

SMPTE ENGINEERING GUIDELINE**Digital Source Processing —
Color Processing for D-Cinema**

Page 1 of 81 pages

Table of Contents**Page**

Foreword	3
Intellectual Property	3
Introduction.....	3
1 Scope	5
2 Conformance Notation	5
3 Order in which the Color Processing Steps are Described.....	6
4 Flow of Color through the Digital Cinema System	6
4.1 Digital Source Master	6
4.2 D-Cinema Image Color Flow Diagram	6
4.3 Reference Projector Input Color Data Flow	7
4.4 Exhibition Projector Input Color Data Flow	7
5 D-Cinema Colorimetry Encoding	8
5.1 Equations for DCDM Color Encoding	9
5.2 Equations for DCDM Color Decoding	10
5.3 Comments on the DCDM Encoding and Decoding Equations	10
6 Measurements of Projected Images	11
6.1 Measuring Equipment	12
6.2 Measuring Locations within the Review Room or Exhibition Theater.....	13
6.3 Projector and Theater Environment.....	13
6.4 Measurement and Ambient Light	13
6.5 Measurement of the Luminance of White	13
6.6 Measurement of the Luminance of Theater Black	15
6.7 Measurement of the Sequential Contrast	15
6.8 Measurement of Intra-Frame (Checkerboard) Contrast	16
6.9 Visual Verification of Gray Scale Tracking.....	16
6.10 Visual Assessment of Contouring	18
6.11 Measurement of the Transfer Function Exponent	18
6.12 Measurement of the Color Gamut (Color Primaries)	18
6.13 Specification of the Color Accuracy of any Displayed Colors.....	19
7 Conversion of Reference Projector R'G'B' Code Values to DCDM Code Values and then to Linear Projector Code Values	20
7.1 Background and Theory.....	20
7.2 Derivation of the RGB-to-XYZ and XYZ-to-RGB Matrices, General Equations	21

7.3 Derivation of the RGB-to-XYZ and XYZ-to-RGB Matrices, Reference Projector	22
7.4 Explanation of Annex C in SMPTE RP 431-2, Reference Projector (conversion example for R'G'B' to XYZ to $X'Y'Z'$)	24
8 Gamut Mapping and the Value of the Mastering Projector Metadata	28
9 An Example of Color Processing through the Entire System	32
9.1 Specification of Color in the DSM	32
9.2 Conversion from the DSM Film Printing Density Color Encoding to $X'Y'Z'$	39
Annex A Bibliography (Informative)	41
Annex B Encoding Schemes Considered (Informative)	43
Annex C Location of the Encoding Primaries (Informative)	45
Annex D Reason for the Constant 2.6 (Informative)	47
Annex E Reason for the Constant 4095 (Informative)	50
Annex F Minimum Linear RGB Bit Depth Needed in the Reference Projector (Informative)	53
Annex G Reason for the Constant 52.37 (Informative)	55
Annex H Encoding White Points Considered (Informative)	60
Annex I Encoding of Colorimetry above Theater Black (Informative)	61
Annex J Conversions among xyY, XYZ and $X'Y'Z'$ (Informative)	64
Annex K Calculation of the NPM using the Method in RP 177 (Informative)	66
Annex L Description of CIE Lab Space and Delta E*ab (Informative)	71
Annex M Explanation of Annex B in SMPTE 428-1 (Informative)	76
Annex N Glossary and Acronyms (Informative)	77

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 exemplified progression step, converts the DSM image

representation data to CIE linear XYZ tristimulus values. The second exemplified 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.

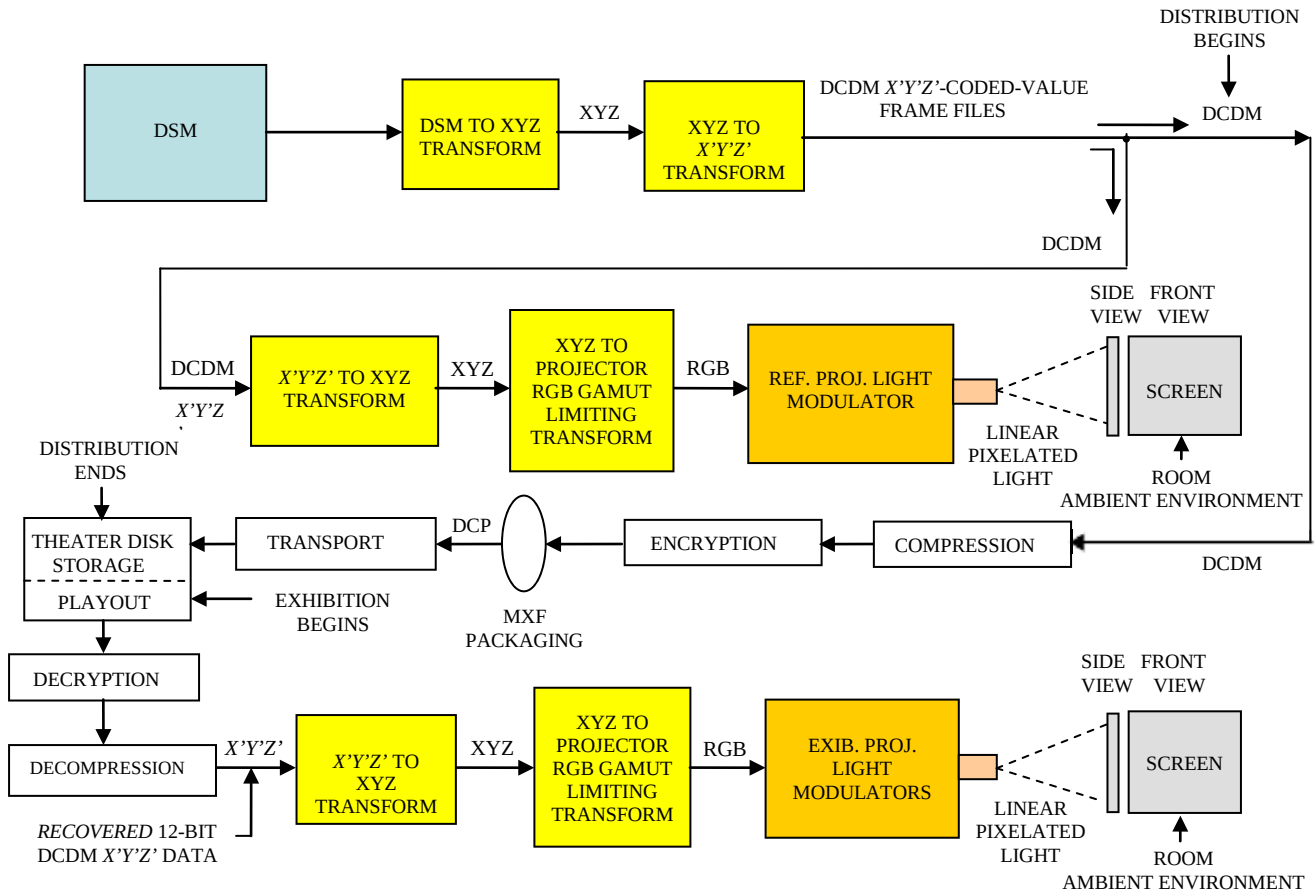


Figure 4-1 – D-Cinema Image Color Data Flow

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.

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

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

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

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

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

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

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

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/m² 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 communication, 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 $\pm 0.5 \text{ cd/m}^2$ ($\pm 0.2 \text{ fL}$) for white field measurements and $\pm 0.007 \text{ cd/m}^2$ ($\pm 0.002 \text{ fL}$) 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/m^2 . 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 been 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 $5\% \pm 1\%$ 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/m ² (14.0 fL)	±3.5 cd/m ² (± 1.00 fL)	±10.2 cd/m ² (± 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/m ²
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/m ²
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

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

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/m ²
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/m ²
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.

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

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.

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

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/m².

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

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/m ²
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/m ²
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

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

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/m² and this sum should equal the luminance of the white, which is 48.00 cd/m². 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

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

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

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

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/m ²	Y, cd/m ²
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

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

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

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

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

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

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

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

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.