ICOLIM 2025

Arc energy calculation method for selecting PPE against arc flash in the medium voltage range

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***Abstract*— The selection of PPE against arc flash tested in the box test in accordance with IEC 61482-1-2 requires the determination of the electric arc energy to be expected at the work place. Experience has shown that the transferability of the methods and empirical calculation equations, developed for the low-voltage range (e.g. in DGUV-I 203-077), to medium-voltage systems is limited. In some cases, very high, unrealistic values are determined, which would lead to unfounded safety reserves or a lack of solutions in the selection of PPE.**

Based on literature data and the evaluation of measurement results, an algorithm is proposed that is specially tailored to the conditions in medium-voltage systems. It stepwise enables a rough estimate, a worst-case estimate and a detailed analysis taking into account the electrode gap. An AC-MV selection tool has been created for users.

The method and tool supplementing DGUV-I 203-077 calculations are presented in the paper.

Keywords*— *arc flash, personal protective equipment, medium voltage, arc flash risk assessment, PPE selection

I. INTRODUCTION

When using common calculation methods such as DGUV-I 203-077 [1] or software tools [2,3] for selecting the PPEaA (personal protective equipment against the thermal hazards of an electric fault arc) for medium-voltage systems (MV; e.g. U_{Nn} = 10 kV or 20 kV), it has been noticed that sometimes unrealistic values of the arc power and arc energy are determined. These values are both physically unfounded and unjustified with regard to safety reasons. This may result in extremely large, unacceptable safety margins to real values, which has consequences for the required PPEaA.

Regarding the theoretical maximum value of the power transfer factor k_{Pmax} (according [1] and [4]),

$$k_{Pmax} = \frac{0.29}{(R/X)^{0.17}} \tag{1}$$

values of around 0.43 (for R/X = 0.1) are calculated, which does not make sense for MV conditions. It would mean arc voltage values of approx. 3000 V at a system voltage of 10 kV, which is far from being achieved in the MV range. Maximum values of 1000...2000 V are realistic, which lead to a range of the power transfer factor k_P = 0.04...0.08, as shown in Tab. 3.2 of [1] for switchgear 10 kV and 20 kV. The equation for k_{Pmax} in [1,4] is only relevant for the worst-case consideration in the low-voltage range (also verified for this), but not for the medium-voltage level.

The approaches in the software tools [2,3] are also based on the incorrect theoretical maximum values k_{Pmax} for worst-case consideration in the MV range. In addition, these software tools also use the empirical equations of the arc voltage of [4], which only apply to low-voltage systems, in the detailed calculation with taking the electrode gap d into account. In both cases, arc powers and energies are calculated with practically unacceptable values.

For MV systems, separate approaches must be developed which are based on specifications or an approximate determination of the arc voltage derived from literature data and verified by empirical data obtained from laboratory tests.

The previous assessments of inappropriately high values for the relevant parameters for MV systems are also confirmed by exemplary comparisons of PPEaA selection. Comparisons of the arc protection class (APC) of PPEaA required for medium-voltage applications according to the above-mentioned 'low-voltage approaches' with the PPEaA selected according to North American standards also show extreme differences. These considerations cannot be broken down to the values for arc voltage, arc power and arc energy, as the American calculation standards (such as IEEE 1584 [5], NFPA [6] and others) use different selection algorithms and only the arc flash current level and the thermal incident energy are determined. However, it is clear that the differences are due to significantly different energy values.

In [7], the selection of PPEaA made on base of DGUV-I 203-077 is compared with the results of the calculation according IEEE 1584 for the same workplaces. Although a direct comparison of the required PPEeA protection levels (APC and arc rating ATPV, ELIM, E_{bt}) is not possible, the results can be compared indirectly via the selected PPEaA, which was tested / rated in accordance with the two standards IEC 61482-1-1 and IEC 61482-1-2 (each of which corresponds to the selection algorithms). It turns out that PPEaA selected according to both methods is comparable for workplaces in the low-voltage range. However, PPEaA for working on MV systems, which is comparable to the results of IEEE 1584, can only be found with the calculation algorithm of DGUV Information 203-077 if a modified determination of the value of the power transfer factor k_p is used (see section V). Using the 'low-voltage approach' for MV applications would result in extremely high protection levels and PPEaA that cannot be compared in any way with those selected by means of IEEE 1584.

An additional DGUV-I 203-077 calculation approach for MV applications has to be provided.

II. THEORETICAL CONSIDERATIONS TO ARC POWER

According to [4], a generalized model can be assumed to determine the arc power, which works with related variables and is therefore not restricted by application limits in relation to voltage levels, etc. It is based on the assumption of an in intervals constant arc voltage for a quasi-stationary state of the electrical system in which a 3-phase arc fault exists. As the result a generalized graphical function can be derived, representing the relationship between the power transfer factor $k_P = P_{arc}/S_k$” and the related arc voltage k_U. Fig. 1 shows this function which applies to the relevant 3-phase arcing faults where the value k_P is the ratio of the total arc power to the short-circuit capacity of the system $S‘_{k3p}$, while the related arc voltage factor k_U is [4,8]

$$k_U = 0.544\frac{U_{arc}}{U_{Nn}} \qquad (2)$$

The R/X ratio of the network impedance at the fault location must be taken into account as parameter. By means of the grid parameters and the arc voltage U_{arc}, the power transfer factor and subsequently the arc power and arc energy can be easily determined. If the distance dependence of the arc voltage is known, the electrode distance can also be taken into account [4,8].

Using the typical arc voltage values specified in [4] for air-insulated MV switchgear, the ranges shown in Table I are received for the related arc voltage k_U and power transfer factor k_P.

To simplify matters, the arc power can also be derived from another approach, which also assumes an in intervals constant arc voltage, but neglects a possible DC component of the short-circuit current curve and the current attenuation due to the arc fault, so that the current attenuation factor [1] is $k_B = 1$ and so arc flash current $I_{k,arc} = I‘_{k3}$ [1,8].

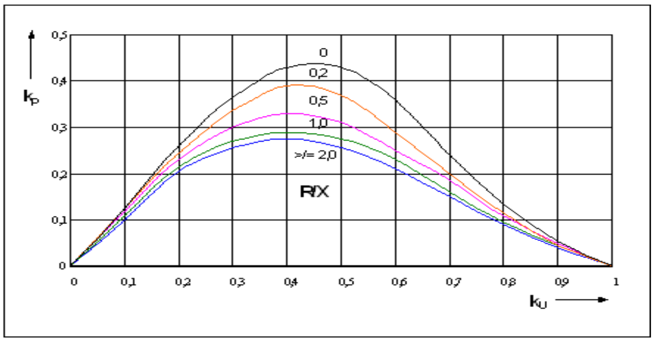

Fig. 1. General dependency between power transfer factor k_P and related arc voltage k_U according to the model in [4,8].

TABLE I. TYPICAL RANGES OF THE ARC VOLTAGE, RELATED ARC VOLTAGE AND POWER TRANSFER FACTOR ACCORDING TO [4]

U_{Nn}	U_{arc}	k_U	k_P
10 kV	800…1000	0,044…0,054	0,048…0,08
20 kV	1000…1500	0,027…0,041	0,030…0,06
30 kV	1500…2000	0,027…0,036	0,029…0,055

Both neglections are justified for the relatively low arc voltages. The total arc power in a 3-phase arc flash can be calculated as the mean value from the integration of the products of arc voltage and arc current (sum for all partial arcs) according to the general definition

$$P_{arc} = \frac{1}{T}\int\sum u_{arc}\cdot i_{arc}\cdot \mathrm{dt} = \frac{3\cdot\sqrt{2}}{\pi}\cdot U_{arc}\cdot I_{arc} \qquad (3)$$

$$P_{arc} = 1.35\cdot U_{arc}\cdot I_{arc}$$

With the simplifications ($I_{k,arc} = I‘_{k3}$) there is

$$P_{arc} = 1.35\cdot U_{arc}\cdot I_{k3}^{'} \qquad (4)$$

and

$$k_P = \frac{P_{arc}}{S_{k3}^{''}} = \frac{\sqrt{3}\cdot\sqrt{2}}{\pi}\cdot\frac{U_{arc}}{U_{Nn}} = 0.78\cdot\frac{U_{arc}}{U_{Nn}} \qquad (5)$$

The electrical arc energy follows as

$$W_{arc} = P_{arc}\cdot t_{arc} = k_P\cdot S_k^{''}\cdot t_{arc} \qquad (6)$$

since the arc duration t_{arc} is given by the clearing time or switch-off time of the protective devices t_k.

III. SPECIAL FEATURES OF MV FAULT ARCS

In air-insulated equipment, arc flashes are usually formed by 3-phase arcing with partial arcs between the conductors. The level of the arc voltages U_{arc} is mainly determined by the arc length and thus the electrode gaps d. The voltage values also show certain tendencies to become higher with increasing system voltage and greater short-circuit currents. However, the arc length does not usually correspond to the electrode gap alone, but may even be several times greater, mainly due to widening of the arc loops and migration processes as a result of thermal buoyancy, magnetic influences and other thermodynamic effects. Changes in the arc length often occur during the arc fault, so that arc voltage values more or less increase during the fault.

In addition to system voltage and short-circuit current, the conductor arrangement and configuration (horizontal, vertical, coplanar or triangular) as well as the conductor environment and ambient conditions (enclosures, encapsulations, partitions, barriers) also have an influence on the formation and extension of the arc columns. This results in large value or scattering ranges of the arc voltages for a specific fault, so that even average values are difficult to specify with general validity. This is particularly true for open systems. However, in addition, there is generally a wide range of other influences from conductor and environment configurations of the various systems, so that reliable arc voltage values must cover a majority of possible scenarios. The arc voltages must be known in order to be able to determine the arc power and arc energy.

Considering all individual special equipment configurations is practically impossible due to the variety and number of different systems and the lack of data to statistically validate the typical values for each. It is therefore advisable to derive guide values from laboratory measurements that guarantee the widest possible coverage.

For this reason, calculation approaches for the expected values of arc energy in the medium-voltage range require separate characteristic values.

IV. Characteristic Arc Voltage Values and Calculation Approaches for Electrical Arc Power and Arc Energy in MV systems

The arc voltage values listed in Table II were found in former literature research [4] and may be used for rough estimations. Furthermore, it is also shown the arc voltage dependencies from the electrode gap d which are known from lab measurements [9, 10, 11].

TABLE II. Arc Voltage values from lab measurements

U_{Nn} = 10/12 kV	U_{Nn} = 20/24 kV	conditions	source
$U_{arc} \approx 800$ V	$U_{arc} \approx 1300$ V	$I_k \approx 10…20$ kA	[9]
U_{arc} = 400 V + 14,5 • d		$I_k \approx 2$ kA (7 kA)	[10]
$U_{arc} \approx 570$ V (d =120 mm)	$U_{arc} \approx 750$ V (d = 240 mm)		
U'_{arc} =40 V/cm		Maximum values at $I_k \geq 20$ kA	[11]
$U_{arc} \approx 480$ V (d =120 mm)	$U_{arc} \approx 960$ V (d = 240 mm)		

The values apply to configurations that are typical for air-insulated, metal-enclosed switchgear. The test laboratory investigations in [10] were carried out with basic arrangements that correspond to the main busbar systems in switchgear with parallel busbars. Both coplanar (busbars running in one plane) and triangular arrangements were investigated, with the triangular configurations resulting in the higher values of arc voltage. The specified equation for U_{arc} describes the mean value of this arrangement (gamma distribution) and thus also covers the coplanar configuration. The value of the length-related arc voltage taken from [10], on the other hand, represents the maximum value determined in the measurements, whereby the reference basis is the electrode gap. The value therefore includes the deviations of the actual arc length from the electrode gap. In general, it can be stated that the influence of the grid voltage level results primarily from the correlating electrode gap (usually determined by the necessary isolation distances). With larger electrode gaps, the arc voltage is more clearly linearly linked to the distances between electrodes, whereas with smaller electrode gaps, the actual arc length deviates from the electrode gap to a greater extent that cannot be differentiated in more detail (large length-independent value).

From the literature, the general description of the current-voltage characteristic of an arc according to Stokes/Oppenlander [12] is known, which is not precisely defined in terms of its validity, but may be therefore not restricted in principle. The equation

$$U_{arc} = (20\,V + 5.34 \cdot l \frac{V}{cm}) \cdot I_{arc}{}^{0.12} \quad (I_{arc} \text{ in A}) \qquad (7)$$

includes both the length and current dependency, so that calculations must be performed iteratively. With regard to the length l, the arc length l_{arc} should be meant from a physical point of view; however, the electrode gap d is often used in applications of the equation (it is possible that the electrode distance was only taken into account in the description or evaluation of the basic data from the measurements performed; this is not clearly recognizable from the source). However, short-circuit current I_k" can be used as a good approximation for the arc current under medium-voltage conditions (see section III).

Arc voltage values which are calculated on this base are listed in Table III.

TABLE III. Arc Voltage Values Calculated according to [13]

U_{Nn} in kV	d in mm	I_k" in kA	U_{arc} in V	U'_{arc} in V/cm
10	120	2	209,4	17,5
		10	253,9	21,0
		20	275,8	23,0
20	240	2	368,9	15,3
		10	447,4	18,6
		20	486,0	20,2

Table III also contains a value for the arc voltage in relation to the electrode gap $U'_{arc} = U_{arc}/d$. As can be seen, arc voltages in the range of approx. 210...276 V (for short-circuit currents of 2 to 20 kA) can be calculated for the 10 kV level for an electrode gap d = 120 mm, for example, which corresponds to a length-related arc voltage $U'_{arc} = U_{arc}/d$ of 17.5...23 V/cm. For 20 kV and d = 240 mm, arc voltages of U_{arc} = 369...486 V and related values of U'_{arc} = 15.3... 20.2 V/cm result for the same current range, which are very low values compared to the measurement results in Table II.

Similarly low values are also stated in a number of publications and calculation tools from the North American region [13-19]. Lee [13] specifies a range for the related arc voltage of 10...16 V/cm, which should apply to currents of 100 A to 80 kA. In the Privette calculator [14], for example, a value of 11.8 V/cm is used. The ArcPro tool [15] uses voltage values of 15.6 V/cm at 5 kA and 16.6 V/cm at 10 kA for a 25 cm arc.

The equation according to [12] applies to an arc between two opposing electrodes. For three-phase arcs between parallel electrodes, arcs of greater length occur. For arcs with burning times of 100 ms and more, there can be a successive lengthening of the arc columns over time, which can result in additional voltage components of 2 V/cm. In [13], a range of 5...10 V/cm is given for the arc voltage in relation to the arc length and it is estimated that the actual arc length can generally be 2...6 times the value of the electrode gap d. This results in a range U'_{arc} = 10...60 V/cm for the related arc voltage. These significant deviations between the actual arc length and electrode gap can of course also occur with opposing electrodes or ejected arcs (arcs at the ends of a parallel conductor arrangement, also 3-phase).

In general, the arrangement of the electrodes is very important with regard to arc voltage and arc length. The largest values result from the extreme expansion of the arc columns at end burn points and ejected arcs. With reservation, from exemplary measured values for a mains voltage of 2700 V [20], a related arc voltage of around 120 V/cm can be calculated from the power data for the HOA arrangement specified in [5] (open arrangement of parallel horizontal electrodes), although there is no general confirmation by measurements (unfortunately, no further measurement results for the arc voltage are reported from for the very extensive series of measurements presented in [20]).

In [18,19], very long arcs of up to approx. 90 cm are reported for horizontal electrodes in the housing and in open arrangements with system voltage levels of 5...35 kV. Arc voltages of 578 V at 15 kV and 833 V at 25 kV were measured in this voltage range, which correlate on average with arc lengths of 25...38 cm. In [19], measured mean values and value ranges of the arc voltages are listed for three analysed configurations. The authors calculate equivalent arc lengths under the condition U'_{arc} = 16 V/cm. These values are shown in Table IV.

TABLE IV. EQUIVALENT ARC LENGTH FOR MEASURED ARC VOLTAGE VALUES

Configuration	U_{arc} in V		equivalent l_{arc} in cm	
	Mean value	*range*	*Mean value*	*range*
1	594	301…954	38	19…61
2	368	222…630	25	14…41
3	605	235…1058	38	14…66

There are arc lengths are up to 66 cm; the actual electrode distance may be probably around 25...30 cm.

The above-mentioned calculation models are bases for the selection of PPEaA in North America. Using the relatively small values of the related arc voltage, one can assume that the actual (also average) arc length, which is generally much greater than the electrode gap, is not taken into account. As a result, the incident energies may be determined too small. In the North American standards for PPEaA selection (e.g. [5,6]), however, the arc voltages are not used as bases, and the fault currents and incident energies are determined using empirical regression equations obtained from measurements.

Some North American publications on laboratory measurements at specific MV equipment [18,19] state that the measured incident energies are in some cases significantly greater than the expected values from calculations. In the PPEaA selection, there can result clear discrepancies to the PPEaA really needed, which entails the uncertainty that the necessary PPEaA should have a higher protection value. To remedy this, correction factors in the range of 2...6 are proposed for the calculated incident energies for the individual constellations. However, due to the very complex interrelationships, no conclusions can be drawn regarding corrections to the arc voltages. As mentioned above, the American standards follow algorithms that do not explicitly use the arc voltages and refer directly to recursion equations for the incident energy that were derived from series of measurements (the very extensive data pool, where the determination equations in [5] are based on, does not contain information on the arc voltages and arc power values).

In summary, it can be stated that related arc voltages of 5...20 V/cm lead to arc voltages values and consequently to arc power values and arc energies that are too low compared to measured levels, if it is not taken into account that the actual arc length and electrode distance may differ significantly. In practice, it makes sense to use a calculation value that determines the arc voltage from the electrode gap. The above-mentioned related arc voltage of U'_{arc} = 40 V/cm is a value that can cover a large number of scenarios. Consequently, the values according to [10] and [11] are useful for considerations in the medium voltage range.

V. CONCLUSIONS FOR A SEPARATE SUPPLEMENTARY ALGORITHM FOR ARC ENERGY CALCULATION IN THE MV RANGE

Based on the considerations in Section II, the guide values for the power transfer factor, for which a value range of 0.04...0.08 is specified in DGUV-I 203-077 [1] can be used for very rough estimations.

Furthermore, for the worst-case assessment, it is also possible to use slightly more differentiated guide values for the arc voltage of 800 V for the 10 kV, 1300 V for 20 kV and 1800 V for 30 kV (switchgear) and 2000 V for transformers.

For even more precise and detailed considerations, taking into account the electrode gap, it is recommended to select the larger value of the arc voltage from the two empirical equations U_{arc} = 400 V + 14.5 V/cm and U_{arc} = 40 V/cm • d. The first equation covers the range for electrode gaps $d < 15.7$ cm; the second equation applies for d = 15.7 cm and larger gaps. These characteristic values have been derived on the basis of literature data in order to obtain reliable results that cover or include as far as possible all conditions of arc formation, grid parameters and environmental influences, which naturally have a wide range (see section III). In both cases, the arc voltages are used to determine the power transfer factor according to the approximation equation (5), which is derived from a 3-phase arc model with arc voltages being constant in intervals [8,9].

A new, supplementary AC-MV Excel sheet will be developed and made available on the DGUV/BG ETEM website. The algorithm used there, reflects the following procedure for calculating the arc energy:

- Rough estimation with k_P = 0.04...0.08 for 10 kV and 20 kV switchgear
- Worst-case consideration - without taking into account the electrode gap d: Assumption of arc voltages U_{arc} of
  a. 800 V for 10 kV (switchgear)
  b. 1300 V for 20 kV (switchgear)
  c. 1800 V for 30 kV (switchgear) and
  d. 2000 V (transformers)
- Exact determination (with consideration of electrode gap d): Determination of the arc voltage as the maximum value $U_{arc} = \max\{U_{arc1}; U_{arc2}\}$ from the 2 empirical equations (Table II)
  a. U_{arc1} = 400 V + 14,5 • d
  b. U_{arc2} = 40 V/cm • d
- Determination of the power transfer factor k_P from the U_{arc} values with

  $k_P = 0.78 \cdot U_{arc}/U_{Nn}$.
- Calculation of the electrical arc power

  $P_{arc} = k_P \cdot S_k'$

  and electrical arc energy

  $W_{arc} = P_{arc} \cdot t_{arc}$.

This new Excel user tool AC-MV is specially tailored to the conditions in the medium voltage range (greater than 1 kV to 30 kV). It supplements the 2nd edition of DGUV-I 203-077.

VI. Summary

The selection of PPE against arc flash tested in the box test in accordance with IEC 61482-1-2 requires the determination of the electric arc energy to be expected at the work place. Experience has shown that the transferability of the methods and empirical calculation equations, developed for the low-voltage range (e.g. in DGUV-I 203-077), to medium-voltage systems is limited.

Based on theoretical considerations, literature data and the evaluation of measurement results, the situation in MV equipment was analysed and data for the arc voltage values typical for MV system were derived. Conclusions were drawn on what input data may be used for MV considerations in order to come to reasonable and reliable results regarding the arc power and electrical arc energy, which also represent a base for proper PPEaA selection.

As the result, an algorithm is proposed that is specially tailored to the conditions in medium-voltage systems. It stepwise enables a rough estimate, a worst-case estimate and a detailed analysis taking into account the electrode gap. The algorithm is described and confirmed. An AC-MV selection tool has been created for users.

References

[1] DGUV-I 203-077: Thermal Hazards due to Electric Fault Arcing – Guide for Selecting Personal Protective Equipment, Berlin: DGUV, 2nd edition, English version 07-2021.

[2] DIgSILENT PowerFactory. Power System Solutions. Product specification, functions, 2022.

[3] ETAP Power System Design and Operation Software, User Guide 19.0, ETAP Operation Technology, CA, USA, 02/2019.

[4] Schau, H.; Halinka A.; Winkler, W.: Elektrische Schutzeinrichtungen in Industrienetzen und -anlagen. Hüthig & Pflaum Verlag München/Heidelberg 2008.

[5] IEEE 1584: Guide for performing arc-flash hazard calculations, IEEE 2018.

[6] NFPA 70E: Standard for Electrical Safety in the Workplace, 2018.

[7] Jordan, T.; Kauschke, M.: Selection of PPE — Practical experience of different arc assessment methods and their comparison, 12th International Conference on Live Maintenance (ICOLIM), Strasbourg, France, 2017.

[8] Schau, H.: Berechnung des Leistungsumsatzes bei Lichtbogenkurzschlüssen. Leipzig: Wissenschaftliche Zeitschrift der TH Leipzig 13 (1989) 5, S. 279...287.

[9] Wehlich, D.: Zur Ausbildung mehrpoliger Störlichtbögen und zur Innendruckentwicklung in luftisolierten, metallgekapselten Mittelspannungs-Schaltzellen, TU Dresden, Dissertation, 1984.

[10] Klaus, A.: Optische Störlichtbogendetektion in luftisolierten Mittelspannungs-Schaltanlagen, TU Ilmenau, Dissertation, 2001.

[11] AiF-Forschungsvereinigung Elektrische Anlagen: Reduzierung der Druckbeanspruchung elektrischer Anlagen im Störlichtbogenfall, Mannheim, Forschungsbericht, 2011.

[12] Stokes, A. D.; Oppenlander, W. T.: Electric arcs in open air. Journal of Physics D: Applied Physics, 1991, pp. 26-35.

[13] A. D. Stokes, A.D; Sweeting, D.K.: Electric arcing burn hazards, IEEE Trans. Ind. Appl., vol. 42, no. 1, pp. 134–141, Jan./Feb. 2006.

[14] Wilkins, R.; Allison, M.; Lang, M.: Effect of electrode orientation in arc flash testing. Conf. Rec. IEEE-IAS Annual Meeting vol. 1, 2005, pp. 459–465.

[15] Kinectrics: User's Guide for ARCPRO, version 2.0, Toronto, Ontario, Canada, 2002.

[16] Kinectrics: State-of-Art Report on Arc Hazard Modeling in Distribution Arc Flash: Analysis Methods and Arc Characteristics, Electric Power Research Institute, Palo Alto, CA, 2008.

[17] Short, T. A.: Arc flash analysis approaches for medium-voltage distribution, IEEE Rural Electric Power Conference (REPC), 2009.

[18] Eblen; M. L.; Lee, W.-J.: MV arc flash in switchgear and life-front transformers. IEEE Transactions on Industry Applications, vol. 49, no. 1, pp. 100-109, 2013.

[19] Short, T. A.; Eblen, M. L.: Medium-Voltage Arc Flash in Open Air and Padmounted Equipment, IEEE Transactions on Industry Applications, vol. 48, no. 1, pp. 245-253, Jan.-Feb. 2012.

[20] Lee, W.-J.; Gammon, T. et.al.: Arc models and Incident-energy calculation. Laboratory measurement evaluations. Report Meeting Technical Advisory Committee, 2010.