.

printing density: A density measured or calculated when the light source is a printer light and the sensitivity is the spectral sensitivity of the print material. See also density.

reference projector: A working, practical projector for digital cinema that is defined by its capabilities, not by its technology, and is defined in SMPTE RP 431-2.

review room: A theatre in which decisions are made about images projected onto a screen.

RGB: Abbreviation for Red, Green, and Blue.

RP: A Recommended Practice published by SMPTE.

RP as a subscript: Reference Projector

RPGB: Reference Projector Gamut Boundary, the limits of the colors that can be displayed by the Reference Projector.

saturation: The colorfulness of an area judged in proportion to its brightness. On a chromaticity diagram, the saturation of a color increases as its distance from the white point on the diagram increases. Also, on a chromaticity diagram, the points that plot at the same xy coordinates, but have different Y values, form a series in colors that have the same saturation, but different brightness.

sequential contrast: The ratio of the luminance of the white divided by the luminance of the black, normalized to a denominator of 1,when the white and black that are measured are projected onto the screen as full frame images. This is usually expressed as number:1, for example 2000:1.

StEM: Standard Evaluation Material. Also called the ASC/DCI Standard Evaluation Material or the DCI-ASC Mini-Movie. Motion content that was shot on film, scanned, and used for D-Cinema and image quality testing. The material is available from SMPTE as of the writing of this guideline.

theatre ambient: The light reflected from the screen in a theatre due to sources such as exit signs and foot lights, but not due to the projection mechanism (projector lamp is turned off or is doused).

theatre black: The light reflected from the screen in a theatre due to sources such as exit signs and foot lights plus the light from the projection system when the lowest code value is sent to the projector.

transfer function: The equation that shows luminance as a function of the DCDM Y' code value, Y = f(Y'), Equation 6-5.

transform: An image processing operation that changes the code values defining an image.

xyY: The xy chromaticity coordinates and the Y tristimulus value.

XYZ: A shorthand notation for the CIE tristimulus values. See also CIE tristimulus values.

***X'Y'Z'*:** A shorthand notation for the DCDM encoded code values. See Equations 5-1 to 5-6. Notably, the DCDM encoded code values are normalized to a maximum code value of 4095 and have a non-linear transfer function of 1 / 2.6.

Y: CIE luminance.

white: A color that is judged to be perfectly achromatic and to have a luminance factor of 1.