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Arc-flash analysis of utility power systems

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ARC-FLASH ANALYSIS OF UTILITY POWER SYSTEMS

By

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A REPORT

Submitted in partial fulfillment of the requirements for the degree of

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This report, “Arc-Flash Analysis of Utility Power Systems,” is hereby approved in partial fulfillment of the requirements of the Degree of Master of Science in Electrical Engineering.

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Abstract

The electric utility business is an inherently dangerous area to work in with employees exposed to many potential hazards daily. One such hazard is an arc flash. An arc flash is a rapid release of energy, referred to as incident energy, caused by an electric arc. Due to the random nature and occurrence of an arc flash, one can only prepare and minimize the extent of harm to themself, other employees and damage to equipment due to such a violent event.

Effective January 1, 2009 the National Electric Safety Code (NESC) requires that an arc-flash assessment be performed by companies whose employees work on or near energized equipment to determine the potential exposure to an electric arc.

To comply with the NESC requirement, Minnesota Power's (MP's) current short circuit and relay coordination software package, ASPEN OneLiner™ and one of the first software packages to implement an arc-flash module, is used to conduct an arc-flash hazard analysis. At the same time, the package is benchmarked against equations provided in the IEEE Std. 1584-2002 and ultimately used to determine the incident energy levels on the MP transmission system.

This report goes into the depth of the history of arc-flash hazards, analysis methods, both software and empirical derived equations, issues of concern with calculation methods and the work conducted at MP. This work also produced two offline software products to conduct and verify an offline arc-flash hazard analysis.

Chapter 1: Introduction

Electric utility equipment, like any other product we use in everyday activities, is prone to failure and requires preventative maintenance and repair. During these maintenance activities, employees become exposed to a potential arc-flash incident. An arc-flash incident is a violent event exposing employees to not only high temperatures and noise levels but also shrapnel from the equipment involved in the arc flash. This incident may be caused by the employee themselves or by a random equipment failure on nearby equipment.

Effective January 1st, 2009 NESC requires that an arc-flash assessment be performed by companies whose employees work on or near energized equipment to determine the potential exposure to an electric arc employers are. For this reason detailed research has been conducted on the behavior of arc flashes and emperical equations have been developed to predict the energy released during the event and IEEE Std. 1584-2002 enforces the equations. Figure 1.1 below captures what an employee may experience if subjected to an arc-flash incident [1].

Figure 1.1: Lab demonstration of arc-flash explosion

Arc-flash assessments are not easy studies to conduct. These studies require both knowledge of the power system and the protective devices used on the system. The effort required to conduct a full system analysis has been greatly reduced with the integration of arc-flash analysis tools in present short circuit software in coordination with protective device data.

The largest effort required in an arc-flash assessment is data collection. There are many variables required as inputs into the detailed equations developed. Some of these variables are also used in short circuit analyses and are readily available while some require engineering judgment to determine which variable to use. The arc energy could be calculated by hand but this also requires a large effort and close attention when entering the data. Several short circuit software programs have implemented an arc-flash analysis module including ASPEN OneLiner™ which was used to conduct this system assessment.

ASPEN OneLiner™ is a short circuit and relay coordination program used by protection engineers to simulate different types of faults on a transmission system. Engineers can make changes to relay settings and the configuration of the system and see the effects without needing to re-calculate time consuming short-circuit equations by hand.

One of the objectives of this project is to benchmark the newly released ASPEN® arc-flash module to verify the equations programmed performed to the IEEE Std. 1584-2002.

A second objective of the project is to perform MP's transmission system arc-flash assessment to ensure that the company was in compliance with the NESC standards.

Chapter 2 discusses the history of arc-flash hazards, pre-existing work to develop the empirical equations used to calculate the incident energy released during the arc flash, and the behavior of arcs.

Chapter 3 explains the different ways to determine the potential incident energy at a location on the system by using the empirical equations derived in Chapter

2, by using tables developed by the NESC based on system parameters or by using the ASPEN® arc-flash module. Also it details the methodology of benchmarking the software package against the empirical equations.

Chapter 4 provides issues of concerns with the empirical equations based on fault type and the faulted equipment. This chapter also discusses the level of energy exposure due to protective coordination and the voltage level at the fault location.

Chapter 5 will outline potential mitigation methods to be implemented to reduce the hazard exposure with system modifications during maintenance, applying state of the art relay applications or special operating procedures.

Chapter 6 provides conclusions and recommendation for future work.

Chapter 2: Background Information and Preexisting Work

This chapter provides background information, preexisting work and the history of arc-flash hazards and analysis.

2.1 Literature Search

An arc-flash hazard, as defined by IEEE Std. 1584-2002, is a dangerous condition associated with the release of energy caused by an electric arc. The release of energy is caused by an electric current passing through air between ungrounded conductors or between ungrounded conductors and grounded conductors which is capable of producing temperatures of 35,000^{o}F. Exposure to these temperatures can burn human skin and ignite the clothing, adding to the burn injury. These high temperatures also cause the explosive expansion of both the surrounding air and the metal in the arc path.

Copper, a metal commonly used in electric equipment, expands by a factor of 67,000 times when it turns from a solid to a vapor. The expansion of the air and metal can cause high pressures, intense sound, and flying shrapnel. The high pressures can exceed hundreds or even thousands of pounds per square foot, possibly knocking workers off ladders, rupturing eardrums, and collapsing lungs. The sounds associated with these pressures can exceed 160 dB resulting in hearing damage. The shrapnel and molten metal will be expelled away from the arc at speeds exceeding 700 miles per hour which is fast enough to completely penetrate the human body. Each year at least 2,000 people in the U.S. are admitted to burn centers with severe arc-flash burns. Arc flashes can and do kill at distances of 10 feet [2].

According to the NESC 2007 edition Part 4, effective January 1, 2009 employers shall ensure that an assessment is performed to determine potential exposure to an electric arc for employees who work on or near energized parts or equipment. The assessment is to determine the potential incident energy levels to which employees could be exposed while performing work on energized equipment.

If the assessment reveals that the potential exposure is greater than 2 cal/cm^2 at the distance the employee is working from the energized parts (1.2 cal/cm^2 is equivalent to the onset of a second degree burn) the employer shall require the employee to wear clothing or a clothing system that has an effective arc rating not less than the anticipated level of arc energy.

When an arc-flash hazard analysis is performed, it shall include a calculation of the estimated arc energy based on the available fault current, the duration of the arc (cycles), and the distance from the arc to the employee. Two exceptions to the analysis are listed below [3]. The clothing or clothing system level required to be worn based on the potential energy released will be discussed in the Chapter 3.

EXCEPTION 1: If the clothing required by this rule has the potential to create additional and greater hazards than the possible exposure to the heat energy of the electric arc, then clothing with an arc rating or arc thermal performance value (ATPV) less than that required by the rule can be worn.

EXCEPTION 2: For secondary systems below 1000 V, applicable work rules required by this part and engineering controls shall be utilized to limit exposure. In lieu of performing an arc-flash hazard analysis, clothing or a clothing system with a minimum effective arc rating of 4 cal/cm^2 shall be required to limit the likelihood of ignition.

2.2 History of Work and Theoretical Foundations

Prior to 1982 it was assumed that electric shock was the major risk associated with live electrical work [4]. In 1982, Ralph Lee published a paper, *The Other Electrical Hazard, Electric Arc Blast Burns*, where he describes the thermal event associated with an electric arc and its effect on the human body. In this paper he defines the 1.2 cal/cm^2 “curable burn level” that is still used today and the calculations to determine the curable burn distance for an arc in air. Lee’s paper is considered by many people as the first research assessing the hazards associated with arc flashes. In 1987 Lee published a second paper regarding arc-flash hazards, *Pressures Developed from Arcs*. In this paper he describes the sound and pressure effects of an arc in air.

He also provides charts to determine the pressure wave forces at distances from an arc based on the fault level [5]. In 1990, the threat of an arc flash was well-established, and OSHA updated 29 CFR-1910 Subpart S to recognize the need for arc-flash safety [4].

Two other papers have been published that look at the energies in arcing faults. The first published in 1997, *Testing Update on Protective Clothing and Equipment for Electric Arc Exposure*, uses empirical test data to determine the incident energy at distances from a low voltage arcing fault. This was the first paper to address the directional effect of an arc in an enclosure. The second paper published in 2000, *Predicting Incident Energy to Better Manage the Electric Arc Hazard on 600-V Power Distribution Systems*, provided equations to determine incident energy based on the fault level, working distance and the clearing time for arcs in air and in an enclosure on a 600 volt system

$$E_{MA} = 5271 * D_A^{-19593} * t_A * [0.0016 * F^2 - 0.0076 * F + 0.8939] \quad (2.1)$$

$$E_{MB} = 1038.7 * D_B^{-1.4738} * t_A * [0.0093 * F^2 - 0.3453 * F + 5.9675] \quad (2.2)$$

where

E_{MA} = incident Energy (cal/cm^2) for an arc in open air

E_{MB} = incident Energy (cal/cm^2) for an arc in a box (20 in. maximum)

D_A, D_B = distance from the arc in inches

F = bolted Fault Current (kA)

t_A = time of arc exposure (seconds)

(2.1) and (2.2) were developed based on test data collected from three-phase arc tests conducted in testing laboratories. These tests were conducted under specific conditions in order to collect different incident energy levels. Curve fit equations were then applied to the data to allow the incident energy of the system to be predicted. As can be seen in the equations, the simple form of energy at a given distance, I^2t/d^3, isn't clearly evident. By examining the equations closely each component of the simple energy equation can be seen, even if they aren't in the exact same form. This is due to the empirical equations taking into consideration the electrode spacing, whether the arc is in a box or air and other variables not addressed in the simple energy equation.

The work expressed in this paper was used in the formation of the 2000 edition of NFPA-70E *Standard for Electrical Safety Requirements for Employee Workplaces* in developing safe work practices in regards to arc-flash hazards. The only limitation was that the equations were only good for low voltage applications. The work also formed a basis for future research that resulted in the publication of IEEE Std. 1584-2002, *IEEE Guide for Performing Arc-Flash Hazard Calculations* [5]. The same year that the standard was introduced, the first requirement for arc-flash warning labels appeared in the 2002 version of the National Electric Code (NEC) [4]. Equations developed in the IEEE standard will be addressed in the Chapter 3.

2.3 Behavior of Arcs

By flashover or from the introduction of some conductive material, an arc is the flow of current through a path consisting of the vapor of the terminal material. This vapor has substantially higher resistance than the solid metal, to the extent that voltage drop in the arc ranges between 75 and 100 V/in, several thousand times its drop in a solid conductor. Since the inductance of the arc is not appreciably different from that of a solid conductor of the same length, the arc current is substantially resistive in nature. Voltage drop in a faulted large solid or stranded conductor is about 0.5 to 1 V/ft.

For low voltage circuits, the arc, at 75 to 100 V/in length, consumes a substantial portion of the available voltage, leaving only the difference between source voltage and arc voltage to force the fault current through the total system impedance, including that of the arc. This is the reason for the stabilization of arc current on 277/480 volt circuits when the arc length is of the order of 4 inches.

For higher voltages, the arc lengths can be substantially greater, say 1 inch per 100 V of supply, before the system impedance starts to regulate or limit the fault current. The arc voltage drop and the source voltage drop add in quadrature, the former resistive, and the latter substantially reactive. Thus, the length, or size, of arcs in the higher voltage systems can be greater, so they can readily bridge the gap from energized parts to ground or other polarities with little drop in fault current.

In a bolted fault, there is no arc, so little heat will be generated there. Should there be appreciable resistance at the fault point, temperature there could rise to the melting and boiling points of metal and an arc would be started. The longer the arc becomes, the greater the amount of available system voltage will be consumed in it, so the voltage will be available to overcome the supply impedance and the total current will decrease. This is shown in Figure 2.2 [6].

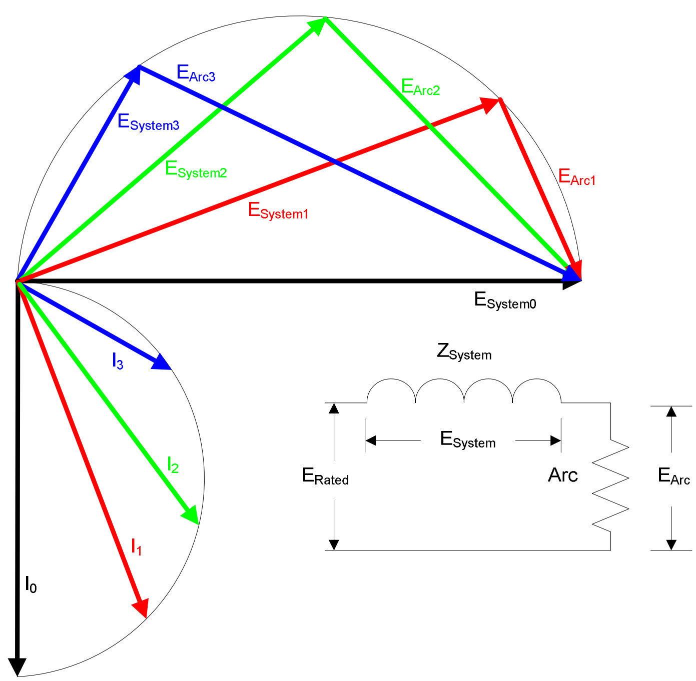

Figure 2.1: Vector diagram of arc drop as arc length is varied

The system has rated voltage E_{Rated} and total impedance to the fault of Z_{System}. Four arc conditions are shown, one of zero length (bolted fault), one of short length (subscript 1), one of moderate length (subscript 2) and one of greater length (subscript 3). Since the arc impedance is almost purely resistive and that of the supply system almost purely inductive, the voltage drop across arc and supply system are out of phase by 90^o for all arc lengths. The locus of the intersection of the vectors of supply voltage drop (E_{System}) and arc voltage drop (E_{Arc}) is a semicircle with diameter of $E_{System0}$, the supply system drop for a bolted fault, also equal to E_{Rated}. For this range of arc lengths, the total current is represented by current vectors I_0, I_1, I_2, and I_3, all at right angles to the corresponding E_{System}. The magnitude of vectors I are proportional to that of the E_{System} vectors, since they are related by the constant Z_{System}, ($I=E_{System} / Z_{Sytem}$).

The total energy in the arc then is the product of E_{Arc} and I. This is zero for the bolted fault, appreciable for condition 1, very substantial for subscript 2, then decreasing for condition subscript 3, where the arc voltage increases only moderately while the current decreases substantially. Also, somewhere in the region of subscript 2 to subscript 3, the length of the arc may become so long that the arc is self-extinguishing or at least self-stabilizing at a low current level. This would be the condition in burndown of 480/277 V buses with wide spacing, where the arc current stabilizes about 1500 A for 4 inch spacing at 277 V.

It has been found that condition 2, where the arc voltage drop equals the supply system drop, yields the maximum arc wattage condition. Here, the arc voltage drop is 70.7 percent of the supply voltage and the current is 70.7 percent of the bolted fault level. These are in phase, so the product is pure power, even though the system power factor is 45^o lagging at the time, due to the supply system impedance of 0 power factor. Under these conditions the maximum arc wattage is 0.707^2 or 0.5 times the maximum kVA bolted fault capability of the system at that point [6].

Chapter 3: Arc-Flash Calculation Methods

In this chapter, the standards applicable to an arc-flash analysis will be discussed both in the theoretical explanation and how the equations developed to determine incident energy levels are implemented in software packages to be used on large scales on a full power system. Also the benchmarking of the software package used in this project will be discussed.

3.1 Applicable Standards

There are a couple different methods proposed to conduct an arc-flash analysis. The two methods addressed and examined with this project are IEEE Std. 1584-2002, *Guide for Performing Arc-Flash Hazard Calculations* and NESC C2-2007. Each of these will be discussed in detail in this chapter.

When using the IEEE equations to determine the incident energy of a specific point in a system, such as at a bus or switchgear, the equations look and seem overwhelming because of the many variables used which also vary based on the voltage of the system. Along with the many variables there are a few steps that need to be followed in order to calculate the incident energy. These steps are shown below along with the equations needed in each. It should be noted that these equations are not valid for single phase or dc systems. These models are based on measured arc current incident energy under a specific set of test conditions and on theoretical work. These models will enable users to calculate the estimated maximum incident energy and the estimated arc-flash boundary distance. Real arc exposures may be more or less severe than indicated by these models.

The first step that needs to be conducted is to determine the bolted fault current at the point in the system that is being analyzed. The three phase fault current at the location is needed for these calculations. The next step is to determine the voltage level at the point of interest. Voltage levels are broken up into two different categories, less than 1 kV and 1 to 15 kV, and based on these ranges different equations are used to calculate the arcing current. For voltages less than 1 kV (3.1) is used and for voltages from 1 kV to 15 kV (3.2) is used. Both equations are shown below along with what each of the variables represent. The equation for voltages greater than 15 kV will be discussed later.

3.2 Emperical Equations

For applications with a system voltage less than or equal to 1 kV,

$$l_g I_a = K + 0.662 * l_g I_F + 0.0966 * V + 0.000526 * G + 0.558 * V * (l_g I_F) - 0.00304 * G * (l_g I_F) \quad (3.1)$$

For applications with a system voltage of 1 to 15 kV,

$$l_g I_a = 0.00402 + 0.983 * l_g I_F \quad (3.2)$$

where

l_g = log10

I_a = arcing current (kA)

K = -0.153 for open configurations (no enclosure) and -0.097 for box configurations (enclosed equipment)

I_F = bolted fault current for three-phase faults (symmetrical RMS) (kA)

V = system voltages (kV)

G = gap between conductors (mm)

Table 3-1 provides a list of equipment for the different voltage classes, the typical gap between conductors of that equipment and a distance factor that will be used in later equations.

Table 3.1: Factors for equipment and voltage class

System voltage (kV)	Equipment type	Typical gap between conductors (mm)	Distance X factor
0.208-1	Open air	10-40	2.000
	Switchgear	32	1.473
	MCC and panels	25	1.641
	Cable	13	2.000
greater than 1 to 5	Open air	102	2.000
	Switchgear	13-102	0.973
	Cable	13	2.000
greater than 5 to 15	Open air	13-153	2.000
	Switchgear	153	0.973
	Cable	13	2.000

By raising 10 to the power of $l_g I_a$ in (3.3),

$$I_a = 10^{l_g I_a} \tag{3.3}$$

arcing current is determined and can be used in following equations for the incident energy. The next step in the analysis is to calculate the incident energy based on data normalized for an arc of 0.2 seconds and distance from the possible arc point to the person of 610 mm. (3.4) is used in the calculation for both voltage ranges of less than or equal to 1 kV and 1 to 15 kV

$$l_g E_n = K_1 + K_2 + 1.081 * l_g I_a + 0.0011 * G \tag{3.4}$$

where

E_n = incident energy (J/cm^2) normalized for time and distance

K_1 = -0.792 for open configurations (no enclosure) and -0.555 for box configurations (enclosed equipment)

K_2 = 0 for ungrounded and high-resistance grounded systems and -0.113 for grounded systems

G = gap between conductors (mm) (Table 3.1)

By raising 10 to the power of l_gE_n in (3.5), incident energy can be used in (3.6) to convert from the normalized state.

$$E_a = 10^{l_g E_n} \tag{3.5}$$

After calculating the normalized incident energy, it must be converted to cal/cm^2 at the specific working distance and with the devices clearing time. (3.6) is used in the conversion

$$E = 4.184 * C_f * E_a * \left(\frac{t}{0.2}\right) * \left(\frac{610^X}{D^X}\right) * 0.24 \tag{3.6}$$

where

E	=	incident energy (cal/cm^2)
C_f	=	calculation factor
E_a	=	normalized incident energy
t	=	arcing time (seconds)
D	=	working distance (mm)
X	=	distance exponent (Table 3.1)
0.24	=	conversion factor

These equations are valid for voltages up to 15 kV and arc gaps between 10 and 153 mm. Equations associated with equipment up to 15 kV are based on the lab testing and data used to develop (2.1) and (2.2) and are applied in the IEEE Std. 1584-2002.

When the voltages are greater than 15 kV or the arc gap is outside of the range, a theoretical equation, called the Lee Equation, is used as shown in (3.7) were the arc current is considered to be equal to the bolted fault current. This equation is also applied in the IEEE Std. 1584-2002.

$$E = 2.142 * 10^6 * V * I_a * \left(\frac{t}{D^2}\right) * 0.24 \quad (3.7)$$

where

E = incident energy (cal/cm^2)

V = system voltage (kV)

t = arcing time (seconds)

D = working distance (mm)

I_a = bolted fault current (kA)

The next step in the calculations is to determine the flash protection boundary. This is an approach distance at which a worker will receive a second-degree burn if an arc flash would occur; this is the level of 1.2 cal/cm^2. (3.8) provides the equation to determine this distance

$$D_b = \left[4.184 * C_f * E_a * \left(\frac{t}{0.2}\right) * \left(\frac{610^X}{E_b}\right)\right]^{\frac{1}{X}} \quad (3.8)$$

where

D_b = distance of flash protection boundary from arc (mm)

C_f = calculation factor of 1.5 for voltages less than or equal to 1 kV

E_a = normalized incident energy

E_b = incident energy in J/cm^2 at the flash protection boundary: typically 5 J/cm^2 which is equal to 1.2 cal/cm^2

t = arcing time (seconds)

X = distance exponent

610 = normalized distance of 24 inches converted to millimeters

0.2 = normalized 0.2 second clearing time

(3.8) is based on the current being interrupted by a non-current limiting device. Additional equations are needed if these devices are present.

3.3 National Electrical Safety Code Look-up Tables

The NESC provides look-up tables beginning with the NESC-2007 version of the code. These tables provide arc-flash potentials which can be used instead of performing an arc-flash hazard analysis and provide effective arc rating of clothing or a clothing system to be worn at voltages 1000 V and above. Table 3.2 provides the level of PPE required based on the fault current and the maximum clearing time of the fault for equipment with voltages from 1 to 46 kV.

Table 3.2: PPE required given equipment voltage, fault current and clearing time

Phase-to-phase voltage (kV)	Fault current (kA)	4-cal System Maximum clearing times in cycles (seconds)	8-cal System Maximum clearing times in cycles (seconds)	12-cal System Maximum clearing times in cycles (seconds)
1 to 15	5	46.5 (.775)	93 (1.55)	139.5 (2.325)
	10	18 (.3)	36.1 (.6017)	54.1 (.9017)
	15	10 (.1667)	20.1 (.335)	30.1 (.5017)
	20	6.5 (.1083)	13 (.2167)	19.5 (.325)
15.1 to 25	5	27.6 (.46)	55.2 (.92)	82.8 (1.38)
	10	11.4 (.19)	22.7 (.3783)	34.1 (.5683)
	15	6.6 (.11)	13.2 (.22)	19.8 (.33)
	20	4.4 (.0733)	8.8 (.1467)	13.2 (.22)
25.1 to 36	5	20.9 (.3483)	41.7 (.695)	62.6 (1.0433)
	10	8.8 (.1467)	17.6 (.2933)	26.5 (.4417)
	15	5.2 (.0867)	10.4 (.1733)	15.7 (.2617)
	20	3.5 (.0583)	7.1 (.1183)	10.6 (.1766)
36.1 to 46	5	16.2 (.27)	32.4 (.54)	48.6 (.81)
	10	7 (.1167)	13.9 (.2317)	20.9 (.3483)
	15	4.3 (0717)	8.5 (.1417)	12.8 (.2133)
	20	3 (.05)	6.1 (.1017)	9.1 (.1517)

This table was built using a commercially available computer software program, not specifically listed in the NESC documentation. Also this table is based on an open air phase-to-ground arc and is not intended to be used for phase-to-phase arcs or enclosed arcs. Assumptions of a 15 inch separation from the arc to the employee and arc gaps of 2 inches for 1 to 15 kV, 4 inches for 15.1 to 25 kV, 6 inches for 25.1 to 36 kV and 9 inches for 36.1 to 46 kV based on the IEEE Standard 4-1995 [3].

Table 3.3 provides the same information except for voltages from 46.1 to 800 kV was also developed using a computer software program and has its own list of assumptions. First, the air gap was calculated by using the phase-to-ground voltage and dividing by 10; this represents the dielectric strength of air at 10 kV per inch. Second, the distance from the arc was calculated by using the minimum approach distance from Table 441-2 in the NESC-2007 and subtracting two times the assumed arc gap length.

Table 3.3: Live-line tool work PPE required given equipment voltage, fault current and clearing time

Phase-to-phase voltage (kV)	Fault current (kA)	4-cal System Maximum clearing times in cycles (seconds)	8-cal System Maximum clearing times in cycles (seconds)	12-cal System Maximum clearing times in cycles (seconds)
46.1 to 72.5	20	8.5 (.1417)	17 (.2833)	25.5 (.425)
	30	5.3 (.0883)	10.5 (.175)	15.8 (.2633)
	40	3.7 (.0617)	7.3 (.1217)	11 (.1833)
	50	2.8 (.0467)	5.5 0917)	8.3 (.1383)
72.6 to 121	20	8.2 (.1367)	16.5 (.275)	24.7 (.4117)
	30	4.7 (.0783)	9.4 (.1567)	14.1 (.235)
	40	3.1 (.0517)	6.2 (.1033)	9.3 (.155)
	50	2.2 (.0367)	4.4 (.0733)	6.6 (.11)
138 to 145	20	9.8 (.1633)	19.5 (.325)	29.3 (.4883)
	30	5.6 (.0933)	11.2 (.1867)	16.8 (.28)
	40	3.7 (.0617)	7.4 (.1233)	11.1 (.185)
	50	2.6 (.0433)	5.3 (.0883)	7.9 (.1317)
161 to 169	20	9.3 (.155)	18.6 (.31)	27.9 (.465)
	30	5.7 (.095)	11.5 (.1917)	17.2 (.2867)
	40	4 (.0667)	8 (.1333)	12 (.2)
	50	3 (.05)	6 (.1)	9 (.15)
230 to 242	20	10.4 (.1733)	20.9 (.3483)	31.3 (.5217)
	30	6.4 (.1067)	12.9 (.215)	19.3 (.3217)
	40	4.5 (.075)	9 (.15)	13.5 (.225)
	50	3.4 (.0567)	6.8 (.1133)	10.1 (.1683)
345 to 362	20	22.6 (.3767)	45.3 (.755)	67.9 (1.1317)
	30	14 (.2333)	28.1 (.4683)	42.1 (.7017)
	40	9.8 (.1633)	19.6 (.3267)	29.4 (.49)
	50	7.4 (.1233)	14.7 (.245)	22.1 (.3683)
500 to 550	20	18.9 (.315)	37.8 (.63)	56.7 (.945)
	30	11.7 (.195)	23.3 (.3883)	35 (.5833)
	40	8.1 (.135)	16.3 (.2717)	24.4 (.4067)
	50	6.1 (.1017)	12.2 (.2033)	18.3 (.305)
765 to 800	20	43.6 (.7267)	87.3 (1.455)	130.9 (2.182)
	30	27 (.45)	53.9 (.8983)	80.9 (1.3483)
	40	18.9 (.315)	37.8 (.63)	56.7 (.945)
	50	14.2 (.2367)	28.4 (.4733)	42.6 (.71)

3.4 ASPEN® Software

ASPEN OneLiner™ was used for this project due to the fact that MP's relay engineers use this product for their short circuit and relay coordination on the power system and is a highly recognized product in the power industry; OneLiner has a 46% market share according to an independent survey conducted in 2009. Figure 3.1 is a screen shot of an example one line system in ASPEN® selecting a position to run the arc-flash calculator. Figure 3.2 shows the user interface for the arc-flash calculator after it has been selected.

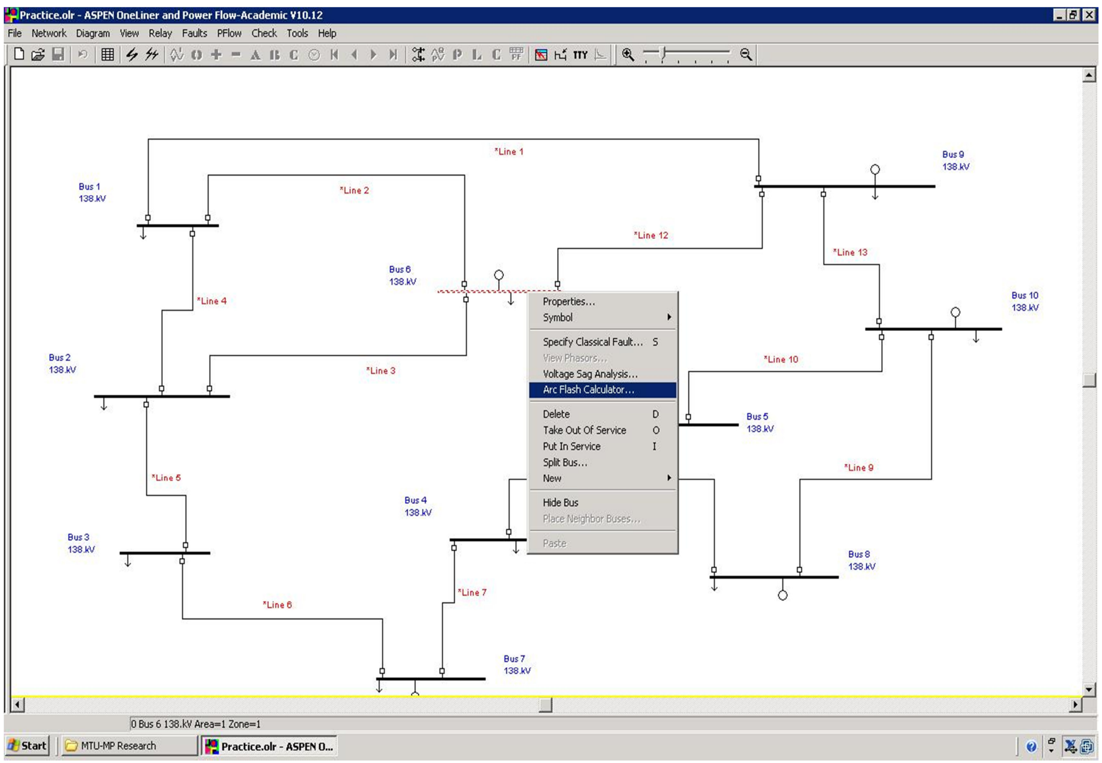

Figure 3.1: ASPEN® with bus selected to run arc-flash calculator

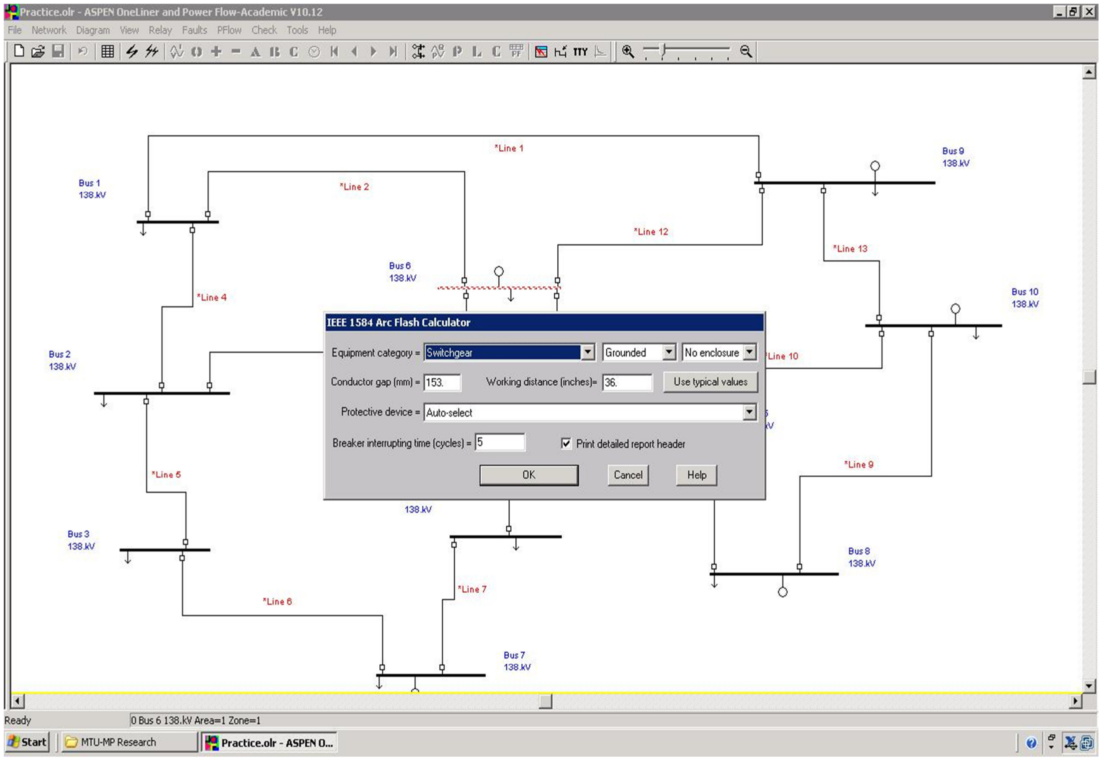

Figure 3.2: ASPEN® arc-flash calculator displayed

Prior to the kick-off of this project ASPEN® had just released their arc-flash calculator which allowed users to carry out the calculation on one equipment location on the system at a time. Figure 3.3 is a zoomed in view of the dialog box user interface with the calculator to enter options about the location of the equipment analyzed. The calculator uses IEEE Std. 1584-2002 equations, explained above in section 3.2, to calculate arcing current and the incident energy level at both 100% and 85% of the fault current. The calculation results are output to the TTY window.

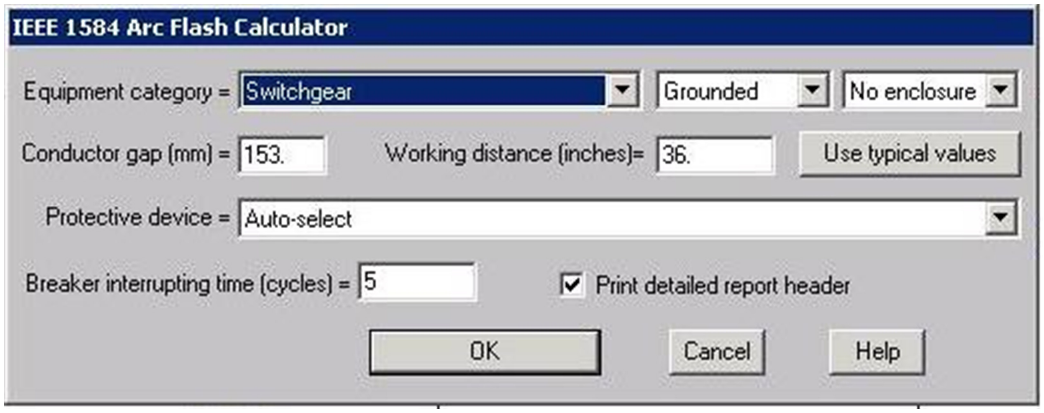

Figure 3.3: ASPEN® arc-flash hazard calculator user interface

3.4.1 Software Benchmarking

Since the calculator was released just prior to the project implementation, some benchmarking was recommended to test that the calculator was performing correctly and also to provide some practice in using the interface and reading the results in the TTY window.

Since the ASPEN® calculator uses IEEE Std. 1584-2002 equations, two different offline tools were developed to validate the calculator. The first tool built was an Excel spreadsheet, shown in Appendix B, including the IEEE Std. 1584-2002 equations allowing the user to input values from the ASPEN® calculator and solve for the arc current, normalized incident energy and incident energy. This tool proved to work well but it was quickly realized that the screen space needed to enter inputs, determine which set of equations to use based on voltage and view outputs was rather large.

The second tool built followed the same idea as the Excel spreadsheet but instead was implemented in MATLAB. The user interface and code are shown below in Appendix B. The user interface was greatly reduced and it reduced the chance of the user entering data into the incorrect cell. After the MATLAB calculator was built the equations in the code were verified against hand calculations of the IEEE Std. 1584-2002 equations.

After the verification of the MATLAB calculator was completed the ASPEN® calculator was tested against the MATLAB calculator based on the test system shown below in Appendix C.

During in-house benchmarking at the university, the ASPEN® calculator performed correctly but it wasn't until the actual MP arc-flash analysis was underway that three software bugs were discovered. The first of these bugs was that reclosers were not recognized as protective devices. This was discovered when clearing times reported were much longer than anticipated based on protective data entered into the power flow model. This bug required a revision to the software code to include these protective devices.

The second bug was the break point for level 2 of incident energy at the equipment location. The IEEE standard has the break point at 4 cal/cm^2 while the calculator uses 5 cal/cm^2 based on the NFPA 70E-2000.

The third and final bug found was the calculation of the incident energy using 85% of the arcing current. To ensure the worst case incident energy level is calculated, the ASPEN® calculator also takes 85% of the arcing current and runs it through the equations. This was discovered when the voltage level of the system was below 15 kV. Using these equations, the full short circuit level was being applied when in fact only 85% of the fault current was to be entered. This was not an issue when the voltage was above 15 kV since only the short circuit current is used to determine the incident energy.

All these issues were brought to ASPEN®'s attention with ASPEN® providing resolution in updated Oneliner.exe files to replace current files on the computers being used to conduct the arc-flash analysis.

Chapter 4: Issues of Concern

In this chapter, two areas of concern will be discussed, both of which are main factors affecting the incident energy of an arc flash. The first of these concerns is the type of fault used to conduct an arc-flash analysis. Assumptions of the fault may or may not be correct based on the equipment or location of the fault analyzed. Second, the amount of energy exposure personnel could be exposed could potentially differ based on assumptions of the protective equipment used to clear faults. Each of these points is addressed below.

4.1 Faults

During all the research for and implementation of an arc-flash analysis it was determined that there is some discontinuity for the type of fault to be used on different type of equipment. If we look at typical power system there is a correlation to the type of fault personnel could be exposed to depending on the equipment they may be working on. Out in a switch yard working on a 345 kV gang operated disconnect switch, a three phase fault is rarely heard of. On the other hand, a three phase fault inside of some switch gear in a motor control panel is very plausible.

If you look at the IEEE standard a three phase fault current is used based on any voltage level or type of equipment at the point where the analysis is being conducted. For voltage levels up to 15 kV this is justifiable because those equations are based on three phase fault lab test results. With the equation for voltage levels greater than 15 kV it is assumed the fault is a three phase fault. But if you look at Table 3-2 shown above, which is provided by the NESC gives a quick reference look-up table for arc-flash values, a phase to ground fault is used to develop the table. Looking at Table 3-3, NESC doesn't state the type of fault used to develop the table.

An example of this discontinuity can be seen on the test system used to benchmark the ASPEN® software in Figure 4.1.

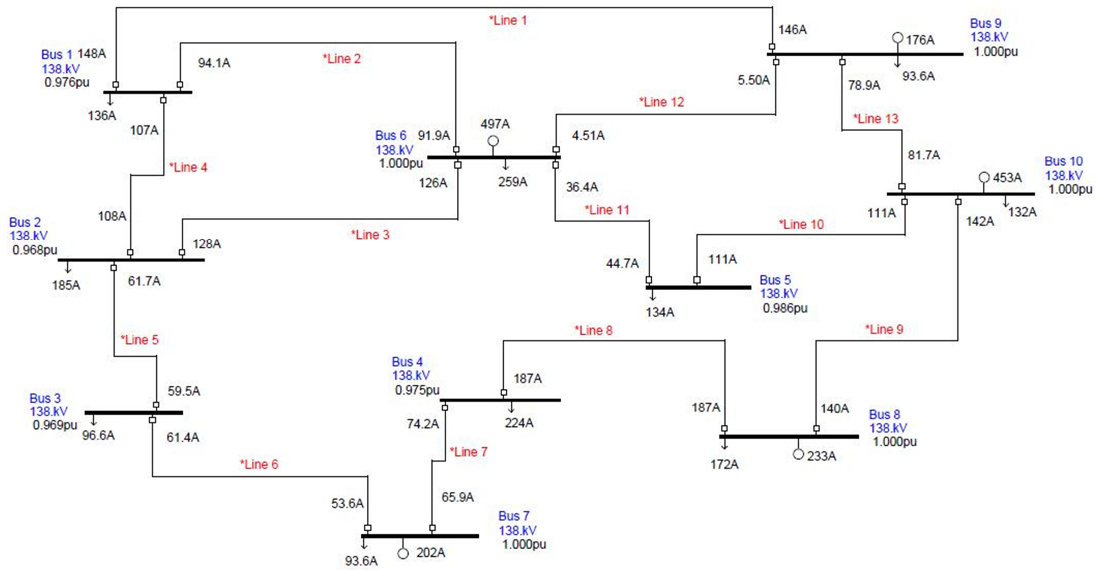

Figure 4.1: Example system oneline diagram

If we look at the 138 kV bus, Bus 1, in ASPEN®, the three phase fault current is 4.228 kA with a clearing time of 0.11 seconds. These values result in a requirement of PPE level 3. If the NESC table is used, which doesn't state what type of fault to be used, and use the three phase fault current and clearing time from ASPEN®, the table doesn't provide a reference meaning the level is below the minimum 4 calorie system typical substation personnel wear to conduct minor activities, such as a walk around visual inspection.

When it comes to personnel safety, requiring individuals to wear PPE levels 3 and 4 when it isn't required may cause other safety hazards while they perform their assigned tasks. Also, it may cost the company undue expenses in purchasing PPE equipment not really required.

4.2 Energy Exposure

When the potential level of incident energy is at or above 40 cal/cm^2, the IEEE Std. 1584-2002 says that work cannot be conducted on the energized equipment. Equipment may never be serviced under this requirement and could fail causing further issues on the system.

The amount of incident energy personnel may become subject to can vary based on two specific variables; the time duration of the fault and the voltage level of the equipment subject to the fault. This chapter will discuss how each of these specific variables affects the potential incident energy.

4.2.1 50/51 Application

The application of a 50/51 relay on a bus or line for fault protection uses either an instantaneous trip, the 50 contact, or a time delayed trip based on a relay curve, the 51 contact. Either application is acceptable but choosing one over the other can greatly affect your level of arc-flash hazard present at the fault location. In Appendix E.1, a test system has been built to emphasize this point. In System 1, initially the 51 contact is used to protect both lines of the system. Under this configuration, Bus 2 has an arc-flash category level 2 of 5.5 cal/cm^2 and Bus 3 has an arc-flash category level 0 of 1.01 cal/cm^2. By using the 50 contact, which will reduce the total clearing time to essentially the time needed to operate the breaker, reduces the Bus 2 and 3 arc-flash categories 0 and 0, 0.88 and 0.62 cal/cm^2 respectively. The full details of the four different results can be seen in Appendix E.2 and E.3.

4.2.2 Discontinuity Due to Voltage Levels

The second variable to be evaluated is the voltage level of the equipment. As mentioned earlier in section 3.2, 1 kV is a break point for which equation to use in calculating the arcing current and 15 kV is a break point at which empirical equations are not to be used in analysis but instead the Lee equation. On a typical transmission or distribution system, voltages can range from 0.95 to 1.05 per unit on an intact system. For a 1 kV system the voltage could run between 0.95 to 1.05 kV and for a 15 kV system the voltage range could run between 14.25 and 15.75 kV. This results in two different set of equations to be considered when evaluating one piece of equipment. If the incorrect equation is used, lower levels of incident energy may be calculated in turn causing lower levels of PPE worn by the employee which may not properly protect the individual for an arc-flash incident.

An evaluation of this condition was studied on the same test system used for the 50/51 contact evaluation. One system was set to a system voltage of 14.9 kV and the second system was set to a voltage level of 15.1 kV displayed in Figure 4.2. The same condition was applied to a 1 kV system except the low level was set to 0.9 kV and the high to 1.1 kV.

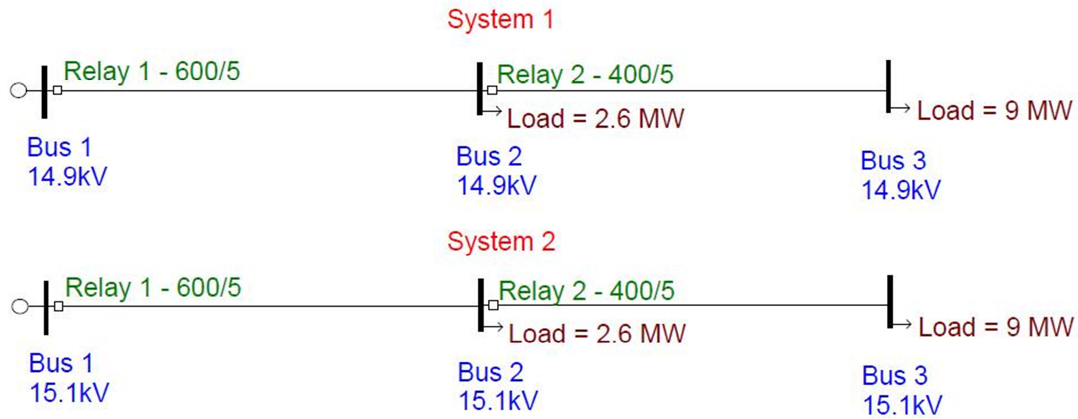

Figure 4.2: Voltage level test systems

This allows both sets of arc-flash equations to be tested with only a 200 volt difference between the two systems. In the field this could easily be found by placing a distribution capacitor into service to boost service voltages or if the employee is working on the piece of equipment under a lighter load timeframe.

As shown in the simulations on the 1 kV system and only using the equation for equipment below 1kV, the incident energy at bus 3 increases exponentially as the voltage increases. This can be seen below in Figure 4.3.

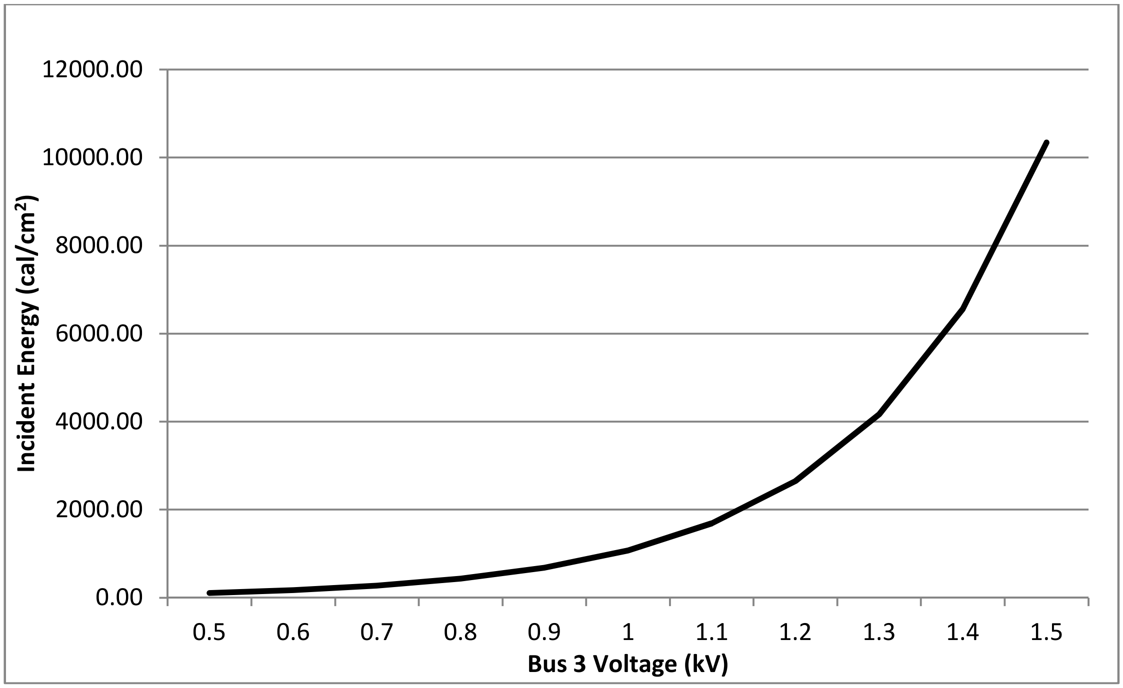

Figure 4.3: Incident energy based on empirical equation for equipment less than 1 kV

The opposite trend is found when only using the equation for equipment above 1 kV and less than 15 kV. This can be seen below in Figure 4.4.

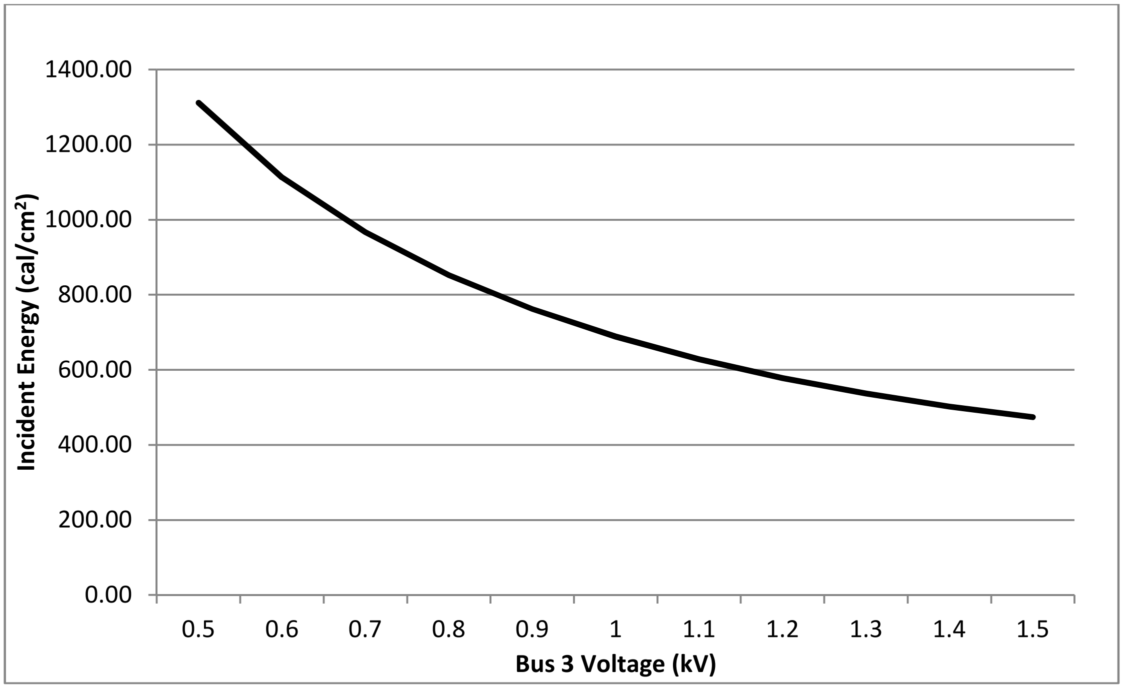

Figure 4.4: Incident energy using equation for equipment above 1 kV and less than 15 kV

Figure 4.5 is a plot of the incident energy using the equation required based on the bus voltage. As it shows, the incident energy increases as the voltage increases until it reaches 1 kV. At this point, the equation for equipment above 1 kV and less than 15 kV takes over and we see a slight increase in incident energy up to 1.1 kV and then the incident energy decreases. The discontinuity can be associated to two factors.

First, in the equation for equipment less than 1 kV, (3.1) above, uses the conductor gap to calculate the arcing current. This full value isn't applied to the equation but a fraction of it is, increasing the log of the arcing current available. This gap isn't applied in the equation for equipment greater than 1 kV and less than 15 kV, (3.2) above.

Second, in equation (3.1), the equipment voltage is used to calculate the arcing current. When the voltage is less than 1 kV, this applies a fraction of the log of the arcing current. When the log of the arcing current is then applied to find the normalized incident energy, the normalized incident energy is also reduced. Once the voltage is greater than 1 kV, the log of the arcing currents starts to decrease causing the decrease in incident energy. An example of this can be seen using the values from the test system. When the voltage is at 900 volts, the l_gI_a is equal to 3.55 kA when using equation (3.1) and 3.76 kA when using equation (3.2). When the voltage is at 1.1 kV, the l_gI_a is equal to 3.92 kA when using equation (3.1) and 3.68 kA when using equation (3.2). If the voltage was to be applied in the equation (3.1), there would be a multiplying factor anywhere from 1.1 to 15 times and the incident energy would continue to increase.

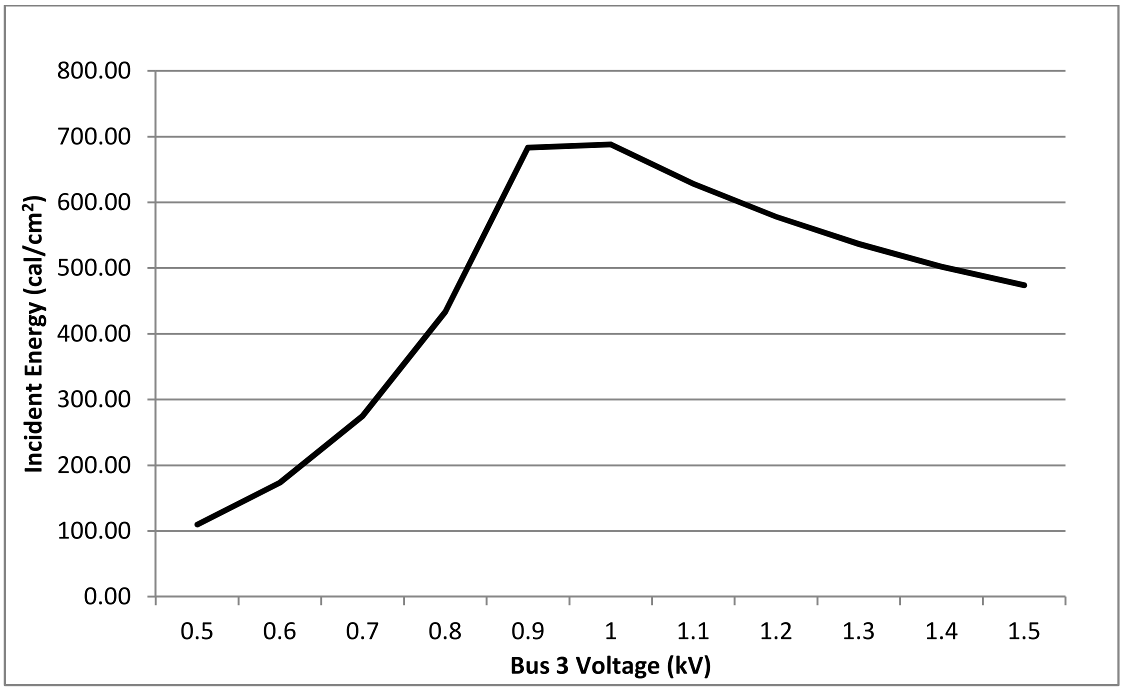

Figure 4.5: Incident energy based on given bus voltage

As shown in the simulation, the incident energy of both buses in the 15.1 kV system increased to levels well above the level found in the 14.9 kV system. For bus 2 the incident energy increased from 5.5 to 130.16 cal/cm^2 and bus 3 increased from 1.0 to 25.01 cal/cm^2. Figure 4.6 is a plot of the bus 3 incident energy against the bus 3 voltage using the derived equations only based off of lab testing. We see that as the voltage increases the incident energy increases linearly.

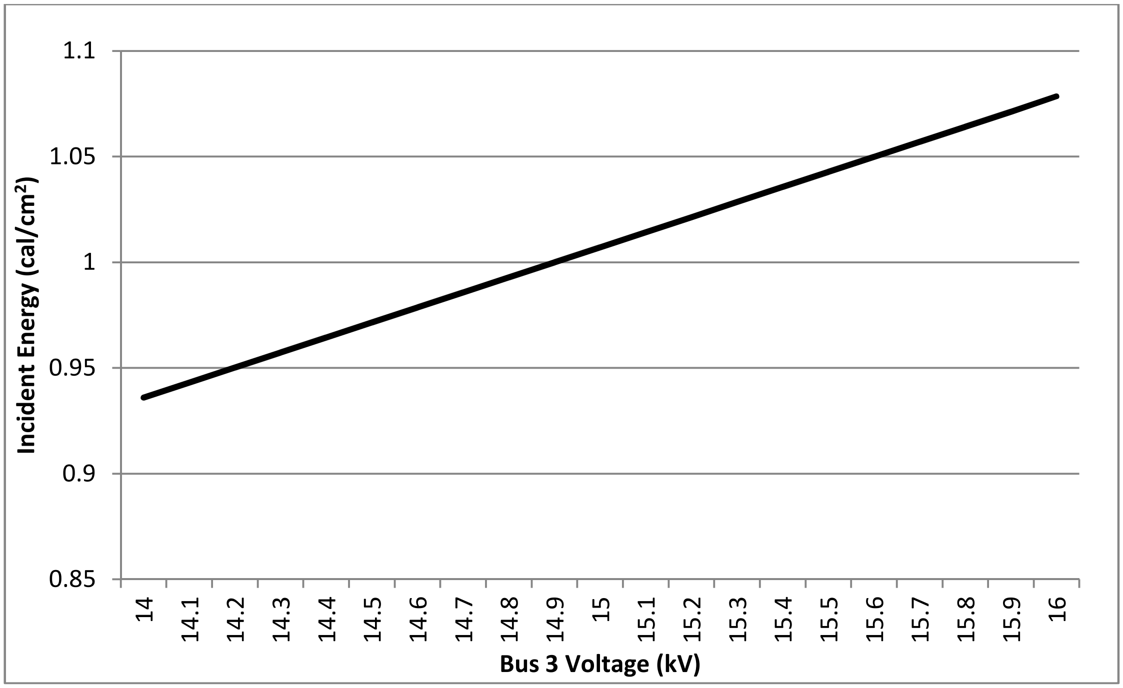

Figure 4.6: Incident energy based on empirical equations only

Figure 4.7 is a plot of the bus 3 incident energy against the bus 3 voltage using the Lee equation only. Again we see the incident energy increase linearly as the bus voltage increases.

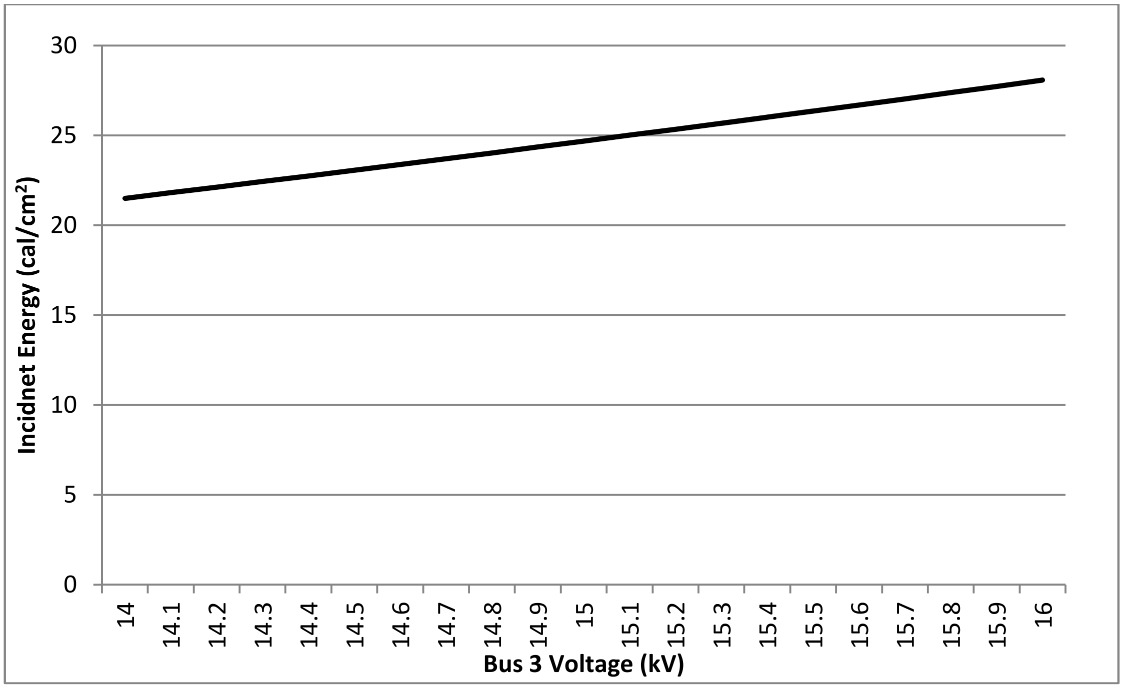

Figure 4.7: Incident energy based on Lee equation only

Figure 4.8 is a plot of the incident energy using the equation required based on the bus voltage. As it shows, at the 15 kV voltage level, the incident energy makes a significant jump from around 1 cal/cm^2 up to above 24 cal/cm^2. This is due to the change to using the Lee Equation. It should be noted that the significant change does not occur in a real life application. The equipment under analysis would provide similar incident energy levels whether the voltage was at 14.9 or 15.1 kV. Using the higher incident energy could cause employees to wear over bearing PPE potentially causing more risk during their job duties and require wrong field labels placed on the equipment. Also, if the incident energy levels were high enough that the equipment would need to be de-energized before the employee could perform their job, this could cause jeopardy to the reliability of the system and lost revenue to the company. If lab tests were to be conducted on equipment with voltages greater than 15 kV, the derived equations potentially would continue linearly and not provide the significant jump causing unrealistic incident energy levels. Equipment around the 15 kV level should be examined closely by hand to verify the correct incident energy is being applied to the system.

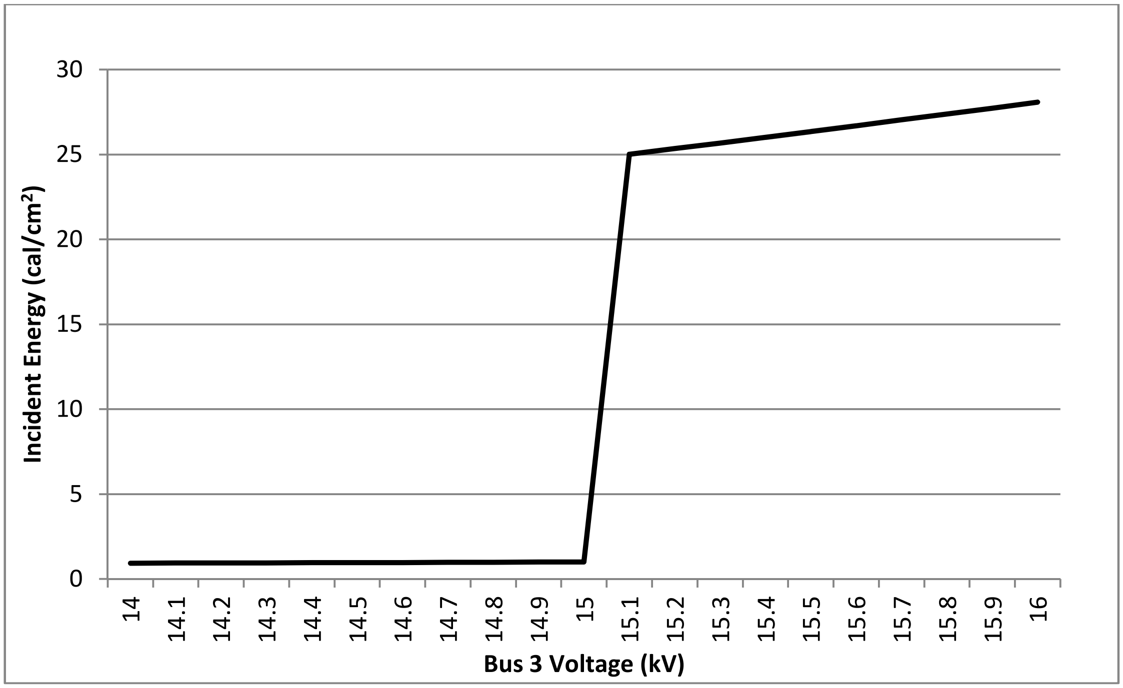

Figure 4.8: Incident energy following given bus voltage

Table 4.1 has the incident energy calculated from the voltage test system based on which set of equations were selected. These values were used to create Figures 4.3, 4.4 and 4.5.

Table 4.2 has the incident energy calculated from the voltage test system based on which set of equations were selected. These values were used to create Figures 4.6, 4.7 and 4.8.

Table 4.1: 1 kV voltage level test system incident energy values

Bus Voltage (kV)	Incident Energy (cal/cm^2)		
	Empirical Equation	Lee Equation	Based on Bus Voltage
0.5	109.89	1311.72	109.89
0.6	173.60	1112.42	173.60
0.7	274.65	966.29	274.65
0.8	433.71	852.72	433.71
0.9	683.28	761.94	683.28
1	1074.61	688.33	688.33
1.1	1688.36	628.00	628.00
1.2	2651.74	578.13	578.13
1.3	4167.63	536.78	536.78
1.4	6558.29	502.31	502.31
1.5	10345.38	473.69	473.69

Table 4.2: 15 kV voltage level test system incident energy values

Bus Voltage (kV)	Incident Energy (cal/cm^2)		
	Empirical Equation	Lee Equation	Based on Bus Voltage
14.0	0.94	21.50	0.94
14.1	0.94	21.81	0.94
14.2	0.95	22.12	0.95
14.3	0.96	22.43	0.96
14.4	0.96	22.75	0.96
14.5	0.97	23.07	0.97
14.6	0.98	23.38	0.98
14.7	0.99	23.70	0.99
14.8	0.99	24.03	0.99
14.9	1.00	24.36	1.00
15.0	1.01	24.68	1.01
15.1	1.01	25.01	25.01
15.2	1.02	25.34	25.34
15.3	1.03	25.68	25.68
15.4	1.04	26.02	26.02
15.5	1.04	26.35	26.35
15.6	1.05	26.69	26.69
15.7	1.06	27.04	27.04
15.8	1.06	27.38	27.38
15.9	1.07	27.73	27.73
16.0	1.08	28.08	28.08

This is especially concerning due to the fact the NESC does not specify at what conditions the analysis is to be conducted; i.e. under light load or peak load conditions.

Special consideration needs to be taken when analyzing systems where the voltage of the equipment can vary between two different sets of equations.

4.3 Linearity of Incident Energy

When comparing the incident energy levels over a range of possible current levels, both load and fault levels, it needs to be mentioned that the incident energy increase linearly and not exponentially. Figure 4.9 shows a standard U.S. U2 inverse time overcurrent curve of tripping times of a relay, either in a mechanical or electrical relay.

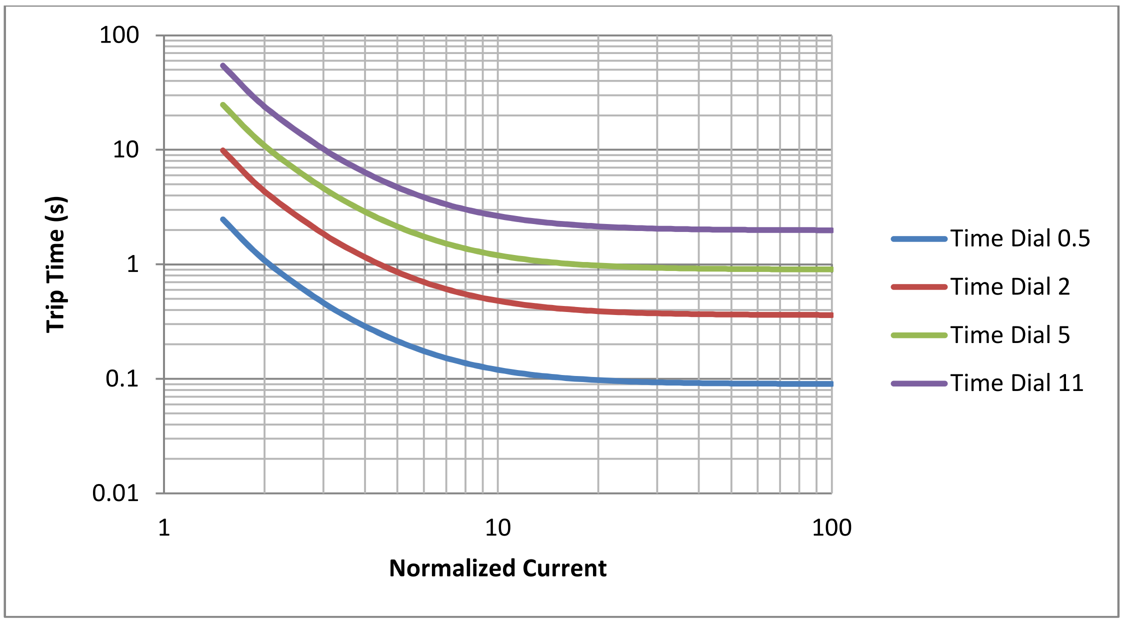

Figure 4.9: U.S. U2 inverse time overcurrent curves

When the overcurrent curves are applied to a piece of equipment and the energy through the equipment is calculated, it can be seen that the energy increases exponentially. Figure 4.10 depicts energy through a 6 inch piece of copper over a range of currents. In the equation for energy, the resistance is held constant; independent of the current. As the current increases the total time the current is applied to the equipment decreases due to the inverse overcurrent curve. Since the current is squared and the value of the current is much larger than any component in the equation, the energy curve becomes exponential.

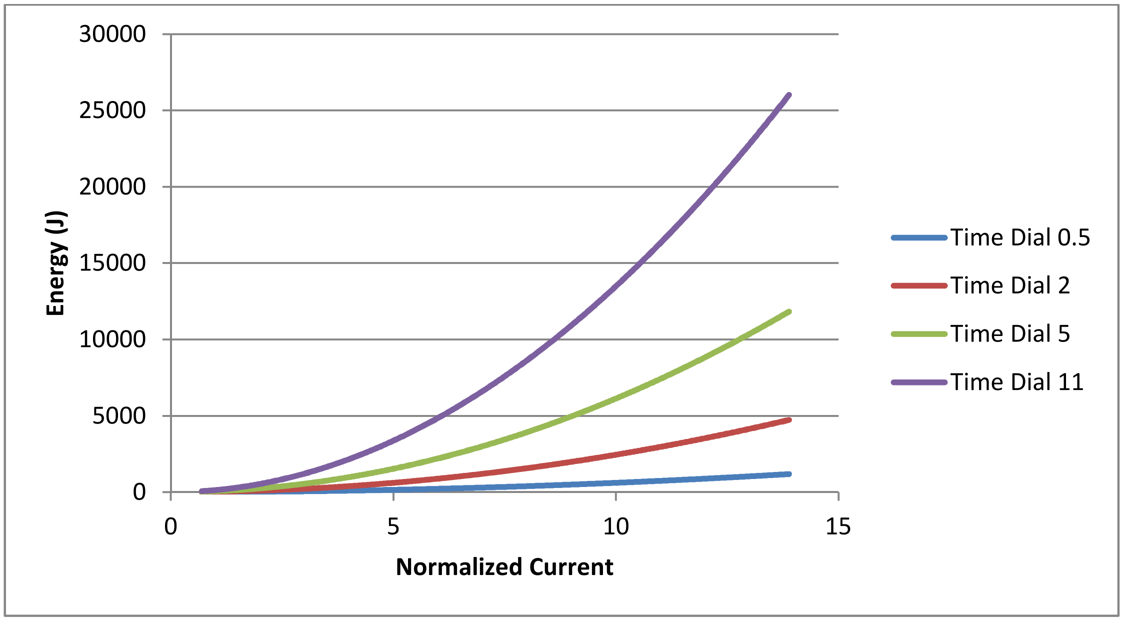

Figure 4.10: Energy through equipment as current increases

Now looking at the plots of the incident energy in Figure 4.11, using the same overcurrent curves and range of currents, the incident energy is linear. This is due to the fact that never in the equation is the current squared.

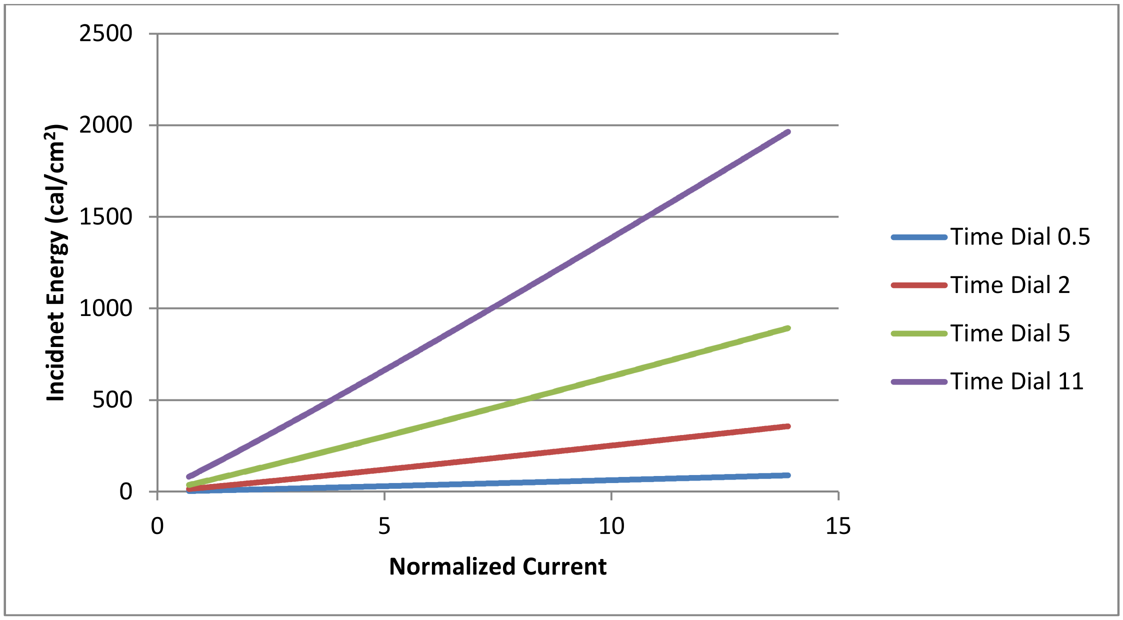

Figure 4.11: Potential incident energy in equipment as current increases

It needs to be noted that the energy calculated is only in Joules and is not directly comparable to cal/cm^2, which is what incident energy is measured in. These plots are shown to depict the discontinuity of the calculated level of energy between the two sets of equations. All data for the three plots in section 4.3 can be found in Appendix F. The parameters and assumptions used to build Figures 4.10 and 4.11 are as follows, the relay was using a 600/5 current transformer, tap setting of 6 amps, normal load current of 700 amps, a piece of wire 6 inches long with a diameter of 0.005 meters resulting in a resistance of 0.0001314 ohms and a system voltage between 1 kV and less than 15 kV.

4.4 Radial Feeders

Radial feeders are common on the distribution system in any utility power system. It's nearly impossible to network all load in the system due to a number of factors; location, cost and need to name a few. When determining the incident energy at the end of a radial feeder, the modeling can be simplified down to the source of the feeder and using the calculated incident energy for the whole feeder.

If we refer to Figure 4.2 were we have two radial feeders connected to the system. In our case the load at bus 2 is 350 amps and bus 3 is 100 amps giving a total current at bus 1 to be 450 amps. Since bus 1 is the closest to the system it will have the highest fault current available with bus 2 being the second largest and bus 3 is the lowest on the feeder. When using inverse time overcurrent curves like those in Figure 4.6 and applying them to the fault currents on each bus down the feeder, we see that the largest incident energy will be at bus 1 and reduces as we move down the feeder towards bus 3 in the same fashion as Figure 4.8 depicts.

If a 50/51 relay was to be used instead of just a 51 relay, then the feeder would have two points where the incident energy would need to be calculated; one at the feeder source and one at the position were the 50 relay would stop operating and the 51 relay would start operating.

Chapter 5: Mitigation Methods and Hazard Reduction

In order to conduct work on energized equipment, several different methods could be implemented to reduce the level of potential incident energy available. The ultimate hazard reduction would be to de-energize the equipment where the work is to take place. Unfortunately, working on energized equipment still needs to occur in the process of de-energizing the equipment requiring the maintenance. Below are different methods to be considered to reduce the arc-flash hazard.

5.1 System Modifications

One method to be evaluated when looking to reduce the incident energy level of an arc flash would be to remove system equipment from service. Removing a line from service, perhaps a parallel line to the location where work is to be conducted could reduce the fault current being supplied to the location. This would in turn reduce the arcing current. A study should be carried out though because lowering the fault current could increase the time needed to initiate the relay trip of the breaker.

Another piece of equipment to be considered is generators. If maintenance can be postponed to coordinate with a scheduled generator outage, this could also reduce fault current on the system. Again special consideration needs to be taken during these system configurations since a lower fault current can increase relay pickup times.

5.2 Relay Application Changes

There are a couple of changes that can be applied to relays before work is conducted to help reduce the level of arc-flash hazard presented to the personnel. The two following sections address each.

5.2.1 50 Application

As proven earlier in section 4.2.1, applying the instantaneous trip application to a piece of equipment can reduce the potential incident energy provided to an employee. With the move from electromechanical relays to microprocessor based relays, applying this technique can be very simple. In many cases the change can be applied by a protection engineer in the home office by remote access. This ensures that the correct relay is changed and the correct settings are applied.

5.2.2 Optical Detectors

In addition to the conditions of an arc flash described above in section 2.1, light is also a product of the event. Light intensity can be thousands of times higher than normal ambient light. Optical sensors, in association with current transformers, can be used to detect an arc-flash condition and reduce tripping times down to 25 milliseconds. Both a fault current and sudden increase in light simultaneously will initiate a trip signal. This type of protection can be a stand-alone application. Two positives of using these relays are one, they requiring no coordination with existing protective devices and two, they are always in service and don’t require any external intervention. This reduces the chance of forgetting to put a high speed protective device into service before the employee conducts the required work [7].

Chapter 6: Conclusions and Recommendations

This chapter provides observations and conclusions obtained during the research and implementation of this project. Suggestions and recommendations for future work are also presented.

6.1 Observations and Conclusions

- The arc-flash module provided by ASPEN® proved to perform as required based on the equations defined in IEEE Std. 1584-2002 except for the three instances where the code needed to be updated. The update ensured any other company/customer using the arc-flash module is using the correct code to perform their own analyses.
- Discontinuity around equipment at 15 kV can be associated to two variables. The first is the system voltage is a variable in the Lee Equation and not in the empirical equation. This adds a multiple of at least 15.1 to the incident energy equation. The second is the full fault current is applied to the Lee Equation and the arcing current, which is a fraction of the fault current, is applied to the empirical equation.
- Two offline arc-flash analysis tools were developed to perform an analysis by hand without causing the user to enter values into multiple equations with the risk of entering the incorrect constants.
- The incident energy increases linearly in both the derived equations and in the Lee equation as the voltage is changed. When the voltage changes from 15 to 15.1 kV, the calculated incident energy can increase by 25 times the level with the Lee equation.
- The results of Minnesota Power's transmission system did not produce any current conditions where employees were at risk of an arc flash requiring PPE greater than employees currently wear.

6.2 Recommendations

- Perform additional lab testing on equipment greater than 15 kV to verify the continuity of the IEEE Std. 1584-2002 equations previously developed. This would provide data based equations for higher voltage distribution equipment.
- Perform an industry survey to find out how current standards are being applied; are industry participants using the IEEE Std. 1584-2002 equations or applying the tables provided in the NESC 2009 code. Also in the survey find out how often the industry is conducting an arc-flash analysis ensuring they are using current potential incident energy levels.
- Perform testing on the effects of the X/R ratio of the system and the DC offset of faults. X/R ratios and the DC offset can affect the fault magnitude which can affect the level of potential incident energy. Modeling of arcs in an EMTP program would show the effects.
- The thermal effects of arcs have been studied extensively. Arcs also produce high levels of pressure which can cause injury to the employee. Perform detailed studies into the level of pressures associated with arcs and develop pressure PPE to be worn together with the thermal PPE to assist in preventing injury to the employee.
- Verify that 10 kV/in was actually used as the dielectric strength of air in calculating the air gap in Table 410-2 of the NESC 2009 code.
- Perform lab testing on equipment, such as a 345 kV breaker, were the more realistic fault to occur is a single line to ground. A bolted three phase fault on this equipment is unrealistic and could require the employee to wear unnecessary PPE which may hinder work activities.
- Perform a system analysis using a single line to ground fault, on equipment starting at given level such as 69 kV, where this type of fault is the most common especially given the needed conditions to create a bolted three phase fault.
- Verify the ASPEN® arc-flash module is updated with any changes made to assumptions or equations in IEEE Std. 1584-2002.

- Perform a full system analysis if the equations in IEEE Std. 1584-2002 were to be updated based on the above mentioned lab testing.
- Use the results found in ASPEN® to assign arc-flash hazard levels rather than using NESC look-up tables. The tables provided by the NESC contradict the assumptions made in IEEE Std. 1584-2002 and could potentially mask a high arc-flash level and put employees in situations that could cause them undue harm, even death.
- Rather than applying Exception 2 from the NESC 2009 code which allows employers to not perform an analysis on equipment below 1 kV, perform a full arc-flash hazard analysis. Not performing the analysis could put employees in situations that could cause them undue harm, even death. NESC 2012 now requires a detailed analysis or Tables 410-1, 410-2 or 410-3 must be used on equipment at or above 50 volts.
- Ensure an up-to-date protection database and model is maintained to reduce the analysis time if future studies are required.
- Develop a method to analyze multiple, pre-defined points on a power flow model by initializing a single run. This would greatly reduce the total run time and allow more time to analyze the output results.

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Appendix A Procedure for Arc-Flash Analysis

The 12 steps below are to be used when conducting an arc-flash analysis.

1. Obtain data about the electrical system to be studied. This includes, but is not limited to, source/utility company, impedance data, overcurrent device data and arc-flash study parameters.
2. Develop a single line diagram to document and organize the arc-flash results.
3. Model the power system in an available computer program to assist in performing the required calculations based on the models developed in IEEE Std. 1584-2002.
4. Calculate the arcing short circuit. This is determined based on the available three phase bolted short circuit of the system and applying the IEEE Std. 1584-2002 equations.
5. Determine the clearing time of the overcurrent device upstream, using the time current characteristics, based on the arcing current.
6. Calculate the incident energy using the equations provided in IEEE Std. 1584-2002 based on the values found in steps four and five.
7. Calculate the flash protection boundary using the IEEE Std. 1584-2002 equations based on the incident energy found in step six.
8. Determine the minimum PPE required based on the incident energy found in step six.
9. Develop arc-flash warning labels including the incident energy, flash protection boundary, required PPE and shock hazard approach limits.

10. Develop a report of the analysis including recommendations on how to reduce incident energy exposure.
11. Integrate the study results into the company's electrical safety program.
12. Train all affected workers on how to interpret the information provided by the study [9]-[11].

Appendix B Arc-Flash Analyzer Verification Tools

B.1 Microsoft Excel Verification Tool

Table B.1: Arc-flash hazard calculator

Arc-Flash Hazard Calculator		
User Inputs are in yellow		
For system voltages < 1kV, enter values below		
Fault Current		kA
System Voltage		V
K (-0.153 for open air, -0.097 for enclosed)		
Conductor Gap		mm
k_1 (-0.792 for open air, -0.555 for enclosed)		
k_2 (0 for ungrounded, -0.113 for grounded)		
Arc Duration		sec
Working Distance		inches
Distance Factor (2 for open air and cable, 1.473 for switch gear, 1.641 for MCC and panels)		
Arc Current	#NUM!	kA
Normalized Incident Energy	#NUM!	J/cm^2
Incident Energy	#NUM!	cal/cm^2
For system voltages > 1kV to 15kV, enter values below		
Fault Current		kA
K (-0.153 for open air, -0.097 for enclosed)		
Conductor Gap		mm
k_1 (-0.792 for open air, -0.555 for enclosed)		
k_2 (0 for ungrounded, -0.113 for grounded)		
Arc Duration		sec
Working Distance		inches
Distance Factor (2 for open air and cable, 0.973 for switch gear)		
Arc Current	#NUM!	kA
Normalized Incident Energy	#NUM!	J/cm^2
Incident Energy	#NUM!	cal/cm^2
For system voltages >15kV, enter values below		
System Voltage		kV
Fault Current		kA
Arc Duration		sec
Working Distance		inches
Incident Energy	#DIV/0!	cal/cm^2

B.2 Microsoft Excel Verification Tool with Equations

Table B.2: Arc-flash hazard calculator with equations

Arc-Flash Hazard Calculator		
User Inputs are in yellow		
For system voltages < 1kV, enter values below		
Fault Current		kA
System Voltage		V
K (-0.153 for open air, -0.097 for enclosed)		
Conductor Gap		mm
k_1 (-0.792 for open air, -0.555 for enclosed)		
k_2 (0 for ungrounded, -0.113 for grounded)		
Arc Duration		sec
Working Distance		inches
Distance Factor (2 for open air and cable, 1.473 for switch gear, 1.641 for MCC and panels)		
Arc Current	10^(B8+(0.662*LOG(B6))+(0.0966*(B7/1000))+(0.000526*B9)+(0.5588*(B7/1000)*LOG(B6))-(0.00304*B9*LOG(B6)))	kA
Normalized Incident Energy	10^(B10+B11+(1.081*LOG(B15))+(0.0011*B9))	J/cm^2
Incident Energy	4.184*1.5*B16*(B12/0.2)*((610^B14)/((25.4*B13)^B14))*0.24	cal/cm^2
For system voltages > 1kV to 15kV, enter values below		
Fault Current		kA
K (-0.153 for open air, -0.097 for enclosed)		
Conductor Gap		mm
k_1 (-0.792 for open air, -0.555 for enclosed)		
k_2 (0 for ungrounded, -0.113 for grounded)		
Arc Duration		sec
Working Distance		inches
Distance Factor (2 for open air and cable, 0.973 for switch gear)		
Arc Current	10^(0.00402+(0.983*LOG(B21)))	kA
Normalized Incident Energy	10^(B24+B25+(1.081*LOG(B29))+(0.0011*B23))	J/cm^2
Incident Energy	4.184*B30*(B26/0.2)*((610^B28)/((25.4*B27)^B28))*0.24	cal/cm^2
For system voltages >15kV, enter values		

below		
System Voltage		kV
Fault Current		kA
Arc Duration		sec
Working Distance		inches
Incident Energy	(2.142*10^6*B35*B36*(B37/((25.4*B38)^2)))*0.24	cal/cm^2

B.3 MATLAB Verification Tool

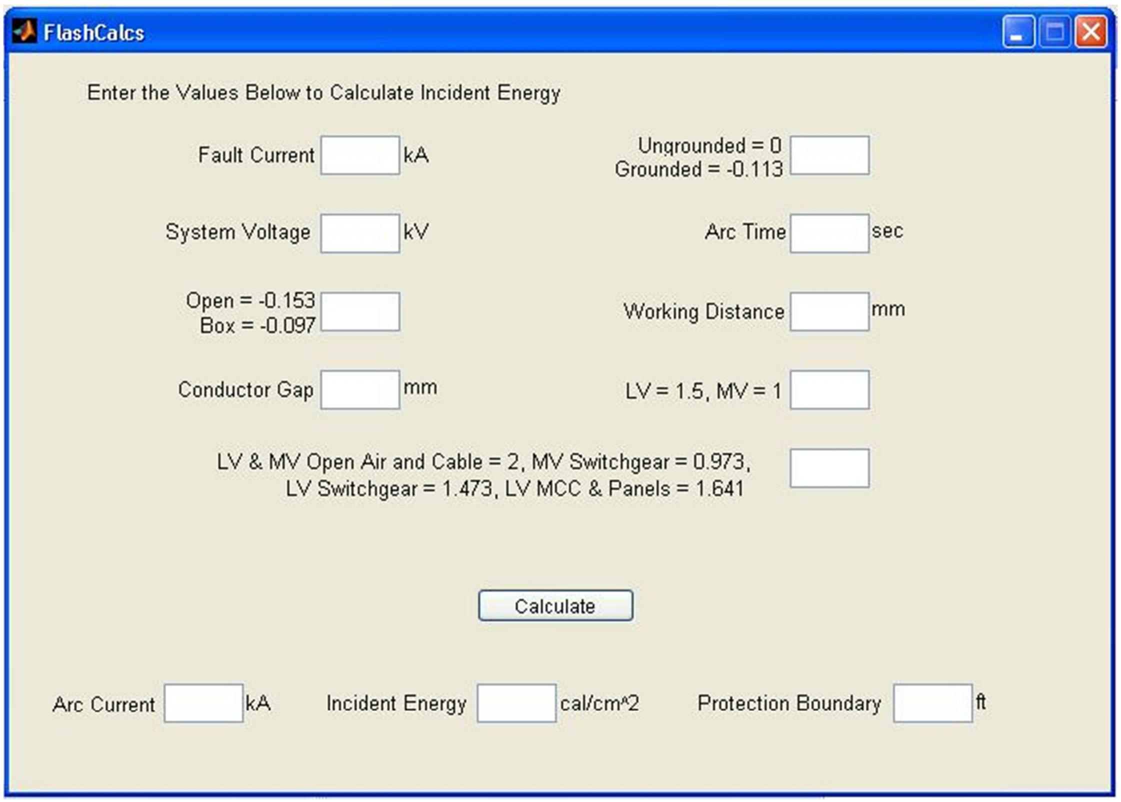

Figure B.1: MATLAB verification tool user interface

B.3.1 MATLAB Program

```
function varargout = FlashCalcs(varargin)
% FLASHCALCS M-file for FlashCalcs.fig
%      FLASHCALCS, by itself, creates a new FLASHCALCS or raises the existing
%      singleton*.
%
%      H = FLASHCALCS returns the handle to a new FLASHCALCS or the handle to
%      the existing singleton*.
%
```

```
%     FLASHCALCS('CALLBACK',hObject,eventData,handles,...) calls the local
%     function named CALLBACK in FLASHCALCS.M with the given input arguments.
%
%     FLASHCALCS('Property','Value',...) creates a new FLASHCALCS or raises the
%     existing singleton*.  Starting from the left, property value pairs are
%     applied to the GUI before FlashCalcs_OpeningFunction gets called.  An
%     unrecognized property name or invalid value makes property application
%     stop.  All inputs are passed to FlashCalcs_OpeningFcn via varargin.
%
%     *See GUI Options on GUIDE's Tools menu.  Choose "GUI allows only one
%     instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES

% Copyright 2002-2003 The MathWorks, Inc.

% Edit the above text to modify the response to help FlashCalcs

% Last Modified by GUIDE v2.5 20-Apr-2008 16:51:18

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                   'gui_Singleton',  gui_Singleton, ...
                   'gui_OpeningFcn', @FlashCalcs_OpeningFcn, ...
                   'gui_OutputFcn',  @FlashCalcs_OutputFcn, ...
                   'gui_LayoutFcn',  [] , ...
                   'gui_Callback',   []);
if nargin && ischar(varargin{1})
   gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
   [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
   gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT

% --- Executes just before FlashCalcs is made visible.
function FlashCalcs_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to FlashCalcs (see VARARGIN)

% Choose default command line output for FlashCalcs
handles.output = hObject;
```

```
% Update handles structure
guidata(hObject, handles);

% UIWAIT makes FlashCalcs wait for user response (see UIRESUME)
% uiwait(handles.figure1);

% --- Outputs from this function are returned to the command line.
function varargout = FlashCalcs_OutputFcn(hObject, eventdata, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;

function edit1_Callback(hObject, eventdata, handles)
% hObject    handle to edit1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit1 as text
%        str2double(get(hObject,'String')) returns contents of edit1 as a double

% --- Executes during object creation, after setting all properties.
function edit1_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc
    set(hObject,'BackgroundColor','white');
else
    set(hObject,'BackgroundColor',get(0,'defaultUicontrolBackgroundColor'));
end

function edit2_Callback(hObject, eventdata, handles)
% hObject    handle to edit2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit2 as text
%        str2double(get(hObject,'String')) returns contents of edit2 as a double

% --- Executes during object creation, after setting all properties.
function edit2_CreateFcn(hObject, eventdata, handles)
```

```
% hObject    handle to edit2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc
    set(hObject,'BackgroundColor','white');
else
    set(hObject,'BackgroundColor',get(0,'defaultUicontrolBackgroundColor'));
end

function edit3_Callback(hObject, eventdata, handles)
% hObject    handle to edit3 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit3 as text
%        str2double(get(hObject,'String')) returns contents of edit3 as a double

% --- Executes during object creation, after setting all properties.
function edit3_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit3 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc
    set(hObject,'BackgroundColor','white');
else
    set(hObject,'BackgroundColor',get(0,'defaultUicontrolBackgroundColor'));
end

function edit4_Callback(hObject, eventdata, handles)
% hObject    handle to edit4 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit4 as text
%        str2double(get(hObject,'String')) returns contents of edit4 as a double

% --- Executes during object creation, after setting all properties.
function edit4_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit4 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
```

```
%       See ISPC and COMPUTER.
if ispc
    set(hObject,'BackgroundColor','white');
else
    set(hObject,'BackgroundColor',get(0,'defaultUicontrolBackgroundColor'));
end

function edit5_Callback(hObject, eventdata, handles)
% hObject    handle to edit5 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit5 as text
%        str2double(get(hObject,'String')) returns contents of edit5 as a double

% --- Executes during object creation, after setting all properties.
function edit5_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit5 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc
    set(hObject,'BackgroundColor','white');
else
    set(hObject,'BackgroundColor',get(0,'defaultUicontrolBackgroundColor'));
end

% --- Executes on button press in pushbutton1.
function pushbutton1_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Get user inputs from GUI
FaultCurrent = str2double(get(handles.edit2,'String'));
Voltage = str2double(get(handles.edit3,'String'));
Kvalue = str2double(get(handles.edit4,'String'));
Gap = str2double(get(handles.edit5,'String'));
Ground = str2double(get(handles.edit8,'String'));
Time = str2double(get(handles.edit9,'String'));
Distance = str2double(get(handles.edit10,'String'));
DistanceFactor = str2double(get(handles.edit11,'String'));
Cf = str2double(get(handles.edit12,'String'));

if Voltage <= 1
    FaultCurrent = Kvalue + 0.662*log10(FaultCurrent) + 0.0966*Voltage +0.000526*Gap +
0.5588*Voltage*log10(FaultCurrent) - 0.00304*Gap*log10(FaultCurrent);
```

```
else
   FaultCurrent = 0.00402 + 0.983*log10(FaultCurrent);
end

ArcCurrent = 10^FaultCurrent;

ArcCurrent = num2str(ArcCurrent);
set(handles.edit6,'String',ArcCurrent);

if Kvalue == -0.153
   K1 = -0.792;
else
   K1 = -0.555;
end

Normalized = K1 + Ground + 1.081*FaultCurrent + 0.0011*Gap;

Normalized = 10^Normalized;

IncidentEnergy =
4.184*Cf*Normalized*(Time/0.2)*((610^DistanceFactor)/(Distance^DistanceFactor))*0.24;

IncidentEnergy = num2str(IncidentEnergy);
set(handles.edit7,'String',IncidentEnergy);

Boundary =
((4.184*Cf*Normalized*(Time/0.2)*((610^DistanceFactor)/5))^(1/DistanceFactor))/304.8;

Boundary = num2str(Boundary);
set(handles.edit13,'String',Boundary);

function edit6_Callback(hObject, eventdata, handles)
% hObject    handle to edit6 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit6 as text
%        str2double(get(hObject,'String')) returns contents of edit6 as a double

% --- Executes during object creation, after setting all properties.
function edit6_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit6 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc
   set(hObject,'BackgroundColor','white');
```

```
else
   set(hObject,'BackgroundColor',get(0,'defaultUicontrolBackgroundColor'));
end

function edit7_Callback(hObject, eventdata, handles)
% hObject    handle to edit7 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit7 as text
%        str2double(get(hObject,'String')) returns contents of edit7 as a double

% --- Executes during object creation, after setting all properties.
function edit7_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit7 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc
   set(hObject,'BackgroundColor','white');
else
   set(hObject,'BackgroundColor',get(0,'defaultUicontrolBackgroundColor'));
end

function edit8_Callback(hObject, eventdata, handles)
% hObject    handle to edit8 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit8 as text
%        str2double(get(hObject,'String')) returns contents of edit8 as a double

% --- Executes during object creation, after setting all properties.
function edit8_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit8 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc
   set(hObject,'BackgroundColor','white');
else
   set(hObject,'BackgroundColor',get(0,'defaultUicontrolBackgroundColor'));
end

function edit9_Callback(hObject, eventdata, handles)
```

```
% hObject    handle to edit9 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit9 as text
%        str2double(get(hObject,'String')) returns contents of edit9 as a double

% --- Executes during object creation, after setting all properties.
function edit9_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit9 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc
    set(hObject,'BackgroundColor','white');
else
    set(hObject,'BackgroundColor',get(0,'defaultUicontrolBackgroundColor'));
end

function edit10_Callback(hObject, eventdata, handles)
% hObject    handle to edit8 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit8 as text
%        str2double(get(hObject,'String')) returns contents of edit8 as a double

% --- Executes during object creation, after setting all properties.
function edit10_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit8 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc
    set(hObject,'BackgroundColor','white');
else
    set(hObject,'BackgroundColor',get(0,'defaultUicontrolBackgroundColor'));
end

function edit11_Callback(hObject, eventdata, handles)
% hObject    handle to edit10 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit10 as text
```

```
%        str2double(get(hObject,'String')) returns contents of edit10 as a double

% --- Executes during object creation, after setting all properties.
function edit11_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit10 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc
    set(hObject,'BackgroundColor','white');
else
    set(hObject,'BackgroundColor',get(0,'defaultUicontrolBackgroundColor'));
end

function edit12_Callback(hObject, eventdata, handles)
% hObject    handle to edit9 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit9 as text
%        str2double(get(hObject,'String')) returns contents of edit9 as a double

% --- Executes during object creation, after setting all properties.
function edit12_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit9 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc
    set(hObject,'BackgroundColor','white');
else
    set(hObject,'BackgroundColor',get(0,'defaultUicontrolBackgroundColor'));
end

function edit13_Callback(hObject, eventdata, handles)
% hObject    handle to edit13 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit13 as text
%        str2double(get(hObject,'String')) returns contents of edit13 as a double

% --- Executes during object creation, after setting all properties.
function edit13_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit13 (see GCBO)
```

```
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc
    set(hObject,'BackgroundColor','white');
else
    set(hObject,'BackgroundColor',get(0,'defaultUicontrolBackgroundColor'));
end
```

Appendix C Example System Data

C.1 System Online Diagram

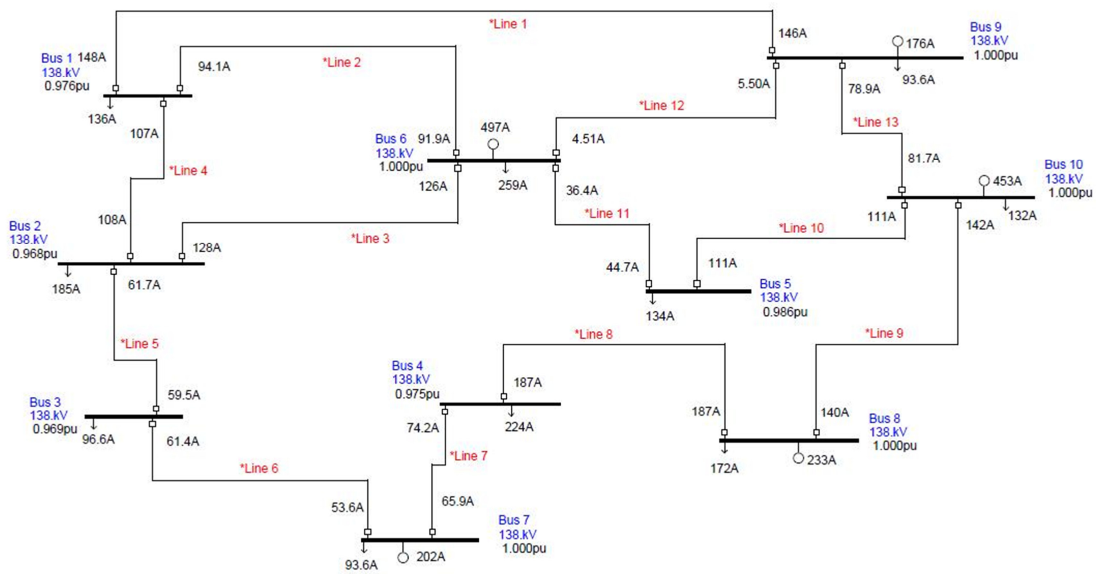

Figure C.1: Example system oneline diagram

C.2 Generator Data

Table C.1: Example system generator data

Bus	Min/Max MW	Min/Max MVAR	Values in per unit all for Subtansient, Transient, Synchronous, Negative Sequence and Zero Sequence	
			R	X
6	25/150	-10/50	0.09149	0.09149
7	10/75	0/20	0.09576	0.09576
8	15/100	-5/30	0.09237	0.09237
9	5/80	-5/25	0.0958	0.0958
10	50/200	-15/60	0.09044	0.09044

C.3 Load Data

Table C.2: Example system load data

Bus	Pload (MW)	Qload (MVAR)
1	30	10
2	40	15
3	20	10
4	50	15
5	30	10
6	60	15
7	20	10
8	40	10
9	20	10
10	30	10

C.4 Line Data

Table C.3: Example system line data

	Values in per unit							
Line	R	X	B1	B2	R-0	X-0	B1-0	B2-0
1	0.0366	0.14639	0.01093	0.01093	0.0366	0.014639	0.01093	0.01093
2	0.0549	0.22873	0.01093	0.01093	0.0366	0.014639	0.01093	0.01093
3	0.0549	0.22873	0.01093	0.01093	0.0366	0.014639	0.01093	0.01093
4	0.0183	0.07319	0.00546	0.00546	0.0366	0.014639	0.01093	0.01093
5	0.0549	0.22873	0.01093	0.01093	0.0366	0.014639	0.01093	0.01093
6	0.0549	0.22873	0.01093	0.01093	0.0366	0.014639	0.01093	0.01093
7	0.0366	0.14639	0.01093	0.01093	0.0366	0.014639	0.01093	0.01093
8	0.0549	0.22873	0.01093	0.01093	0.0366	0.014639	0.01093	0.01093
9	0.0366	0.14639	0.01093	0.01093	0.0366	0.014639	0.01093	0.01093
10	0.0549	0.22873	0.01093	0.01093	0.0366	0.014639	0.01093	0.01093
11	0.0366	0.14639	0.01093	0.01093	0.0366	0.014639	0.01093	0.01093
12	0.0183	0.07319	0.00546	0.00546	0.0366	0.014639	0.01093	0.01093
13	0.07319	0.29278	0.01366	0.01366	0.0366	0.014639	0.01093	0.01093

C.5 Relay Data

Table C.4: Example system relay data

Relay Name	CT Ratio	Tap Setting (Pickup)	Time Dial	Relay Curve	Tap Unit
Line 1 Bus 1	120/5	6.25	0.5	ABB CO-9	GC2
Line 2 Bus 1	120/5	4	0.5	ABB CO-9	GC2
Line 4 Bus 1	120/5	4.5	0.5	ABB CO-9	GC2
Line 1 Bus 9	120/5	6.25	0.5	ABB CO-9	GC2
Line 12 Bus 9	60/5	0.5	0.5	ABB CO-9	GC1
Line 13 Bus 9	120/5	3.5	0.5	ABB CO-9	GC2
Line 13 Bus 10	120/5	3.5	0.5	ABB CO-9	GC2
Line 9 Bus 10	120/5	6	0.5	ABB CO-9	GC2
Line 10 Bus 10	120/5	4.75	0.5	ABB CO-9	GC2
Line 9 Bus 8	120/5	6	0.5	ABB CO-9	GC2
Line 8 Bus 8	120/5	8	0.5	ABB CO-9	GC3
Line 8 Bus 4	120/5	8	0.5	ABB CO-9	GC3
Line 7 Bus 7	120/5	3	0.5	ABB CO-9	GC1
Line 6 Bus 7	120/5	2.25	0.5	ABB CO-9	GC1
Line 6 Bus 3	120/5	2.75	0.5	ABB CO-9	GC1
Line 5 Bus 3	120/5	2.5	0.5	ABB CO-9	GC1
Line 5 Bus 2	120/5	2.75	0.5	ABB CO-9	GC1
Line 3 Bus 2	120/5	5.5	0.5	ABB CO-9	GC2
Line 4 Bus 2	120/5	4.75	0.5	ABB CO-9	GC2
Line 3 Bus 6	120/5	5.5	0.5	ABB CO-9	GC2
Line 2 Bus 6	120/5	4	0.5	ABB CO-9	GC2
Line 12 Bus 6	60/5	0.5	0.5	ABB CO-9	GC1
Line 11 Bus 6	120/5	1.75	0.5	ABB CO-9	GC1
Line 11 Bus 5	120/5	2	0.5	ABB CO-9	GC1
Line 10 Bus 5	120/5	4.75	0.5	ABB CO-9	GC2
Line 7 Bus 4	120/5	3.25	0.5	ABB CO-9	GC1

Appendix D Example System ASPEN® Output Data

D.1 ASPEN® Results

Bus = Bus 1 138kV
Equipment category = Open Air
Grounded = Yes
Enclosed = No
Breaker interrupting time (cycles) = 3.0
Working distance (inches) = 53.0
Conductor gap (mm) = 202.4
Bolted 3PH fault current (kA) = 4.228
Arcing current (kA) = 4.228
Interrupting device = [OC relay] Line 4 Bus 1 on 0 Bus 1 138.kV - 0 Bus 2 138.kV 1 L Line 1
Clearing time (seconds) = 0.11
Incident energy (cal/cm2) = 17.70
Interrupting device @85% current = [OC relay] Line 4 Bus 1 on 0 Bus 1 138.kV - 0 Bus 2 138.kV 1 L Line 1
Clearing time @85% current (seconds) = 0.11
Incident energy @85% current (cal/cm2) = 15.79
Required PPE cat. per NFPA 70E = 3
PPE cat. 1 flash hazard boundary (inches) = 203.5
PPE cat. 2 flash hazard boundary (inches) = 99.7
PPE cat. 3 flash hazard boundary (inches) = 78.8
PPE cat. 4 flash hazard boundary (inches) = 44.6

==

Bus = Bus 2 138kV
Equipment category = Open Air
Grounded = Yes
Enclosed = No
Breaker interrupting time (cycles) = 3.0
Working distance (inches) = 53.0
Conductor gap (mm) = 202.4
Bolted 3PH fault current (kA) = 3.819
Arcing current (kA) = 3.819
Interrupting device = [OC relay] Line 12 Bus 6 on 0 Bus 6 138.kV - 0 Bus 9 138.kV 1 L Line 11
Clearing time (seconds) = 0.09
Incident energy (cal/cm2) = 13.43
Interrupting device @85% current = [OC relay] Line 12 Bus 6 on 0 Bus 6 138.kV - 0 Bus 9 138.kV 1 L Line 1
Clearing time @85% current (seconds) = 0.09
Incident energy @85% current (cal/cm2) = 11.48
Required PPE cat. per NFPA 70E = 3
PPE cat. 1 flash hazard boundary (inches) = 177.3
PPE cat. 2 flash hazard boundary (inches) = 86.9
PPE cat. 3 flash hazard boundary (inches) = 68.7
PPE cat. 4 flash hazard boundary (inches) = 38.8

==

Bus = Bus 3 138kV
Equipment category = Open Air
Grounded = Yes
Enclosed = No
Breaker interrupting time (cycles) = 3.0
Working distance (inches) = 53.0
Conductor gap (mm) = 202.4
Bolted 3PH fault current (kA) = 2.471
Arcing current (kA) = 2.471
Interrupting device = [OC relay] Line 6 Bus 7 on 0 Bus 7 138.kV - 0 Bus 3 138.kV 2 L Line 6
Clearing time (seconds) = 0.09
Incident energy (cal/cm2) = 9.05
Interrupting device @85% current = [OC relay] Line 6 Bus 7 on 0 Bus 7 138.kV - 0 Bus 3 138.kV 2 L Line 6
Clearing time @85% current (seconds) = 0.10
Incident energy @85% current (cal/cm2) = 7.87
Required PPE cat. per NFPA 70E = 3
PPE cat. 1 flash hazard boundary (inches) = 145.6
PPE cat. 2 flash hazard boundary (inches) = 71.3
PPE cat. 3 flash hazard boundary (inches) = 56.4
PPE cat. 4 flash hazard boundary (inches) = 31.9

==

Bus = Bus 4 138kV
Equipment category = Open Air
Grounded = Yes
Enclosed = No
Breaker interrupting time (cycles) = 3.0
Working distance (inches) = 53.0
Conductor gap (mm) = 202.4
Bolted 3PH fault current (kA) = 3.150
Arcing current (kA) = 3.150
Interrupting device = [OC relay] Line 7 Bus 7 on 0 Bus 7 138.kV - 0 Bus 4 138.kV 1 L Line 7
Clearing time (seconds) = 0.09
Incident energy (cal/cm2) = 11.57
Interrupting device @85% current = [OC relay] Line 7 Bus 7 on 0 Bus 7 138.kV - 0 Bus 4 138.kV 1 L Line 7
Clearing time @85% current (seconds) = 0.10
Incident energy @85% current (cal/cm2) = 10.06
Required PPE cat. per NFPA 70E = 3
PPE cat. 1 flash hazard boundary (inches) = 164.5
PPE cat. 2 flash hazard boundary (inches) = 80.6
PPE cat. 3 flash hazard boundary (inches) = 63.7
PPE cat. 4 flash hazard boundary (inches) = 36.1

==

Bus = Bus 5 138kV

Equipment category = Open Air
Grounded = Yes
Enclosed = No
Breaker interrupting time (cycles) = 3.0
Working distance (inches) = 53.0
Conductor gap (mm) = 202.4
Bolted 3PH fault current (kA) = 3.395
Arcing current (kA) = 3.395
Interrupting device = [OC relay] Line 12 Bus 6 on 0 Bus 6 138.kV - 0 Bus 9 138.kV 1 L Line 11
Clearing time (seconds) = 0.09
Incident energy (cal/cm2) = 11.91
Interrupting device @85% current = [OC relay] Line 12 Bus 6 on 0 Bus 6 138.kV - 0 Bus 9 138.kV 1 L Line 1
Clearing time @85% current (seconds) = 0.09
Incident energy @85% current (cal/cm2) = 10.12
Required PPE cat. per NFPA 70E = 3
PPE cat. 1 flash hazard boundary (inches) = 167.0
PPE cat. 2 flash hazard boundary (inches) = 81.8
PPE cat. 3 flash hazard boundary (inches) = 64.7
PPE cat. 4 flash hazard boundary (inches) = 36.6

==

Bus = Bus 6 138kV
Equipment category = Open Air
Grounded = Yes
Enclosed = No
Breaker interrupting time (cycles) = 3.0
Working distance (inches) = 53.0
Conductor gap (mm) = 202.4
Bolted 3PH fault current (kA) = 7.465
Arcing current (kA) = 7.465
Interrupting device = [OC relay] Line 12 Bus 6 on 0 Bus 6 138.kV - 0 Bus 9 138.kV 1 L Line 11
Clearing time (seconds) = 0.09
Incident energy (cal/cm2) = 26.19
Interrupting device @85% current = [OC relay] Line 12 Bus 6 on 0 Bus 6 138.kV - 0 Bus 9 138.kV 1 L Line 1
Clearing time @85% current (seconds) = 0.09
Incident energy @85% current (cal/cm2) = 22.26
Required PPE cat. per NFPA 70E = 4
PPE cat. 1 flash hazard boundary (inches) = 247.6
PPE cat. 2 flash hazard boundary (inches) = 121.3
PPE cat. 3 flash hazard boundary (inches) = 95.9
PPE cat. 4 flash hazard boundary (inches) = 54.2

==

Bus = Bus 7 138kV
Equipment category = Open Air
Grounded = Yes
Enclosed = No

Breaker interrupting time (cycles) = 3.0
Working distance (inches) = 53.0
Conductor gap (mm) = 202.4
Bolted 3PH fault current (kA) = 4.892
Arcing current (kA) = 4.892
Interrupting device = [OC relay] Line 7 Bus 7 on 0 Bus 7 138.kV - 0 Bus 4 138.kV 1 L Line 7
Clearing time (seconds) = 0.11
Incident energy (cal/cm2) = 20.04
Interrupting device @85% current = [OC relay] Line 7 Bus 7 on 0 Bus 7 138.kV - 0 Bus 4 138.kV 1 L Line 7
Clearing time @85% current (seconds) = 0.11
Incident energy @85% current (cal/cm2) = 17.86
Required PPE cat. per NFPA 70E = 3
PPE cat. 1 flash hazard boundary (inches) = 216.6
PPE cat. 2 flash hazard boundary (inches) = 106.1
PPE cat. 3 flash hazard boundary (inches) = 83.9
PPE cat. 4 flash hazard boundary (inches) = 47.5

==

Bus = Bus 8 138kV
Equipment category = Open Air
Grounded = Yes
Enclosed = No
Breaker interrupting time (cycles) = 3.0
Working distance (inches) = 53.0
Conductor gap (mm) = 202.4
Bolted 3PH fault current (kA) = 5.986
Arcing current (kA) = 5.986
Interrupting device = [OC relay] Line 9 Bus 10 on 0 Bus 10 138.kV - 0 Bus 8 138.kV 2 L Line 12
Clearing time (seconds) = 0.11
Incident energy (cal/cm2) = 24.84
Interrupting device @85% current = [OC relay] Line 9 Bus 10 on 0 Bus 10 138.kV - 0 Bus 8 138.kV 2 L Line 1
Clearing time @85% current (seconds) = 0.11
Incident energy @85% current (cal/cm2) = 22.16
Required PPE cat. per NFPA 70E = 3
PPE cat. 1 flash hazard boundary (inches) = 241.1
PPE cat. 2 flash hazard boundary (inches) = 118.1
PPE cat. 3 flash hazard boundary (inches) = 93.4
PPE cat. 4 flash hazard boundary (inches) = 52.8

==

Bus = Bus 9 138kV
Equipment category = Open Air
Grounded = Yes
Enclosed = No
Breaker interrupting time (cycles) = 3.0
Working distance (inches) = 53.0
Conductor gap (mm) = 202.4

Bolted 3PH fault current (kA) = 7.380
Arcing current (kA) = 7.380
Interrupting device = [OC relay] Line 12 Bus 9 on 0 Bus 9 138.kV - 0 Bus 6 138.kV 1 L Line 11
Clearing time (seconds) = 0.09
Incident energy (cal/cm2) = 25.89
Interrupting device @85% current = [OC relay] Line 12 Bus 9 on 0 Bus 9 138.kV - 0 Bus 6 138.kV 1 L Line 1
Clearing time @85% current (seconds) = 0.09
Incident energy @85% current (cal/cm2) = 22.01
Required PPE cat. per NFPA 70E = 4
PPE cat. 1 flash hazard boundary (inches) = 246.2
PPE cat. 2 flash hazard boundary (inches) = 120.6
PPE cat. 3 flash hazard boundary (inches) = 95.4
PPE cat. 4 flash hazard boundary (inches) = 53.9

==

Bus = Bus 10 138kV
Equipment category = Open Air
Grounded = Yes
Enclosed = No
Breaker interrupting time (cycles) = 3.0
Working distance (inches) = 53.0
Conductor gap (mm) = 202.4
Bolted 3PH fault current (kA) = 6.860
Arcing current (kA) = 6.860
Interrupting device = [OC relay] Line 12 Bus 9 on 0 Bus 9 138.kV - 0 Bus 6 138.kV 1 L Line 11
Clearing time (seconds) = 0.10
Incident energy (cal/cm2) = 26.41
Interrupting device @85% current = [OC relay] Line 12 Bus 9 on 0 Bus 9 138.kV - 0 Bus 6 138.kV 1 L Line 1
Clearing time @85% current (seconds) = 0.10
Incident energy @85% current (cal/cm2) = 23.27
Required PPE cat. per NFPA 70E = 4
PPE cat. 1 flash hazard boundary (inches) = 248.6
PPE cat. 2 flash hazard boundary (inches) = 121.8
PPE cat. 3 flash hazard boundary (inches) = 96.3
PPE cat. 4 flash hazard boundary (inches) = 54.5

D.2 PPE Levels Required

Table D.1: Example system PPE level requirements

Substation	Voltage-Equipment	Hazard/Risk Category Required minimum FR clothing rating: 1 (4 cal/cm^2)	2 (8 cal/cm^2)	3 (25 cal/cm^2)	4 (40 cal/cm^2)	N/A (>40 cal/cm^2)	Minimum Approach Distance at 4 cal/cm^2 (ft)
Bus 1	138 kV			X			16.96
Bus 2	138 kV			X			14.78
Bus 3	138 kV			X			12.13
Bus 4	138 kV			X			13.71
Bus 5	138 kV			X			13.92
Bus 6	138 kV				X		20.63
Bus 7	138 kV			X			18.05
Bus 8	138 kV			X			20.09
Bus 9	138 kV				X		20.52
Bus 10	138 kV				X		20.72

Appendix E Discontinuity of Voltage Levels

E.1 Voltage Level Test System

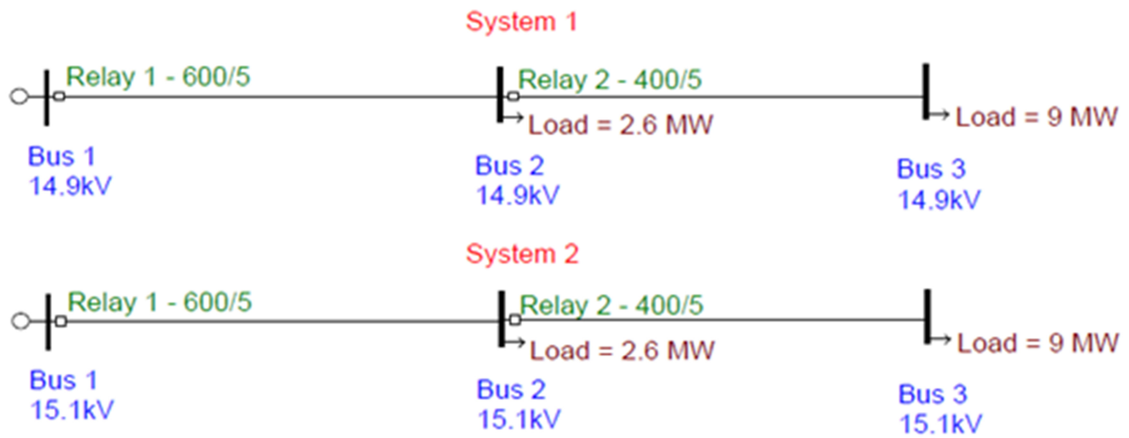

Figure E.1: Voltage level test systems

E.2 ASPEN® Results System 1, 51 Contact

Bus = Bus 3 14.9kV
Equipment category = Open Air
Grounded = Yes
Enclosed = No
Breaker interrupting time (cycles) = 4.0
Working distance (inches) = 27.0
Conductor gap (mm) = 50.8
Bolted 3PH fault current (kA) = 13.962
Arcing current (kA) = 13.497
Interrupting device = [OC relay] System 1 Bus 2 on 0 Bus 2 14.9kV - 0 Bus 3 14.9kV 1 L Line 2
Clearing time (seconds) = 0.11
Incident energy (cal/cm2) = 1.01
Interrupting device @85% current = [OC relay] System 1 Bus 2 on 0 Bus 2 14.9kV - 0 Bus 3 14.9kV 1 L Line
Clearing time @85% current (seconds) = 0.11
Incident energy @85% current (cal/cm2) = 0.85
Required PPE cat. per NFPA 70E = 0
PPE cat. 1 flash hazard boundary (inches) = 24.7
PPE cat. 2 flash hazard boundary (inches) = 12.1
PPE cat. 3 flash hazard boundary (inches) = 9.6
PPE cat. 4 flash hazard boundary (inches) = 5.4

==

Bus = Bus 2 14.9kV
Equipment category = Open Air
Grounded = Yes
Enclosed = No

Breaker interrupting time (cycles) = 4.0
Working distance (inches) = 27.0
Conductor gap (mm) = 50.8
Bolted 3PH fault current (kA) = 19.358
Arcing current (kA) = 18.614
Interrupting device = [OC relay] System 1 Bus 1 on 0 Bus 1 14.9kV - 0 Bus 2 14.9kV 1 L Line 1
Clearing time (seconds) = 0.42
Incident energy (cal/cm2) = 5.50
Interrupting device @85% current = [OC relay] System 1 Bus 1 on 0 Bus 1 14.9kV - 0 Bus 2 14.9kV 1 L Line
Clearing time @85% current (seconds) = 0.43
Incident energy @85% current (cal/cm2) = 4.75
Required PPE cat. per NFPA 70E = 2
PPE cat. 1 flash hazard boundary (inches) = 57.8
PPE cat. 2 flash hazard boundary (inches) = 28.3
PPE cat. 3 flash hazard boundary (inches) = 22.4
PPE cat. 4 flash hazard boundary (inches) = 12.7

E.3 ASPEN® Results System 1, 50 Contact

Bus = Bus 3 14.9kV
Equipment category = Open Air
Grounded = Yes
Enclosed = No
Breaker interrupting time (cycles) = 4.0
Working distance (inches) = 27.0
Conductor gap (mm) = 50.8
Bolted 3PH fault current (kA) = 13.962
Arcing current (kA) = 13.497
Interrupting device = [OC relay] System 1 Bus 2 on 0 Bus 2 14.9kV - 0 Bus 3 14.9kV 1 L Line 2
Clearing time (seconds) = 0.07
Incident energy (cal/cm2) = 0.62
Interrupting device @85% current = [OC relay] System 1 Bus 2 on 0 Bus 2 14.9kV - 0 Bus 3 14.9kV 1 L Line
Clearing time @85% current (seconds) = 0.07
Incident energy @85% current (cal/cm2) = 0.52
Required PPE cat. per NFPA 70E = 0
PPE cat. 1 flash hazard boundary (inches) = 19.4
PPE cat. 2 flash hazard boundary (inches) = 9.5
PPE cat. 3 flash hazard boundary (inches) = 7.5
PPE cat. 4 flash hazard boundary (inches) = 4.3

==

Bus = Bus 2 14.9kV
Equipment category = Open Air
Grounded = Yes
Enclosed = No
Breaker interrupting time (cycles) = 4.0
Working distance (inches) = 27.0
Conductor gap (mm) = 50.8

Bolted 3PH fault current (kA) = 19.358
Arcing current (kA) = 18.614
Interrupting device = [OC relay] System 1 Bus 1 on 0 Bus 1 14.9kV - 0 Bus 2 14.9kV 1 L Line 1
Clearing time (seconds) = 0.07
Incident energy (cal/cm2) = 0.88
Interrupting device @85% current = [OC relay] System 1 Bus 1 on 0 Bus 1 14.9kV - 0 Bus 2 14.9kV 1 L Line
Clearing time @85% current (seconds) = 0.07
Incident energy @85% current (cal/cm2) = 0.74
Required PPE cat. per NFPA 70E = 0
PPE cat. 1 flash hazard boundary (inches) = 23.1
PPE cat. 2 flash hazard boundary (inches) = 11.3
PPE cat. 3 flash hazard boundary (inches) = 9.0
PPE cat. 4 flash hazard boundary (inches) = 5.1

E.4 ASPEN® Results System 2, 51 Contact

Bus = Bus 3 15.1kV
Equipment category = Open Air
Grounded = Yes
Enclosed = No
Breaker interrupting time (cycles) = 4.0
Working distance (inches) = 27.0
Conductor gap (mm) = 50.8
Bolted 3PH fault current (kA) = 13.777
Arcing current (kA) = 13.777
Interrupting device = [OC relay] System 2 Bus 2 on 0 Bus 2 15.1kV - 0 Bus 3 15.1kV 1 L Line 2
Clearing time (seconds) = 0.11
Incident energy (cal/cm2) = 24.40
Interrupting device @85% current = [OC relay] System 2 Bus 2 on 0 Bus 2 15.1kV - 0 Bus 3 15.1kV 1 L Line
Clearing time @85% current (seconds) = 0.11
Incident energy @85% current (cal/cm2) = 20.93
Required PPE cat. per NFPA 70E = 3
PPE cat. 1 flash hazard boundary (inches) = 121.7
PPE cat. 2 flash hazard boundary (inches) = 59.6
PPE cat. 3 flash hazard boundary (inches) = 47.2
PPE cat. 4 flash hazard boundary (inches) = 26.7

==

Bus = Bus 2 15.1kV
Equipment category = Open Air
Grounded = Yes
Enclosed = No
Breaker interrupting time (cycles) = 4.0
Working distance (inches) = 27.0
Conductor gap (mm) = 50.8
Bolted 3PH fault current (kA) = 19.101
Arcing current (kA) = 19.101

Interrupting device = [OC relay] System 2 Bus 1 on 0 Bus 1 15.1kV - 0 Bus 2 15.1kV 1 L Line 1
Clearing time (seconds) = 0.41
Incident energy (cal/cm2) = 130.16
Interrupting device @85% current = [OC relay] System 2 Bus 1 on 0 Bus 1 15.1kV - 0 Bus 2 15.1kV 1 L Line
Clearing time @85% current (seconds) = 0.43
Incident energy @85% current (cal/cm2) = 113.79
Required PPE cat. per NFPA 70E = N/A
PPE cat. 1 flash hazard boundary (inches) = 281.2
PPE cat. 2 flash hazard boundary (inches) = 137.8
PPE cat. 3 flash hazard boundary (inches) = 108.9
PPE cat. 4 flash hazard boundary (inches) = 61.6

E.5 ASPEN® Results Using 50 and 51 Contacts

Table E.1: Incident energy level based on trip contact selected

Station	Voltage-Equipment	Hazard/Risk Category Required minimum FR clothing rating						Minimum Approach Distance at 4 cal/cm^2 (ft)
		0 (< 4 cal/cm^2)	1 (4 cal/cm^2)	2 (8 cal/cm^2)	3 (25 cal/cm^2)	4 (40 cal/cm^2)	N/A (>40 cal/cm^2)	
System 1 Bus 2 50 Contact	14.9 kV	X						1.93
System 1 Bus 2 51 Contact	14.9 kV			X				4.82
System 1 Bus 3 50 Contact	14.9 kV	X						1.62
System 1 Bus 3 51 Contact	14.9 kV	X						2.06

E.6 ASPEN® Results Systems 1 & 2

Table E.2: Voltage level system comparisons

Station	Voltage-Equipment	Hazard/Risk Category Required minimum FR clothing rating						Minimum Approach Distance at 4 cal/cm² (ft)
		0 (< 4 cal/cm²)	1 (4 cal/cm²)	2 (8 cal/cm²)	3 (25 cal/cm²)	4 (40 cal/cm²)	N/A (>40 cal/cm²)	
System 1 Bus 2	14.9 kV			X				4.82
System 2 Bus 2	15.1 kV						X	23.43
System 1 Bus 3	14.9 kV	X						2.06
System 2 Bus 3	15.1 kV				X			10.14

Appendix F Energy Plot Data

Table F.1: U.S. U2 inverse time overcurrent curve data

Multiple of Pickup	Trip Time (s)			
	Time Dial 0.5	Time Dial 2	Time Dial 5	Time Dial 11
1.5	2.47	9.88	24.7	54.34
2	1.081666667	4.326666667	10.81666667	23.79666667
3	0.461875	1.8475	4.61875	10.16125
4	0.288333333	1.153333333	2.883333333	6.343333333
5	0.213958333	0.855833333	2.139583333	4.707083333
6	0.175	0.7	1.75	3.85
7	0.151979167	0.607916667	1.519791667	3.343541667
8	0.137222222	0.548888889	1.372222222	3.018888889
9	0.1271875	0.50875	1.271875	2.798125
10	0.120050505	0.48020202	1.200505051	2.641111111
11	0.114791667	0.459166667	1.147916667	2.525416667
12	0.110804196	0.443216783	1.108041958	2.437692308
13	0.107708333	0.430833333	1.077083333	2.369583333
14	0.10525641	0.421025641	1.052564103	2.315641026
15	0.10328125	0.413125	1.0328125	2.2721875
16	0.101666667	0.406666667	1.016666667	2.236666667
17	0.100329861	0.401319444	1.003298611	2.207256944
18	0.099210526	0.396842105	0.992105263	2.182631579
19	0.098263889	0.393055556	0.982638889	2.161805556
20	0.09745614	0.389824561	0.974561404	2.144035088
21	0.096761364	0.387045455	0.967613636	2.12875
22	0.09615942	0.384637681	0.961594203	2.115507246
23	0.09563447	0.382537879	0.956344697	2.103958333
24	0.095173913	0.380695652	0.95173913	2.093826087
25	0.094767628	0.379070513	0.947676282	2.084887821
26	0.094407407	0.37762963	0.944074074	2.076962963
27	0.094086538	0.376346154	0.940865385	2.069903846
28	0.093799489	0.375197957	0.937994891	2.063588761
29	0.093541667	0.374166667	0.935416667	2.057916667
30	0.093309232	0.37323693	0.933092325	2.052803115
31	0.093098958	0.372395833	0.930989583	2.048177083
32	0.092908113	0.371632454	0.929081134	2.043978495
33	0.092734375	0.3709375	0.92734375	2.04015625
34	0.092575758	0.37030303	0.925757576	2.036666667
35	0.092430556	0.369722222	0.924305556	2.033472222
36	0.092297297	0.369189189	0.922972973	2.030540541
37	0.092174708	0.36869883	0.921747076	2.027843567
38	0.092061677	0.368246708	0.920616771	2.025356895
39	0.091957237	0.367828947	0.919572368	2.023059211
40	0.091860538	0.367442151	0.918605378	2.020931832

41	0.091770833	0.367083333	0.917708333	2.018958333
42	0.091687465	0.366749858	0.916874645	2.01712422
43	0.091609848	0.366439394	0.916098485	2.015416667
44	0.091537468	0.366149871	0.915374677	2.013824289
45	0.091469862	0.365879447	0.914698617	2.012336957
46	0.091406619	0.365626478	0.914066194	2.010945626
47	0.091347373	0.365389493	0.913473732	2.00964221
48	0.091291793	0.365167173	0.912917933	2.008419453
49	0.091239583	0.364958333	0.912395833	2.007270833
50	0.091190476	0.364761905	0.911904762	2.006190476
51	0.091144231	0.364576923	0.911442308	2.005173077
52	0.091100629	0.364402516	0.911006289	2.004213836
53	0.091059473	0.364237892	0.910594729	2.003308405
54	0.091020583	0.364082333	0.910205832	2.00245283
55	0.090983796	0.363935185	0.909837963	2.001643519
56	0.090948963	0.363795853	0.909489633	2.000877193
57	0.090915948	0.363663793	0.909159483	2.000150862
58	0.090884627	0.363538507	0.908846268	1.99946179
59	0.090854885	0.36341954	0.908548851	1.998807471
60	0.090826619	0.363306474	0.908266185	1.998185607
61	0.090799731	0.363198925	0.907997312	1.997594086
62	0.090774135	0.363096539	0.907741348	1.997030965
63	0.090749748	0.362998992	0.90749748	1.996494456
64	0.090726496	0.362905983	0.907264957	1.995982906
65	0.090704309	0.362817235	0.907043087	1.995494792
66	0.090683123	0.362732491	0.906831228	1.995028703
67	0.090662879	0.362651515	0.906628788	1.994583333
68	0.090643522	0.362574086	0.906435215	1.994157474
69	0.090625	0.3625	0.90625	1.99375
70	0.090607267	0.362429067	0.906072668	1.993359869
71	0.090590278	0.362361111	0.905902778	1.992986111
72	0.090573992	0.362295968	0.905739919	1.992627822
73	0.090558371	0.362233483	0.905583709	1.992284159
74	0.090543379	0.362173516	0.90543379	1.991954338
75	0.090528983	0.362115932	0.905289829	1.991637624
76	0.090515152	0.362060606	0.905151515	1.991333333
77	0.090501856	0.362007422	0.905018556	1.991040823
78	0.090489068	0.361956272	0.904890679	1.990759494
79	0.090476763	0.361907051	0.904767628	1.990488782
80	0.090464916	0.361859666	0.904649164	1.990228161
81	0.090453506	0.361814024	0.904535061	1.989977134
82	0.090442511	0.361770043	0.904425108	1.989735237
83	0.090431911	0.361727642	0.904319106	1.989502033
84	0.090421687	0.361686747	0.904216867	1.989277108
85	0.090411822	0.361647287	0.904118217	1.989060078
86	0.090402299	0.361609195	0.904022989	1.988850575

87	0.090393103	0.36157241	0.903931025	1.988648256
88	0.090384218	0.361536872	0.90384218	1.988452796
89	0.090375631	0.361502525	0.903756313	1.988263889
90	0.090367329	0.361469317	0.903673293	1.988081245
91	0.0903593	0.361437198	0.903592995	1.987904589
92	0.09035153	0.361406121	0.903515302	1.987733664
93	0.09034401	0.361376041	0.903440102	1.987568224
94	0.090336729	0.361346916	0.903367289	1.987408036
95	0.090329676	0.361318706	0.903296764	1.987252881
96	0.090322843	0.361291373	0.903228432	1.98710255
97	0.09031622	0.361264881	0.903162202	1.986956845
98	0.090309799	0.361239196	0.90309799	1.986815578
99	0.090303571	0.361214286	0.903035714	1.986678571
100	0.09029753	0.361190119	0.902975298	1.986545655

Table F.2: Energy through equipment curve data

Multiple of Pickup	Energy (J)			
	Time Dial 0.5	Time Dial 2	Time Dial 5	Time Dial 11
0.694444444	2.95689092	11.82756	29.56891	65.0516
0.722222222	3.19814132	12.79257	31.98141	70.359109
0.75	3.44885252	13.79541	34.48853	75.874755
0.777777778	3.70902452	14.8361	37.09025	81.598539
0.805555556	3.97865732	15.91463	39.78657	87.530461
0.833333333	4.25775092	17.031	42.57751	93.67052
0.861111111	4.54630532	18.18522	45.46305	100.01872
0.888888889	4.84432052	19.37728	48.44321	106.57505
0.916666667	5.15179652	20.60719	51.51797	113.33952
0.944444444	5.46873332	21.87493	54.68733	120.31213
0.972222222	5.79513092	23.18052	57.95131	127.49288
1	6.13098932	24.52396	61.30989	134.88176
1.027777778	6.47630852	25.90523	64.76309	142.47879
1.055555556	6.83108852	27.32435	68.31089	150.28395
1.083333333	7.19532932	28.78132	71.95329	158.29724
1.111111111	7.56903092	30.27612	75.69031	166.51868
1.138888889	7.95219332	31.80877	79.52193	174.94825
1.166666667	8.34481652	33.37927	83.44817	183.58596
1.194444444	8.74690052	34.9876	87.46901	192.43181
1.222222222	9.15844532	36.63378	91.58445	201.4858
1.25	9.57945092	38.3178	95.79451	210.74792
1.277777778	10.0099173	40.03967	100.0992	220.21818
1.305555556	10.4498445	41.79938	104.4984	229.89658
1.333333333	10.8992325	43.59693	108.9923	239.78312
1.361111111	11.3580813	45.43233	113.5808	249.87779
1.388888889	11.8263909	47.30556	118.2639	260.1806
1.416666667	12.3041613	49.21665	123.0416	270.69155

1.444444444	12.7913925	51.16557	127.9139	281.41064
1.472222222	13.2880845	53.15234	132.8808	292.33786
1.5	13.7942373	55.17695	137.9424	303.47322
1.527777778	14.3098509	57.2394	143.0985	314.81672
1.555555556	14.8349253	59.3397	148.3493	326.36836
1.583333333	15.3694605	61.47784	153.6946	338.12813
1.611111111	15.9134565	63.65383	159.1346	350.09604
1.638888889	16.4669133	65.86765	164.6691	362.27209
1.666666667	17.0298309	68.11932	170.2983	374.65628
1.694444444	17.6022093	70.40884	176.0221	387.2486
1.722222222	18.1840485	72.73619	181.8405	400.04907
1.75	18.7753485	75.10139	187.7535	413.05767
1.777777778	19.3761093	77.50444	193.7611	426.2744
1.805555556	19.9863309	79.94532	199.8633	439.69928
1.833333333	20.6060133	82.42405	206.0601	453.33229
1.861111111	21.2351565	84.94063	212.3516	467.17344
1.888888889	21.8737605	87.49504	218.7376	481.22273
1.916666667	22.5218253	90.0873	225.2183	495.48016
1.944444444	23.1793509	92.7174	231.7935	509.94572
1.972222222	23.8463373	95.38535	238.4634	524.61942
2	24.5227845	98.09114	245.2278	539.50126
2.027777778	25.2086925	100.8348	252.0869	554.59124
2.055555556	25.9040613	103.6162	259.0406	569.88935
2.083333333	26.6088909	106.4356	266.0889	585.3956
2.111111111	27.3231813	109.2927	273.2318	601.10999
2.138888889	28.0469325	112.1877	280.4693	617.03252
2.166666667	28.7801445	115.1206	287.8014	633.16318
2.194444444	29.5228173	118.0913	295.2282	649.50198
2.222222222	30.2749509	121.0998	302.7495	666.04892
2.25	31.0365453	124.1462	310.3655	682.804
2.277777778	31.8076005	127.2304	318.076	699.76721
2.305555556	32.5881165	130.3525	325.8812	716.93856
2.333333333	33.3780933	133.5124	333.7809	734.31805
2.361111111	34.1775309	136.7101	341.7753	751.90568
2.388888889	34.9864293	139.9457	349.8643	769.70144
2.416666667	35.8047885	143.2192	358.0479	787.70535
2.444444444	36.6326085	146.5304	366.3261	805.91739
2.472222222	37.4698893	149.8796	374.6989	824.33756
2.5	38.3166309	153.2665	383.1663	842.96588
2.527777778	39.1728333	156.6913	391.7283	861.80233
2.555555556	40.0384965	160.154	400.385	880.84692
2.583333333	40.9136205	163.6545	409.1362	900.09965
2.611111111	41.7982053	167.1928	417.9821	919.56052
2.638888889	42.6922509	170.769	426.9225	939.22952
2.666666667	43.5957573	174.383	435.9576	959.10666
2.694444444	44.5087245	178.0349	445.0872	979.19194

2.722222222	45.4311525	181.7246	454.3115	999.48536
2.75	46.3630413	185.4522	463.6304	1019.9869
2.777777778	47.3043909	189.2176	473.0439	1040.6966
2.805555556	48.2552013	193.0208	482.552	1061.6144
2.833333333	49.2154725	196.8619	492.1547	1082.7404
2.861111111	50.1852045	200.7408	501.852	1104.0745
2.888888889	51.1643973	204.6576	511.644	1125.6167
2.916666667	52.1530509	208.6122	521.5305	1147.3671
2.944444444	53.1511653	212.6047	531.5117	1169.3256
2.972222222	54.1587405	216.635	541.5874	1191.4923
3	55.1757765	220.7031	551.7578	1213.8671
3.027777778	56.2022733	224.8091	562.0227	1236.45
3.055555556	57.2382309	228.9529	572.3823	1259.2411
3.083333333	58.2836493	233.1346	582.8365	1282.2403
3.111111111	59.3385285	237.3541	593.3853	1305.4476
3.138888889	60.4028685	241.6115	604.0287	1328.8631
3.166666667	61.4766693	245.9067	614.7667	1352.4867
3.194444444	62.5599309	250.2397	625.5993	1376.3185
3.222222222	63.6526533	254.6106	636.5265	1400.3584
3.25	64.7548365	259.0193	647.5484	1424.6064
3.277777778	65.8664805	263.4659	658.6648	1449.0626
3.305555556	66.9875853	267.9503	669.8759	1473.7269
3.333333333	68.1181509	272.4726	681.1815	1498.5993
3.361111111	69.2581773	277.0327	692.5818	1523.6799
3.388888889	70.4076645	281.6307	704.0766	1548.9686
3.416666667	71.5666125	286.2665	715.6661	1574.4655
3.444444444	72.7350213	290.9401	727.3502	1600.1705
3.472222222	73.9128909	295.6516	739.1289	1626.0836
3.5	75.1002213	300.4009	751.0022	1652.2049
3.527777778	76.2970125	305.1881	762.9701	1678.5343
3.555555556	77.5032645	310.0131	775.0326	1705.0718
3.583333333	78.7189773	314.8759	787.1898	1731.8175
3.611111111	79.9441509	319.7766	799.4415	1758.7713
3.638888889	81.1787853	324.7151	811.7879	1785.9333
3.666666667	82.4228805	329.6915	824.2288	1813.3034
3.694444444	83.6764365	334.7057	836.7644	1840.8816
3.722222222	84.9394533	339.7578	849.3945	1868.668
3.75	86.2119309	344.8477	862.1193	1896.6625
3.777777778	87.4938693	349.9755	874.9387	1924.8651
3.805555556	88.7852685	355.1411	887.8527	1953.2759
3.833333333	90.0861285	360.3445	900.8613	1981.8948
3.861111111	91.3964493	365.5858	913.9645	2010.7219
3.888888889	92.7162309	370.8649	927.1623	2039.7571
3.916666667	94.0454733	376.1819	940.4547	2069.0004
3.944444444	95.3841765	381.5367	953.8418	2098.4519
3.972222222	96.7323405	386.9294	967.3234	2128.1115

4	98.0899653	392.3599	980.8997	2157.9792
4.027777778	99.4570509	397.8282	994.5705	2188.0551
4.055555556	100.833597	403.3344	1008.336	2218.3391
4.083333333	102.219605	408.8784	1022.196	2248.8313
4.111111111	103.615073	414.4603	1036.151	2279.5316
4.138888889	105.020001	420.08	1050.2	2310.44
4.166666667	106.434391	425.7376	1064.344	2341.5566
4.194444444	107.858241	431.433	1078.582	2372.8813
4.222222222	109.291553	437.1662	1092.916	2404.4142
4.25	110.734325	442.9373	1107.343	2436.1551
4.277777778	112.186557	448.7462	1121.866	2468.1043
4.305555556	113.648251	454.593	1136.483	2500.2615
4.333333333	115.119405	460.4776	1151.194	2532.6269
4.361111111	116.600021	466.4001	1166	2565.2005
4.388888889	118.090097	472.3604	1180.901	2597.9821
4.416666667	119.589633	478.3585	1195.896	2630.9719
4.444444444	121.098631	484.3945	1210.986	2664.1699
4.472222222	122.617089	490.4684	1226.171	2697.576
4.5	124.145009	496.58	1241.45	2731.1902
4.527777778	125.682389	502.7296	1256.824	2765.0125
4.555555556	127.229229	508.9169	1272.292	2799.043
4.583333333	128.785531	515.1421	1287.855	2833.2817
4.611111111	130.351293	521.4052	1303.513	2867.7285
4.638888889	131.926517	527.7061	1319.265	2902.3834
4.666666667	133.511201	534.0448	1335.112	2937.2464
4.694444444	135.105345	540.4214	1351.053	2972.3176
4.722222222	136.708951	546.8358	1367.09	3007.5969
4.75	138.322017	553.2881	1383.22	3043.0844
4.777777778	139.944545	559.7782	1399.445	3078.78
4.805555556	141.576533	566.3061	1415.765	3114.6837
4.833333333	143.217981	572.8719	1432.18	3150.7956
4.861111111	144.868891	579.4756	1448.689	3187.1156
4.888888889	146.529261	586.117	1465.293	3223.6437
4.916666667	148.199093	592.7964	1481.991	3260.38
4.944444444	149.878385	599.5135	1498.784	3297.3245
4.972222222	151.567137	606.2685	1515.671	3334.477
5	153.265351	613.0614	1532.654	3371.8377
5.027777778	154.973025	619.8921	1549.73	3409.4066
5.055555556	156.690161	626.7606	1566.902	3447.1835
5.083333333	158.416757	633.667	1584.168	3485.1686
5.111111111	160.152813	640.6113	1601.528	3523.3619
5.138888889	161.898331	647.5933	1618.983	3561.7633
5.166666667	163.653309	654.6132	1636.533	3600.3728
5.194444444	165.417749	661.671	1654.177	3639.1905
5.222222222	167.191649	668.7666	1671.916	3678.2163
5.25	168.975009	675.9	1689.75	3717.4502

5.277777778	170.767831	683.0713	1707.678	3756.8923
5.305555556	172.570113	690.2805	1725.701	3796.5425
5.333333333	174.381857	697.5274	1743.819	3836.4008
5.361111111	176.203061	704.8122	1762.031	3876.4673
5.388888889	178.033725	712.1349	1780.337	3916.742
5.416666667	179.873851	719.4954	1798.739	3957.2247
5.444444444	181.723437	726.8937	1817.234	3997.9156
5.472222222	183.582485	734.3299	1835.825	4038.8147
5.5	185.450993	741.804	1854.51	4079.9218
5.527777778	187.328961	749.3158	1873.29	4121.2371
5.555555556	189.216391	756.8656	1892.164	4162.7606
5.583333333	191.113281	764.4531	1911.133	4204.4922
5.611111111	193.019633	772.0785	1930.196	4246.4319
5.638888889	194.935445	779.7418	1949.354	4288.5798
5.666666667	196.860717	787.4429	1968.607	4330.9358
5.694444444	198.795451	795.1818	1987.955	4373.4999
5.722222222	200.739645	802.9586	2007.396	4416.2722
5.75	202.693301	810.7732	2026.933	4459.2526
5.777777778	204.656417	818.6257	2046.564	4502.4412
5.805555556	206.628993	826.516	2066.29	4545.8379
5.833333333	208.611031	834.4441	2086.11	4589.4427
5.861111111	210.602529	842.4101	2106.025	4633.2556
5.888888889	212.603489	850.414	2126.035	4677.2767
5.916666667	214.613909	858.4556	2146.139	4721.506
5.944444444	216.633789	866.5352	2166.338	4765.9434
5.972222222	218.663131	874.6525	2186.631	4810.5889
6	220.701933	882.8077	2207.019	4855.4425
6.027777778	222.750197	891.0008	2227.502	4900.5043
6.055555556	224.807921	899.2317	2248.079	4945.7743
6.083333333	226.875105	907.5004	2268.751	4991.2523
6.111111111	228.951751	915.807	2289.518	5036.9385
6.138888889	231.037857	924.1514	2310.379	5082.8329
6.166666667	233.133425	932.5337	2331.334	5128.9353
6.194444444	235.238453	940.9538	2352.385	5175.246
6.222222222	237.352941	949.4118	2373.529	5221.7647
6.25	239.476891	957.9076	2394.769	5268.4916
6.277777778	241.610301	966.4412	2416.103	5315.4266
6.305555556	243.753173	975.0127	2437.532	5362.5698
6.333333333	245.905505	983.622	2459.055	5409.9211
6.361111111	248.067297	992.2692	2480.673	5457.4805
6.388888889	250.238551	1000.954	2502.386	5505.2481
6.416666667	252.419265	1009.677	2524.193	5553.2238
6.444444444	254.609441	1018.438	2546.094	5601.4077
6.472222222	256.809077	1027.236	2568.091	5649.7997
6.5	259.018173	1036.073	2590.182	5698.3998
6.527777778	261.236731	1044.947	2612.367	5747.2081

6.555555556	263.464749	1053.859	2634.647	5796.2245
6.583333333	265.702229	1062.809	2657.022	5845.449
6.611111111	267.949169	1071.797	2679.492	5894.8817
6.638888889	270.205569	1080.822	2702.056	5944.5225
6.666666667	272.471431	1089.886	2724.714	5994.3715
6.694444444	274.746753	1098.987	2747.468	6044.4286
6.722222222	277.031537	1108.126	2770.315	6094.6938
6.75	279.325781	1117.303	2793.258	6145.1672
6.777777778	281.629485	1126.518	2816.295	6195.8487
6.805555556	283.942651	1135.771	2839.427	6246.7383
6.833333333	286.265277	1145.061	2862.653	6297.8361
6.861111111	288.597365	1154.389	2885.974	6349.142
6.888888889	290.938913	1163.756	2909.389	6400.6561
6.916666667	293.289921	1173.16	2932.899	6452.3783
6.944444444	295.650391	1182.602	2956.504	6504.3086
6.972222222	298.020321	1192.081	2980.203	6556.4471
7	300.399713	1201.599	3003.997	6608.7937
7.027777778	302.788565	1211.154	3027.886	6661.3484
7.055555556	305.186877	1220.748	3051.869	6714.1113
7.083333333	307.594651	1230.379	3075.947	6767.0823
7.111111111	310.011885	1240.048	3100.119	6820.2615
7.138888889	312.438581	1249.754	3124.386	6873.6488
7.166666667	314.874737	1259.499	3148.747	6927.2442
7.194444444	317.320353	1269.281	3173.204	6981.0478
7.222222222	319.775431	1279.102	3197.754	7035.0595
7.25	322.239969	1288.96	3222.4	7089.2793
7.277777778	324.713969	1298.856	3247.14	7143.7073
7.305555556	327.197429	1308.79	3271.974	7198.3434
7.333333333	329.690349	1318.761	3296.903	7253.1877
7.361111111	332.192731	1328.771	3321.927	7308.2401
7.388888889	334.704573	1338.818	3347.046	7363.5006
7.416666667	337.225877	1348.904	3372.259	7418.9693
7.444444444	339.756641	1359.027	3397.566	7474.6461
7.472222222	342.296865	1369.187	3422.969	7530.531
7.5	344.846551	1379.386	3448.466	7586.6241
7.527777778	347.405697	1389.623	3474.057	7642.9253
7.555555556	349.974305	1399.897	3499.743	7699.4347
7.583333333	352.552373	1410.209	3525.524	7756.1522
7.611111111	355.139901	1420.56	3551.399	7813.0778
7.638888889	357.736891	1430.948	3577.369	7870.2116
7.666666667	360.343341	1441.373	3603.433	7927.5535
7.694444444	362.959253	1451.837	3629.593	7985.1036
7.722222222	365.584625	1462.338	3655.846	8042.8617
7.75	368.219457	1472.878	3682.195	8100.8281
7.777777778	370.863751	1483.455	3708.638	8159.0025
7.805555556	373.517505	1494.07	3735.175	8217.3851

7.833333333	376.180721	1504.723	3761.807	8275.9759
7.861111111	378.853397	1515.414	3788.534	8334.7747
7.888888889	381.535533	1526.142	3815.355	8393.7817
7.916666667	384.227131	1536.909	3842.271	8452.9969
7.944444444	386.928189	1547.713	3869.282	8512.4202
7.972222222	389.638709	1558.555	3896.387	8572.0516
8	392.358689	1569.435	3923.587	8631.8911
8.027777778	395.088129	1580.353	3950.881	8691.9388
8.055555556	397.827031	1591.308	3978.27	8752.1947
8.083333333	400.575393	1602.302	4005.754	8812.6587
8.111111111	403.333217	1613.333	4033.332	8873.3308
8.138888889	406.100501	1624.402	4061.005	8934.211
8.166666667	408.877245	1635.509	4088.772	8995.2994
8.194444444	411.663451	1646.654	4116.635	9056.5959
8.222222222	414.459117	1657.836	4144.591	9118.1006
8.25	417.264245	1669.057	4172.642	9179.8134
8.277777778	420.078833	1680.315	4200.788	9241.7343
8.305555556	422.902881	1691.612	4229.029	9303.8634
8.333333333	425.736391	1702.946	4257.364	9366.2006
8.361111111	428.579361	1714.317	4285.794	9428.7459
8.388888889	431.431793	1725.727	4314.318	9491.4994
8.416666667	434.293685	1737.175	4342.937	9554.4611
8.444444444	437.165037	1748.66	4371.65	9617.6308
8.472222222	440.045851	1760.183	4400.459	9681.0087
8.5	442.936125	1771.745	4429.361	9744.5948
8.527777778	445.835861	1783.343	4458.359	9808.3889
8.555555556	448.745057	1794.98	4487.451	9872.3912
8.583333333	451.663713	1806.655	4516.637	9936.6017
8.611111111	454.591831	1818.367	4545.918	10001.02
8.638888889	457.529409	1830.118	4575.294	10065.647
8.666666667	460.476449	1841.906	4604.764	10130.482
8.694444444	463.432949	1853.732	4634.329	10195.525
8.722222222	466.398909	1865.596	4663.989	10260.776
8.75	469.374331	1877.497	4693.743	10326.235
8.777777778	472.359213	1889.437	4723.592	10391.903
8.805555556	475.353557	1901.414	4753.536	10457.778
8.833333333	478.357361	1913.429	4783.574	10523.862
8.861111111	481.370625	1925.483	4813.706	10590.154
8.888888889	484.393351	1937.573	4843.934	10656.654
8.916666667	487.425537	1949.702	4874.255	10723.362
8.944444444	490.467185	1961.869	4904.672	10790.278
8.972222222	493.518293	1974.073	4935.183	10857.402
9	496.578861	1986.315	4965.789	10924.735
9.027777778	499.648891	1998.596	4996.489	10992.276
9.055555556	502.728381	2010.914	5027.284	11060.024
9.083333333	505.817333	2023.269	5058.173	11127.981

9.111111111	508.915745	2035.663	5089.157	11196.146
9.138888889	512.023617	2048.094	5120.236	11264.52
9.166666667	515.140951	2060.564	5151.41	11333.101
9.194444444	518.267745	2073.071	5182.677	11401.89
9.222222222	521.404001	2085.616	5214.04	11470.888
9.25	524.549717	2098.199	5245.497	11540.094
9.277777778	527.704893	2110.82	5277.049	11609.508
9.305555556	530.869531	2123.478	5308.695	11679.13
9.333333333	534.043629	2136.175	5340.436	11748.96
9.361111111	537.227189	2148.909	5372.272	11818.998
9.388888889	540.420209	2161.681	5404.202	11889.245
9.416666667	543.622689	2174.491	5436.227	11959.699
9.444444444	546.834631	2187.339	5468.346	12030.362
9.472222222	550.056033	2200.224	5500.56	12101.233
9.5	553.286897	2213.148	5532.869	12172.312
9.527777778	556.527221	2226.109	5565.272	12243.599
9.555555556	559.777005	2239.108	5597.77	12315.094
9.583333333	563.036251	2252.145	5630.363	12386.798
9.611111111	566.304957	2265.22	5663.05	12458.709
9.638888889	569.583125	2278.332	5695.831	12530.829
9.666666667	572.870753	2291.483	5728.708	12603.157
9.694444444	576.167841	2304.671	5761.678	12675.693
9.722222222	579.474391	2317.898	5794.744	12748.437
9.75	582.790401	2331.162	5827.904	12821.389
9.777777778	586.115873	2344.463	5861.159	12894.549
9.805555556	589.450805	2357.803	5894.508	12967.918
9.833333333	592.795197	2371.181	5927.952	13041.494
9.861111111	596.149051	2384.596	5961.491	13115.279
9.888888889	599.512365	2398.049	5995.124	13189.272
9.916666667	602.885141	2411.541	6028.851	13263.473
9.944444444	606.267377	2425.07	6062.674	13337.882
9.972222222	609.659073	2438.636	6096.591	13412.5
10	613.060231	2452.241	6130.602	13487.325
10.02777778	616.470849	2465.883	6164.708	13562.359
10.05555556	619.890929	2479.564	6198.909	13637.6
10.08333333	623.320469	2493.282	6233.205	13713.05
10.11111111	626.759469	2507.038	6267.595	13788.708
10.13888889	630.207931	2520.832	6302.079	13864.574
10.16666667	633.665853	2534.663	6336.659	13940.649
10.19444444	637.133237	2548.533	6371.332	14016.931
10.22222222	640.610081	2562.44	6406.101	14093.422
10.25	644.096385	2576.386	6440.964	14170.12
10.27777778	647.592151	2590.369	6475.922	14247.027
10.30555556	651.097377	2604.39	6510.974	14324.142
10.33333333	654.612065	2618.448	6546.121	14401.465
10.36111111	658.136213	2632.545	6581.362	14478.997

10.38888889	661.669821	2646.679	6616.698	14556.736
10.41666667	665.212891	2660.852	6652.129	14634.684
10.44444444	668.765421	2675.062	6687.654	14712.839
10.47222222	672.327413	2689.31	6723.274	14791.203
10.5	675.898865	2703.595	6758.989	14869.775
10.52777778	679.479777	2717.919	6794.798	14948.555
10.55555556	683.070151	2732.281	6830.702	15027.543
10.58333333	686.669985	2746.68	6866.7	15106.74
10.61111111	690.279281	2761.117	6902.793	15186.144
10.63888889	693.898037	2775.592	6938.98	15265.757
10.66666667	697.526253	2790.105	6975.263	15345.578
10.69444444	701.163931	2804.656	7011.639	15425.606
10.72222222	704.811069	2819.244	7048.111	15505.844
10.75	708.467669	2833.871	7084.677	15586.289
10.77777778	712.133729	2848.535	7121.337	15666.942
10.80555556	715.809249	2863.237	7158.092	15747.803
10.83333333	719.494231	2877.977	7194.942	15828.873
10.86111111	723.188673	2892.755	7231.887	15910.151
10.88888889	726.892577	2907.57	7268.926	15991.637
10.91666667	730.605941	2922.424	7306.059	16073.331
10.94444444	734.328765	2937.315	7343.288	16155.233
10.97222222	738.061051	2952.244	7380.611	16237.343
11	741.802797	2967.211	7418.028	16319.662
11.02777778	745.554005	2982.216	7455.54	16402.188
11.05555556	749.314673	2997.259	7493.147	16484.923
11.08333333	753.084801	3012.339	7530.848	16567.866
11.11111111	756.864391	3027.458	7568.644	16651.017
11.13888889	760.653441	3042.614	7606.534	16734.376
11.16666667	764.451953	3057.808	7644.52	16817.943
11.19444444	768.259925	3073.04	7682.599	16901.718
11.22222222	772.077357	3088.309	7720.774	16985.702
11.25	775.904251	3103.617	7759.043	17069.894
11.27777778	779.740605	3118.962	7797.406	17154.293
11.30555556	783.586421	3134.346	7835.864	17238.901
11.33333333	787.441697	3149.767	7874.417	17323.717
11.36111111	791.306433	3165.226	7913.064	17408.742
11.38888889	795.180631	3180.723	7951.806	17493.974
11.41666667	799.064289	3196.257	7990.643	17579.414
11.44444444	802.957409	3211.83	8029.574	17665.063
11.47222222	806.859989	3227.44	8068.6	17750.92
11.5	810.772029	3243.088	8107.72	17836.985
11.52777778	814.693531	3258.774	8146.935	17923.258
11.55555556	818.624493	3274.498	8186.245	18009.739
11.58333333	822.564917	3290.26	8225.649	18096.428
11.61111111	826.514801	3306.059	8265.148	18183.326
11.63888889	830.474145	3321.897	8304.741	18270.431

11.66666667	834.442951	3337.772	8344.43	18357.745
11.69444444	838.421217	3353.685	8384.212	18445.267
11.72222222	842.408945	3369.636	8424.089	18532.997
11.75	846.406133	3385.625	8464.061	18620.935
11.77777778	850.412781	3401.651	8504.128	18709.081
11.80555556	854.428891	3417.716	8544.289	18797.436
11.83333333	858.454461	3433.818	8584.545	18885.998
11.86111111	862.489493	3449.958	8624.895	18974.769
11.88888889	866.533985	3466.136	8665.34	19063.748
11.91666667	870.587937	3482.352	8705.879	19152.935
11.94444444	874.651351	3498.605	8746.514	19242.33
11.97222222	878.724225	3514.897	8787.242	19331.933
12	882.806561	3531.226	8828.066	19421.744
12.02777778	886.898357	3547.593	8868.984	19511.764
12.05555556	890.999613	3563.998	8909.996	19601.991
12.08333333	895.110331	3580.441	8951.103	19692.427
12.11111111	899.230509	3596.922	8992.305	19783.071
12.13888889	903.360149	3613.441	9033.601	19873.923
12.16666667	907.499249	3629.997	9074.992	19964.983
12.19444444	911.647809	3646.591	9116.478	20056.252
12.22222222	915.805831	3663.223	9158.058	20147.728
12.25	919.973313	3679.893	9199.733	20239.413
12.27777778	924.150257	3696.601	9241.503	20331.306
12.30555556	928.336661	3713.347	9283.367	20423.407
12.33333333	932.532525	3730.13	9325.325	20515.716
12.36111111	936.737851	3746.951	9367.379	20608.233
12.38888889	940.952637	3763.811	9409.526	20700.958
12.41666667	945.176885	3780.708	9451.769	20793.891
12.44444444	949.410593	3797.642	9494.106	20887.033
12.47222222	953.653761	3814.615	9536.538	20980.383
12.5	957.906391	3831.626	9579.064	21073.941
12.52777778	962.168481	3848.674	9621.685	21167.707
12.55555556	966.440033	3865.76	9664.4	21261.681
12.58333333	970.721045	3882.884	9707.21	21355.863
12.61111111	975.011517	3900.046	9750.115	21450.253
12.63888889	979.311451	3917.246	9793.115	21544.852
12.66666667	983.620845	3934.483	9836.208	21639.659
12.69444444	987.939701	3951.759	9879.397	21734.673
12.72222222	992.268017	3969.072	9922.68	21829.896
12.75	996.605793	3986.423	9966.058	21925.327
12.77777778	1000.95303	4003.812	10009.53	22020.967
12.80555556	1005.30973	4021.239	10053.1	22116.814
12.83333333	1009.67589	4038.704	10096.76	22212.87
12.86111111	1014.05151	4056.206	10140.52	22309.133
12.88888889	1018.43659	4073.746	10184.37	22405.605
12.91666667	1022.83113	4091.325	10228.31	22502.285

12.94444444	1027.23513	4108.941	10272.35	22599.173
12.97222222	1031.6486	4126.594	10316.49	22696.269
13	1036.07152	4144.286	10360.72	22793.573
13.02777778	1040.50391	4162.016	10405.04	22891.086
13.05555556	1044.94575	4179.783	10449.46	22988.807
13.08333333	1049.39706	4197.588	10493.97	23086.735
13.11111111	1053.85782	4215.431	10538.58	23184.872
13.13888889	1058.32805	4233.312	10583.28	23283.217
13.16666667	1062.80774	4251.231	10628.08	23381.77
13.19444444	1067.29689	4269.188	10672.97	23480.532
13.22222222	1071.7955	4287.182	10717.96	23579.501
13.25	1076.30357	4305.214	10763.04	23678.679
13.27777778	1080.8211	4323.284	10808.21	23778.064
13.30555556	1085.3481	4341.392	10853.48	23877.658
13.33333333	1089.88455	4359.538	10898.85	23977.46
13.36111111	1094.43047	4377.722	10944.3	24077.47
13.38888889	1098.98584	4395.943	10989.86	24177.688
13.41666667	1103.55068	4414.203	11035.51	24278.115
13.44444444	1108.12497	4432.5	11081.25	24378.749
13.47222222	1112.70873	4450.835	11127.09	24479.592
13.5	1117.30195	4469.208	11173.02	24580.643
13.52777778	1121.90463	4487.619	11219.05	24681.902
13.55555556	1126.51677	4506.067	11265.17	24783.369
13.58333333	1131.13837	4524.553	11311.38	24885.044
13.61111111	1135.76943	4543.078	11357.69	24986.927
13.63888889	1140.40995	4561.64	11404.1	25089.019
13.66666667	1145.05994	4580.24	11450.6	25191.319
13.69444444	1149.71938	4598.878	11497.19	25293.826
13.72222222	1154.38829	4617.553	11543.88	25396.542
13.75	1159.06665	4636.267	11590.67	25499.466
13.77777778	1163.75448	4655.018	11637.54	25602.599
13.80555556	1168.45176	4673.807	11684.52	25705.939
13.83333333	1173.15851	4692.634	11731.59	25809.487
13.86111111	1177.87472	4711.499	11778.75	25913.244
13.88888889	1182.60039	4730.402	11826	26017.209

Figure F.3: Potential incident energy in equipment curve data

Multiple of Pickup	Incident Energy (cal/cm^2)			
	Time Dial 0.5	Time Dial 2	Time Dial 5	Time Dial 11
0.694444444	3.70106811	14.80427	37.01068	81.423498
0.722222222	3.85853784	15.43415	38.58538	84.887833
0.75	4.01638871	16.06555	40.16389	88.360552
0.777777778	4.17460738	16.69843	41.74607	91.841362
0.805555556	4.33318143	17.33273	43.33181	95.329991
0.833333333	4.49209929	17.9684	44.92099	98.826184

0.861111111	4.65135015	18.6054	46.5135	102.3297
0.888888889	4.81092387	19.2437	48.10924	105.84033
0.916666667	4.97081094	19.88324	49.70811	109.35784
0.944444444	5.13100241	20.52401	51.31002	112.88205
0.972222222	5.29148984	21.16596	52.9149	116.41278
1	5.45226525	21.80906	54.52265	119.94984
1.027777778	5.61332113	22.45328	56.13321	123.49306
1.055555556	5.77465032	23.0986	57.7465	127.04231
1.083333333	5.93624605	23.74498	59.36246	130.59741
1.111111111	6.09810189	24.39241	60.98102	134.15824
1.138888889	6.26021173	25.04085	62.60212	137.72466
1.166666667	6.42256973	25.69028	64.2257	141.29653
1.194444444	6.58517033	26.34068	65.8517	144.87375
1.222222222	6.74800822	26.99203	67.48008	148.45618
1.25	6.91107834	27.64431	69.11078	152.04372
1.277777778	7.07437583	28.2975	70.74376	155.63627
1.305555556	7.23789604	28.95158	72.37896	159.23371
1.333333333	7.40163452	29.60654	74.01635	162.83596
1.361111111	7.56558698	30.26235	75.65587	166.44291
1.388888889	7.72974934	30.919	77.29749	170.05449
1.416666667	7.89411763	31.57647	78.94118	173.67059
1.444444444	8.05868807	32.23475	80.58688	177.29114
1.472222222	8.223457	32.89383	82.23457	180.91605
1.5	8.38842091	33.55368	83.88421	184.54526
1.527777778	8.55357639	34.21431	85.53576	188.17868
1.555555556	8.71892019	34.87568	87.1892	191.81624
1.583333333	8.88444913	35.5378	88.84449	195.45788
1.611111111	9.05016017	36.20064	90.5016	199.10352
1.638888889	9.21605036	36.8642	92.1605	202.75311
1.666666667	9.38211685	37.52847	93.82117	206.40657
1.694444444	9.54835687	38.19343	95.48357	210.06385
1.722222222	9.71476776	38.85907	97.14768	213.72489
1.75	9.88134693	39.52539	98.81347	217.38963
1.777777778	10.0480919	40.19237	100.4809	221.05802
1.805555556	10.2150001	40.86	102.15	224.73
1.833333333	10.3820694	41.52828	103.8207	228.40553
1.861111111	10.5492973	42.19719	105.493	232.08454
1.888888889	10.7166817	42.86673	107.1668	235.767
1.916666667	10.8842204	43.53688	108.8422	239.45285
1.944444444	11.0519113	44.20765	110.5191	243.14205
1.972222222	11.2197524	44.87901	112.1975	246.83455
2	11.3877416	45.55097	113.8774	250.53032
2.027777778	11.5558771	46.22351	115.5588	254.2293
2.055555556	11.724157	46.89663	117.2416	257.93145
2.083333333	11.8925793	47.57032	118.9258	261.63675
2.111111111	12.0611425	48.24457	120.6114	265.34513

2.138888889	12.2298446	48.91938	122.2984	269.05658
2.166666667	12.3986841	49.59474	123.9868	272.77105
2.194444444	12.5676592	50.27064	125.6766	276.4885
2.222222222	12.7367684	50.94707	127.3677	280.2089
2.25	12.90601	51.62404	129.0601	283.93222
2.277777778	13.0753826	52.30153	130.7538	287.65842
2.305555556	13.2448847	52.97954	132.4488	291.38746
2.333333333	13.4145147	53.65806	134.1451	295.11932
2.361111111	13.5842713	54.33709	135.8427	298.85397
2.388888889	13.754153	55.01661	137.5415	302.59137
2.416666667	13.9241586	55.69663	139.2416	306.33149
2.444444444	14.0942866	56.37715	140.9429	310.0743
2.472222222	14.2645357	57.05814	142.6454	313.81979
2.5	14.4349047	57.73962	144.349	317.5679
2.527777778	14.6053923	58.42157	146.0539	321.31863
2.555555556	14.7759974	59.10399	147.76	325.07194
2.583333333	14.9467186	59.78687	149.4672	328.82781
2.611111111	15.1175549	60.47022	151.1755	332.58621
2.638888889	15.288505	61.15402	152.885	336.34711
2.666666667	15.4595679	61.83827	154.5957	340.11049
2.694444444	15.6307424	62.52297	156.3074	343.87633
2.722222222	15.8020276	63.20811	158.0203	347.64461
2.75	15.9734222	63.89369	159.7342	351.41529
2.777777778	16.1449253	64.5797	161.4493	355.18836
2.805555556	16.3165359	65.26614	163.1654	358.96379
2.833333333	16.488253	65.95301	164.8825	362.74157
2.861111111	16.6600755	66.6403	166.6008	366.52166
2.888888889	16.8320026	67.32801	168.32	370.30406
2.916666667	17.0040332	68.01613	170.0403	374.08873
2.944444444	17.1761665	68.70467	171.7617	377.87566
2.972222222	17.3484015	69.39361	173.484	381.66483
3	17.5207374	70.08295	175.2074	385.45622
3.027777778	17.6931733	70.77269	176.9317	389.24981
3.055555556	17.8657082	71.46283	178.6571	393.04558
3.083333333	18.0383415	72.15337	180.3834	396.84351
3.111111111	18.2110722	72.84429	182.1107	400.64359
3.138888889	18.3838995	73.5356	183.839	404.44579
3.166666667	18.5568227	74.22729	185.5682	408.2501
3.194444444	18.7298409	74.91936	187.2984	412.0565
3.222222222	18.9029533	75.61181	189.0295	415.86497
3.25	19.0761592	76.30464	190.7616	419.6755
3.277777778	19.2494579	76.99783	192.4946	423.48807
3.305555556	19.4228486	77.69139	194.2285	427.30267
3.333333333	19.5963306	78.38532	195.9633	431.11927
3.361111111	19.7699032	79.07961	197.699	434.93787
3.388888889	19.9435656	79.77426	199.4357	438.75844

3.416666667	20.1173172	80.46927	201.1732	442.58098
3.444444444	20.2911573	81.16463	202.9116	446.40546
3.472222222	20.4650852	81.86034	204.6509	450.23188
3.5	20.6391003	82.5564	206.391	454.06021
3.527777778	20.813202	83.25281	208.132	457.89044
3.555555556	20.9873895	83.94956	209.8739	461.72257
3.583333333	21.1616623	84.64665	211.6166	465.55657
3.611111111	21.3360197	85.34408	213.3602	469.39243
3.638888889	21.5104611	86.04184	215.1046	473.23014
3.666666667	21.6849859	86.73994	216.8499	477.06969
3.694444444	21.8595936	87.43837	218.5959	480.91106
3.722222222	22.0342835	88.13713	220.3428	484.75424
3.75	22.2090551	88.83622	222.0906	488.59921
3.777777778	22.3839078	89.53563	223.8391	492.44597
3.805555556	22.558841	90.23536	225.5884	496.2945
3.833333333	22.7338542	90.93542	227.3385	500.14479
3.861111111	22.9089469	91.63579	229.0895	503.99683
3.888888889	23.0841185	92.33647	230.8412	507.85061
3.916666667	23.2593685	93.03747	232.5937	511.70611
3.944444444	23.4346963	93.73879	234.347	515.56332
3.972222222	23.6101015	94.44041	236.101	519.42223
4	23.7855835	95.14233	237.8558	523.28284
4.027777778	23.9611418	95.84457	239.6114	527.14512
4.055555556	24.136776	96.5471	241.3678	531.00907
4.083333333	24.3124856	97.24994	243.1249	534.87468
4.111111111	24.48827	97.95308	244.8827	538.74194
4.138888889	24.6641289	98.65652	246.6413	542.61084
4.166666667	24.8400616	99.36025	248.4006	546.48136
4.194444444	25.0160679	100.0643	250.1607	550.35349
4.222222222	25.1921472	100.7686	251.9215	554.22724
4.25	25.368299	101.4732	253.683	558.10258
4.277777778	25.5445229	102.1781	255.4452	561.9795
4.305555556	25.7208186	102.8833	257.2082	565.85801
4.333333333	25.8971855	103.5887	258.9719	569.73808
4.361111111	26.0736232	104.2945	260.7362	573.61971
4.388888889	26.2501313	105.0005	262.5013	577.50289
4.416666667	26.4267094	105.7068	264.2671	581.38761
4.444444444	26.603357	106.4134	266.0336	585.27385
4.472222222	26.7800738	107.1203	267.8007	589.16162
4.5	26.9568594	107.8274	269.5686	593.05091
4.527777778	27.1337133	108.5349	271.3371	596.94169
4.555555556	27.3106352	109.2425	273.1064	600.83397
4.583333333	27.4876246	109.9505	274.8762	604.72774
4.611111111	27.6646813	110.6587	276.6468	608.62299
4.638888889	27.8418048	111.3672	278.418	612.5197
4.666666667	28.0189947	112.076	280.1899	616.41788

4.694444444	28.1962506	112.785	281.9625	620.31751
4.722222222	28.3735723	113.4943	283.7357	624.21859
4.75	28.5509593	114.2038	285.5096	628.12111
4.777777778	28.7284113	114.9136	287.2841	632.02505
4.805555556	28.9059279	115.6237	289.0593	635.93041
4.833333333	29.0835088	116.334	290.8351	639.83719
4.861111111	29.2611536	117.0446	292.6115	643.74538
4.888888889	29.438862	117.7554	294.3886	647.65497
4.916666667	29.6166337	118.4665	296.1663	651.56594
4.944444444	29.7944683	119.1779	297.9447	655.4783
4.972222222	29.9723654	119.8895	299.7237	659.39204
5	30.1503248	120.6013	301.5032	663.30715
5.027777778	30.3283461	121.3134	303.2835	667.22361
5.055555556	30.5064291	122.0257	305.0643	671.14144
5.083333333	30.6845733	122.7383	306.8457	675.06061
5.111111111	30.8627785	123.4511	308.6278	678.98113
5.138888889	31.0410444	124.1642	310.4104	682.90298
5.166666667	31.2193706	124.8775	312.1937	686.82615
5.194444444	31.3977569	125.591	313.9776	690.75065
5.222222222	31.5762029	126.3048	315.762	694.67646
5.25	31.7547084	127.0188	317.5471	698.60358
5.277777778	31.933273	127.7331	319.3327	702.53201
5.305555556	32.1118965	128.4476	321.119	706.46172
5.333333333	32.2905786	129.1623	322.9058	710.39273
5.361111111	32.469319	129.8773	324.6932	714.32502
5.388888889	32.6481174	130.5925	326.4812	718.25858
5.416666667	32.8269735	131.3079	328.2697	722.19342
5.444444444	33.0058871	132.0235	330.0589	726.12952
5.472222222	33.1848578	132.7394	331.8486	730.06687
5.5	33.3638855	133.4555	333.6389	734.00548
5.527777778	33.5429698	134.1719	335.4297	737.94534
5.555555556	33.7221104	134.8884	337.2211	741.88643
5.583333333	33.9013072	135.6052	339.0131	745.82876
5.611111111	34.0805598	136.3222	340.8056	749.77232
5.638888889	34.259868	137.0395	342.5987	753.7171
5.666666667	34.4392315	137.7569	344.3923	757.66309
5.694444444	34.6186501	138.4746	346.1865	761.6103
5.722222222	34.7981235	139.1925	347.9812	765.55872
5.75	34.9776515	139.9106	349.7765	769.50833
5.777777778	35.1572338	140.6289	351.5723	773.45914
5.805555556	35.3368702	141.3475	353.3687	777.41114
5.833333333	35.5165604	142.0662	355.1656	781.36433
5.861111111	35.6963042	142.7852	356.963	785.31869
5.888888889	35.8761014	143.5044	358.761	789.27423
5.916666667	36.0559516	144.2238	360.5595	793.23094
5.944444444	36.2358548	144.9434	362.3585	797.18881

5.972222222	36.4158106	145.6632	364.1581	801.14783
6	36.5958189	146.3833	365.9582	805.10802
6.027777778	36.7758794	147.1035	367.7588	809.06935
6.055555556	36.9559918	147.824	369.5599	813.03182
6.083333333	37.136156	148.5446	371.3616	816.99543
6.111111111	37.3163717	149.2655	373.1637	820.96018
6.138888889	37.4966387	149.9866	374.9664	824.92605
6.166666667	37.6769568	150.7078	376.7696	828.89305
6.194444444	37.8573258	151.4293	378.5733	832.86117
6.222222222	38.0377454	152.151	380.3775	836.8304
6.25	38.2182155	152.8729	382.1822	840.80074
6.277777778	38.3987358	153.5949	383.9874	844.77219
6.305555556	38.5793062	154.3172	385.7931	848.74474
6.333333333	38.7599264	155.0397	387.5993	852.71838
6.361111111	38.9405962	155.7624	389.406	856.69312
6.388888889	39.1213154	156.4853	391.2132	860.66894
6.416666667	39.3020838	157.2083	393.0208	864.64584
6.444444444	39.4829013	157.9316	394.829	868.62383
6.472222222	39.6637675	158.6551	396.6377	872.60289
6.5	39.8446824	159.3787	398.4468	876.58301
6.527777778	40.0256457	160.1026	400.2565	880.56421
6.555555556	40.2066573	160.8266	402.0666	884.54646
6.583333333	40.3877168	161.5509	403.8772	888.52977
6.611111111	40.5688243	162.2753	405.6882	892.51413
6.638888889	40.7499794	162.9999	407.4998	896.49955
6.666666667	40.9311819	163.7247	409.3118	900.486
6.694444444	41.1124318	164.4497	411.1243	904.4735
6.722222222	41.2937287	165.1749	412.9373	908.46203
6.75	41.4750726	165.9003	414.7507	912.4516
6.777777778	41.6564633	166.6259	416.5646	916.44219
6.805555556	41.8379004	167.3516	418.379	920.43381
6.833333333	42.019384	168.0775	420.1938	924.42645
6.861111111	42.2009138	168.8037	422.0091	928.4201
6.888888889	42.3824896	169.53	423.8249	932.41477
6.916666667	42.5641113	170.2564	425.6411	936.41045
6.944444444	42.7457786	170.9831	427.4578	940.40713
6.972222222	42.9274915	171.71	429.2749	944.40481
7	43.1092497	172.437	431.0925	948.40349
7.027777778	43.2910531	173.1642	432.9105	952.40317
7.055555556	43.4729015	173.8916	434.729	956.40383
7.083333333	43.6547947	174.6192	436.5479	960.40548
7.111111111	43.8367326	175.3469	438.3673	964.40812
7.138888889	44.018715	176.0749	440.1872	968.41173
7.166666667	44.2007418	176.803	442.0074	972.41632
7.194444444	44.3828128	177.5313	443.8281	976.42188
7.222222222	44.5649278	178.2597	445.6493	980.42841

7.25	44.7470866	178.9883	447.4709	984.43591
7.277777778	44.9292892	179.7172	449.2929	988.44436
7.305555556	45.1115354	180.4461	451.1154	992.45378
7.333333333	45.2938249	181.1753	452.9382	996.46415
7.361111111	45.4761577	181.9046	454.7616	1000.4755
7.388888889	45.6585335	182.6341	456.5853	1004.4877
7.416666667	45.8409524	183.3638	458.4095	1008.501
7.444444444	46.023414	184.0937	460.2341	1012.5151
7.472222222	46.2059182	184.8237	462.0592	1016.5302
7.5	46.388465	185.5539	463.8846	1020.5462
7.527777778	46.5710541	186.2842	465.7105	1024.5632
7.555555556	46.7536854	187.0147	467.5369	1028.5811
7.583333333	46.9363587	187.7454	469.3636	1032.5999
7.611111111	47.119074	188.4763	471.1907	1036.6196
7.638888889	47.301831	189.2073	473.0183	1040.6403
7.666666667	47.4846296	189.9385	474.8463	1044.6619
7.694444444	47.6674697	190.6699	476.6747	1048.6843
7.722222222	47.8503512	191.4014	478.5035	1052.7077
7.75	48.0332739	192.1331	480.3327	1056.732
7.777777778	48.2162376	192.865	482.1624	1060.7572
7.805555556	48.3992423	193.597	483.9924	1064.7833
7.833333333	48.5822877	194.3292	485.8229	1068.8103
7.861111111	48.7653738	195.0615	487.6537	1072.8382
7.888888889	48.9485004	195.794	489.485	1076.867
7.916666667	49.1316675	196.5267	491.3167	1080.8967
7.944444444	49.3148747	197.2595	493.1487	1084.9272
7.972222222	49.4981221	197.9925	494.9812	1088.9587
8	49.6814095	198.7256	496.8141	1092.991
8.027777778	49.8647367	199.4589	498.6474	1097.0242
8.055555556	50.0481037	200.1924	500.481	1101.0583
8.083333333	50.2315102	200.926	502.3151	1105.0932
8.111111111	50.4149563	201.6598	504.1496	1109.129
8.138888889	50.5984417	202.3938	505.9844	1113.1657
8.166666667	50.7819663	203.1279	507.8197	1117.2033
8.194444444	50.96553	203.8621	509.6553	1121.2417
8.222222222	51.1491327	204.5965	511.4913	1125.2809
8.25	51.3327742	205.3311	513.3277	1129.321
8.277777778	51.5164544	206.0658	515.1645	1133.362
8.305555556	51.7001733	206.8007	517.0017	1137.4038
8.333333333	51.8839306	207.5357	518.8393	1141.4465
8.361111111	52.0677263	208.2709	520.6773	1145.49
8.388888889	52.2515603	209.0062	522.5156	1149.5343
8.416666667	52.4354324	209.7417	524.3543	1153.5795
8.444444444	52.6193424	210.4774	526.1934	1157.6255
8.472222222	52.8032904	211.2132	528.0329	1161.6724
8.5	52.9872761	211.9491	529.8728	1165.7201

8.527777778	53.1712995	212.6852	531.713	1169.7686
8.555555556	53.3553605	213.4214	533.5536	1173.8179
8.583333333	53.5394589	214.1578	535.3946	1177.8681
8.611111111	53.7235945	214.8944	537.2359	1181.9191
8.638888889	53.9077674	215.6311	539.0777	1185.9709
8.666666667	54.0919774	216.3679	540.9198	1190.0235
8.694444444	54.2762244	217.1049	542.7622	1194.0769
8.722222222	54.4605082	217.842	544.6051	1198.1312
8.75	54.6448288	218.5793	546.4483	1202.1862
8.777777778	54.829186	219.3167	548.2919	1206.2421
8.805555556	55.0135798	220.0543	550.1358	1210.2988
8.833333333	55.19801	220.792	551.9801	1214.3562
8.861111111	55.3824765	221.5299	553.8248	1218.4145
8.888888889	55.5669792	222.2679	555.6698	1222.4735
8.916666667	55.7515181	223.0061	557.5152	1226.5334
8.944444444	55.9360929	223.7444	559.3609	1230.594
8.972222222	56.1207037	224.4828	561.207	1234.6555
9	56.3053503	225.2214	563.0535	1238.7177
9.027777778	56.4900325	225.9601	564.9003	1242.7807
9.055555556	56.6747503	226.699	566.7475	1246.8445
9.083333333	56.8595037	227.438	568.595	1250.9091
9.111111111	57.0442924	228.1772	570.4429	1254.9744
9.138888889	57.2291164	228.9165	572.2912	1259.0406
9.166666667	57.4139756	229.6559	574.1398	1263.1075
9.194444444	57.5988698	230.3955	575.9887	1267.1751
9.222222222	57.7837991	231.1352	577.838	1271.2436
9.25	57.9687632	231.8751	579.6876	1275.3128
9.277777778	58.1537621	232.615	581.5376	1279.3828
9.305555556	58.3387957	233.3552	583.388	1283.4535
9.333333333	58.5238639	234.0955	585.2386	1287.525
9.361111111	58.7089667	234.8359	587.0897	1291.5973
9.388888889	58.8941038	235.5764	588.941	1295.6703
9.416666667	59.0792752	236.3171	590.7928	1299.7441
9.444444444	59.2644808	237.0579	592.6448	1303.8186
9.472222222	59.4497205	237.7989	594.4972	1307.8939
9.5	59.6349943	238.54	596.3499	1311.9699
9.527777778	59.820302	239.2812	598.203	1316.0466
9.555555556	60.0056435	240.0226	600.0564	1320.1242
9.583333333	60.1910188	240.7641	601.9102	1324.2024
9.611111111	60.3764277	241.5057	603.7643	1328.2814
9.638888889	60.5618702	242.2475	605.6187	1332.3611
9.666666667	60.7473461	242.9894	607.4735	1336.4416
9.694444444	60.9328554	243.7314	609.3286	1340.5228
9.722222222	61.1183981	244.4736	611.184	1344.6048
9.75	61.3039739	245.2159	613.0397	1348.6874
9.777777778	61.4895828	245.9583	614.8958	1352.7708

9.805555556	61.6752248	246.7009	616.7522	1356.8549
9.833333333	61.8608997	247.4436	618.609	1360.9398
9.861111111	62.0466074	248.1864	620.4661	1365.0254
9.888888889	62.2323479	248.9294	622.3235	1369.1117
9.916666667	62.4181211	249.6725	624.1812	1373.1987
9.944444444	62.6039269	250.4157	626.0393	1377.2864
9.972222222	62.7897652	251.1591	627.8977	1381.3748
10	62.9756359	251.9025	629.7564	1385.464
10.02777778	63.1615389	252.6462	631.6154	1389.5539
10.05555556	63.3474742	253.3899	633.4747	1393.6444
10.08333333	63.5334417	254.1338	635.3344	1397.7357
10.11111111	63.7194412	254.8778	637.1944	1401.8277
10.13888889	63.9054728	255.6219	639.0547	1405.9204
10.16666667	64.0915362	256.3661	640.9154	1410.0138
10.19444444	64.2776315	257.1105	642.7763	1414.1079
10.22222222	64.4637586	257.855	644.6376	1418.2027
10.25	64.6499174	258.5997	646.4992	1422.2982
10.27777778	64.8361077	259.3444	648.3611	1426.3944
10.30555556	65.0223296	260.0893	650.2233	1430.4913
10.33333333	65.2085828	260.8343	652.0858	1434.5888
10.36111111	65.3948675	261.5795	653.9487	1438.6871
10.38888889	65.5811834	262.3247	655.8118	1442.786
10.41666667	65.7675305	263.0701	657.6753	1446.8857
10.44444444	65.9539088	263.8156	659.5391	1450.986
10.47222222	66.1403181	264.5613	661.4032	1455.087
10.5	66.3267584	265.307	663.2676	1459.1887
10.52777778	66.5132295	266.0529	665.1323	1463.291
10.55555556	66.6997315	266.7989	666.9973	1467.3941
10.58333333	66.8862642	267.5451	668.8626	1471.4978
10.61111111	67.0728275	268.2913	670.7283	1475.6022
10.63888889	67.2594215	269.0377	672.5942	1479.7073
10.66666667	67.446046	269.7842	674.4605	1483.813
10.69444444	67.6327009	270.5308	676.327	1487.9194
10.72222222	67.8193861	271.2775	678.1939	1492.0265
10.75	68.0061017	272.0244	680.061	1496.1342
10.77777778	68.1928475	272.7714	681.9285	1500.2426
10.80555556	68.3796234	273.5185	683.7962	1504.3517
10.83333333	68.5664294	274.2657	685.6643	1508.4614
10.86111111	68.7532654	275.0131	687.5327	1512.5718
10.88888889	68.9401313	275.7605	689.4013	1516.6829
10.91666667	69.1270271	276.5081	691.2703	1520.7946
10.94444444	69.3139526	277.2558	693.1395	1524.907
10.97222222	69.5009079	278.0036	695.0091	1529.02
11	69.6878928	278.7516	696.8789	1533.1336
11.02777778	69.8749073	279.4996	698.7491	1537.248
11.05555556	70.0619513	280.2478	700.6195	1541.3629

11.08333333	70.2490247	280.9961	702.4902	1545.4785
11.11111111	70.4361275	281.7445	704.3613	1549.5948
11.13888889	70.6232595	282.493	706.2326	1553.7117
11.16666667	70.8104208	283.2417	708.1042	1557.8293
11.19444444	70.9976113	283.9904	709.9761	1561.9474
11.22222222	71.1848308	284.7393	711.8483	1566.0663
11.25	71.3720794	285.4883	713.7208	1570.1857
11.27777778	71.559357	286.2374	715.5936	1574.3059
11.30555556	71.7466634	286.9867	717.4666	1578.4266
11.33333333	71.9339986	287.736	719.34	1582.548
11.36111111	72.1213626	288.4855	721.2136	1586.67
11.38888889	72.3087553	289.235	723.0876	1590.7926
11.41666667	72.4961766	289.9847	724.9618	1594.9159
11.44444444	72.6836265	290.7345	726.8363	1599.0398
11.47222222	72.8711049	291.4844	728.711	1603.1643
11.5	73.0586117	292.2344	730.5861	1607.2895
11.52777778	73.2461468	292.9846	732.4615	1611.4152
11.55555556	73.4337103	293.7348	734.3371	1615.5416
11.58333333	73.621302	294.4852	736.213	1619.6686
11.61111111	73.8089219	295.2357	738.0892	1623.7963
11.63888889	73.9965699	295.9863	739.9657	1627.9245
11.66666667	74.1842459	296.737	741.8425	1632.0534
11.69444444	74.3719499	297.4878	743.7195	1636.1829
11.72222222	74.5596819	298.2387	745.5968	1640.313
11.75	74.7474417	298.9898	747.4744	1644.4437
11.77777778	74.9352293	299.7409	749.3523	1648.575
11.80555556	75.1230446	300.4922	751.2304	1652.707
11.83333333	75.3108876	301.2436	753.1089	1656.8395
11.86111111	75.4987583	301.995	754.9876	1660.9727
11.88888889	75.6866565	302.7466	756.8666	1665.1064
11.91666667	75.8745821	303.4983	758.7458	1669.2408
11.94444444	76.0625353	304.2501	760.6254	1673.3758
11.97222222	76.2505158	305.0021	762.5052	1677.5113
12	76.4385236	305.7541	764.3852	1681.6475
12.02777778	76.6265586	306.5062	766.2656	1685.7843
12.05555556	76.8146209	307.2585	768.1462	1689.9217
12.08333333	77.0027103	308.0108	770.0271	1694.0596
12.11111111	77.1908268	308.7633	771.9083	1698.1982
12.13888889	77.3789703	309.5159	773.7897	1702.3373
12.16666667	77.5671408	310.2686	775.6714	1706.4771
12.19444444	77.7553381	311.0214	777.5534	1710.6174
12.22222222	77.9435623	311.7742	779.4356	1714.7584
12.25	78.1318134	312.5273	781.3181	1718.8999
12.27777778	78.3200911	313.2804	783.2009	1723.042
12.30555556	78.5083955	314.0336	785.084	1727.1847
12.33333333	78.6967266	314.7869	786.9673	1731.328

12.36111111	78.8850842	315.5403	788.8508	1735.4719
12.38888889	79.0734683	316.2939	790.7347	1739.6163
12.41666667	79.2618789	317.0475	792.6188	1743.7613
12.44444444	79.4503158	317.8013	794.5032	1747.9069
12.47222222	79.6387792	318.5551	796.3878	1752.0531
12.5	79.8272688	319.3091	798.2727	1756.1999
12.52777778	80.0157846	320.0631	800.1578	1760.3473
12.55555556	80.2043266	320.8173	802.0433	1764.4952
12.58333333	80.3928947	321.5716	803.9289	1768.6437
12.61111111	80.5814889	322.326	805.8149	1772.7928
12.63888889	80.7701092	323.0804	807.7011	1776.9424
12.66666667	80.9587554	323.835	809.5876	1781.0926
12.69444444	81.1474274	324.5897	811.4743	1785.2434
12.72222222	81.3361254	325.3445	813.3613	1789.3948
12.75	81.5248491	326.0994	815.2485	1793.5467
12.77777778	81.7135986	326.8544	817.136	1797.6992
12.80555556	81.9023738	327.6095	819.0237	1801.8522
12.83333333	82.0911747	328.3647	820.9117	1806.0058
12.86111111	82.2800011	329.12	822.8	1810.16
12.88888889	82.4688531	329.8754	824.6885	1814.3148
12.91666667	82.6577306	330.6309	826.5773	1818.4701
12.94444444	82.8466335	331.3865	828.4663	1822.6259
12.97222222	83.0355618	332.1422	830.3556	1826.7824
13	83.2245154	332.8981	832.2452	1830.9393
13.02777778	83.4134943	333.654	834.1349	1835.0969
13.05555556	83.6024985	334.41	836.025	1839.255
13.08333333	83.7915278	335.1661	837.9153	1843.4136
13.11111111	83.9805823	335.9223	839.8058	1847.5728
13.13888889	84.1696619	336.6786	841.6966	1851.7326
13.16666667	84.3587665	337.4351	843.5877	1855.8929
13.19444444	84.5478961	338.1916	845.479	1860.0537
13.22222222	84.7370506	338.9482	847.3705	1864.2151
13.25	84.92623	339.7049	849.2623	1868.3771
13.27777778	85.1154342	340.4617	851.1543	1872.5396
13.30555556	85.3046632	341.2187	853.0466	1876.7026
13.33333333	85.493917	341.9757	854.9392	1880.8662
13.36111111	85.6831955	342.7328	856.832	1885.0303
13.38888889	85.8724986	343.49	858.725	1889.195
13.41666667	86.0618263	344.2473	860.6183	1893.3602
13.44444444	86.2511786	345.0047	862.5118	1897.5259
13.47222222	86.4405553	345.7622	864.4056	1901.6922
13.5	86.6299565	346.5198	866.2996	1905.859
13.52777778	86.8193821	347.2775	868.1938	1910.0264
13.55555556	87.0088321	348.0353	870.0883	1914.1943
13.58333333	87.1983064	348.7932	871.9831	1918.3627
13.61111111	87.387805	349.5512	873.878	1922.5317

13.63888889	87.5773278	350.3093	875.7733	1926.7012
13.66666667	87.7668747	351.0675	877.6687	1930.8712
13.69444444	87.9564458	351.8258	879.5645	1935.0418
13.72222222	88.146041	352.5842	881.4604	1939.2129
13.75	88.3356601	353.3426	883.3566	1943.3845
13.77777778	88.5253033	354.1012	885.253	1947.5567
13.80555556	88.7149705	354.8599	887.1497	1951.7294
13.83333333	88.9046615	355.6186	889.0466	1955.9026
13.86111111	89.0943764	356.3775	890.9438	1960.0763
13.88888889	89.2841151	357.1365	892.8412	1964.2505