Standards for Engine-Starting Capacitors

John R. Miller
JME, Inc.
17210 Parkland Drive
Shaker Heights, OH 44120
<JMEcapacitor@att.net>
216-751-9537

I. Introduction and Background

Over the past few years electrochemical capacitors (ECs) or, as they are so often referred to today, super- or ultracapacitors, have become increasingly interesting for a certain critical group of applications because of their unique attributes. The first of these EC attributes is exceptional power performance, even at very low temperatures. The second is an essentially unlimited cycle life when compared to batteries. And the third is that, once installed, ECs are completely maintenance free. These latter two attributes contrast markedly with those of batteries, which are, by design, intended to and do wear out at some point. An application that has generated much interest in capacitors because of these attributes is the starting of internal combustion engines.

The interest in EC engine starting has grown pointedly in one commercial segment of the engine starting market, namely for use in over-the-road trucks (Classes 6-8) with up to an 80,000 lb gross weight. Although internal combustion (IC) engines for trucks in this class may vary in displacement depending on both their intended loads and intended use in mountainous or plains terrains, cranking the diesel engines in this class of vehicle may today require 2, 3, or even 4 of the large Group-31 size lead-acid batteries, especially during cold temperature conditions. That this many batteries are now needed to meet the requirements of the industry is owed especially to the fact that they are used not only for cranking but to supply power for the off-key loads associated with sleeper cabs. These are the so-called "parasitic" loads that continue to drain the batteries even when the vehicle is not itself in operation. The increasing magnitude of the parasitic load leads inevitably to the question whether using batteries in ever greater numbers is the solution to the problem of how to have enough power available for starting in such situations. It is precisely because of this and in connection with the specific attributes of ECs that a method for rating ECs for engine cranking use has become necessary.

KiloFarad International (KFI),[1] a trade association formed in 2003 to promote the interests of the electrochemical capacitor industry in commercial and regulatory arenas, established a Standards Committee to develop important standards. The initial task of this Committee was to develop a test standard and rating system suitable for capacitors used to crank a broad range of IC engines, including gasoline engines, diesel car engines, large diesel truck engines, marine engines, and large stationary diesel motor-generator sets. Their next task will be to develop guidelines that recommend the capacitor rating for a specific engine size, type, or application. Recommended practices are necessarily outside the standards so that they can be easily and rapidly updated as historic information becomes available and as new engines are designed.

This report outlines the common rationale for the work of the KFI Standards Committee in developing engine cranking standards and presents results in the form of a draft standard for capacitors used to crank internal combustion engines.

II. Existing Battery Standards

Although ECs are very different from batteries, the standards that now apply to starting, lighting, and ignition (SLI) batteries used in cars and trucks provide hints of what the proposed standards for ECs will need to cover. There are currently four rating standards for cranking batteries: Cold Cranking Amps, Cranking Amps, Reserve Capacity, and Ampere-Hour rating.

Cold Cranking Amps (CCA) measures the ability of a battery to start an engine at low temperatures. Unfortunately, North America, the UK, Germany, and the European Union all maintain different specifications for defining CCA. In the SAE standard for North America, for instance, CCA is defined as the current that a new, fully-charged battery at -18° C (0° F) can deliver for 30 seconds, maintaining voltage at 1.2 V per cell or higher. This amounts to 7.2 V for a nominal 12-volt battery. The CCA standard for the United Kingdom, known as the BS standard, calls for a 60 second cranking time with an end voltage of 1.4 V per cell. The EN or European Union standard requires a 10-second cranking time with an end voltage of 1.25 V.

Cranking Amps (CA), a less severe version of CCA used in North America, is measured at 0° C (32° F) as a means of rating engine cranking needs in warmer climates. The Battery Council International (BCI) requires that batteries carrying a CA rating must also carry a CCA rating to guarantee there will be no confusion on a battery's rating. A CA rating in North America can in fact be as much as 30% higher than its CCA rating.

Reserve Capacity (RC) measures the amount of energy available from the battery at a specified consumption rate. RC is defined as the time a fully-charged battery at 80° F (27° C) can supply a constant 25 A current with a cell voltage maintained at 1.75 V or above. RC, as a measure of the usable energy stored in a battery, is given in units of minutes, for instance 60 minutes, 110 minutes, and so on. For a nominal 12-volt system the lower voltage is 10.5 V.

Ampere Hours (Ah), a rating method popular in Europe and Asia, is more often used in connection with batteries in portable electronic devices rather than in vehicles. It measures the capacity of the battery in terms of the current it can provide without the voltage falling below 1.75 V per cell, measured over a 20-hour period. In practice, the battery being measured is discharged from full charge at current I_o down to the minimum 1.75V per cell in 20 hours, and

current I_o in Amperes times the 20 hours produces the Ah rating. For example, a 12-V battery that discharges to 10.5 V in 20 hours with $I_o = 7$ A current would have a capacity of 140 Ah.

Summarizing, battery standards for internal combustion engine cranking focus on <u>current, time of operation</u>, a <u>voltage minimum</u>, and three <u>temperatures</u>: -18° C (0° F), 0° C (32° F), and 80° F (27° C). Standards for ECs used in engine cranking applications will need to focus on these same parameters.

III. Existing Capacitor Standards

What parameters are used to rate capacitors, and how useful are they for developing EC engine cranking standards?

<u>Voltage</u> rating is one parameter used for capacitors. Unlike batteries, capacitors do not have a fixed voltage but rather a <u>range</u> of operating voltages, usually from 0 V up to the maximum specified working voltage. Voltage rating is very important for the engine cranking application.

<u>Capacitance</u>, in units of Farads (F), is a second parameter. Farads measures the charge storage capacity of a capacitor, which is related to number of coulombs of charge that are stored with a 1 V change in the capacitor's voltage. One F is equivalent to one Ampere-second/volt. This parameter has little direct relationship to a capacitor's engine cranking performance.

<u>Equivalent Series Resistance (ESR)</u>, in units of Ohms (Ω), is a third parameter. ESR is the series resistance of the device at the frequency where its reactance is zero (capacitance and inductance buck each other so that the device stores no energy when charged or discharged at that frequency). This parameter is related to energy loss and sometimes is expressed in terms of a unit-less dissipation factor (df). The df is defined as ESR/X_c, where X_c is the capacitor reactance in Ohms. Thus, df is frequency dependent because $X_c = 1 / (2\pi fC)$ where f is frequency in Hertz and C is the capacitance in Farads. Capacitors used to filter 60 Hz ac power have a df rating standard at 120 Hz, which measures internal energy dissipation during normal operation. The ESR may be useful and used to calculate the maximum instantaneous power a capacitor can provide. The df parameter is of little use in the engine cranking application since it is not a single frequency periodic operation.

<u>Time constant (τ)</u>, equal to the capacitance-equivalent series resistance product, $\tau = C*ESR$, describes the characteristic response time of the capacitor. An ideal capacitor, when shorted, will decay to 0.367 times its initial voltage in one time constant. Correspondingly, 87% of the stored energy is released during this time. This parameter may be useful, but ECs usually are not well represented by a single response time due to their use of porous electrode materials that create distributed charge storage and distributed resistance. ECs require multiple time constants to accurately represent their performance. Thus, this parameter has limited value for engine cranking.

So are the capacitor parameters useful in specifying the size of an EC designed for use in engine cranking? The answer is a clear "No." For one thing, the capacitor parameters are so different from those used to rate batteries that there is little possibility of helpful crossover between battery and capacitor standards. For another, the two types of devices are so different in other ways that any comparisons that are made between them can only fail.

Existing capacitor parameters are simply not to the point when it comes to rating engine cranking capability, and batteries and ECs are too unlike each other for battery standards to apply unequivocally to both kinds of devices. This failure is further reinforced by using battery standards to derive parameters for a typical engine cranking capacitor.

Consider a nominal 12 V, 1000 F engine cranking capacitor having an ESR of 0.003 ohms at a temperature of -18 C. The total energy stored in this device at 12.6 V is 79 kJ = 22 Wh (assuming the device is ideal and is discharged from 12.6 to 0 V). Energy in the voltage window 12.6 to 7.2 V is 53.5 kJ = 14.9 Wh. Using today's battery standards, this capacitor would have CCA = 160 A, RC =1.3 minutes, and a 20-hour discharge capacity of 0.6 Ah. These parameters are totally unimpressive for engine cranking, where CCA values for a single battery are typically 500 A or greater. Yet this size capacitor by itself can crank and start large diesel engines at -18 C, further demonstrating that battery standards are of little use for engine cranking capacitors.

IV. Engine Cranking Requirements--the Key

The most promising route to a new standard for ECs used in engine cranking applications begins by considering the engine cranking task itself.

Power. **Figure 1** shows a hypothetical current versus time profile of a starter (powered by an ideal voltage source) that is cranking an un-fueled internal combustion engine. An ideal source has no current limitations. As shown, there initially is very high current demand with a duration of ~0.050 seconds. This is associated with the starter pinion gear being driven to the flywheel gear. After this spike, power drops abruptly to a value less than one-half its initial value while engine static friction and rotational inertial resistance is overcome and crankshaft movement begins (engine break-away). This occurs over the second ~0.050 second period. Then beginning at approximately 0.1 second, current drawn by the starter reaches a constant value as the engine
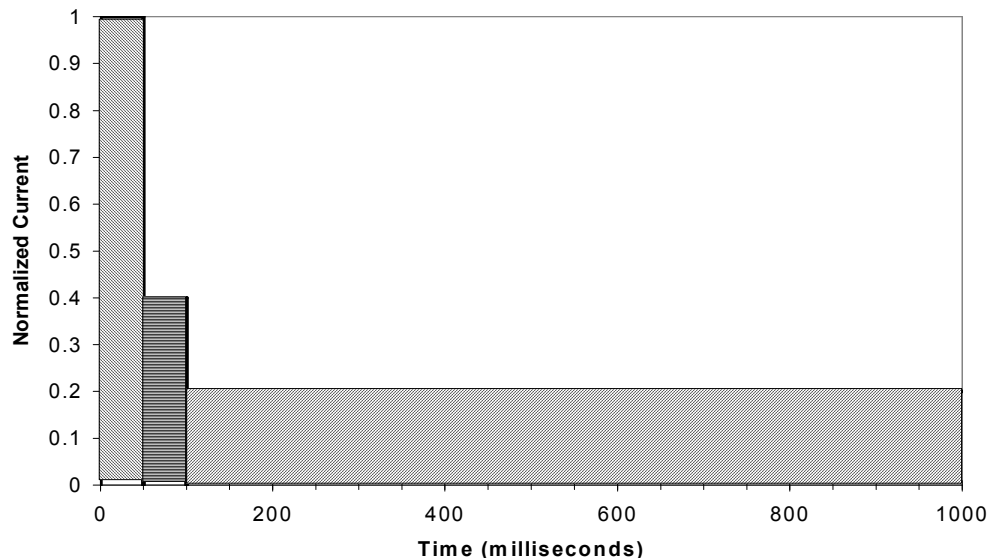

Figure 1: Hypothetical current profile of a starting motor powered by an ideal voltage source during cranking of an internal combustion engine. The first 50 ms is associated with the pinion gear being driven into the flywheel gear, the next 50 ms static friction - rotational inertial crankshaft break-away with the start of rotation, and the remainder of the time associated with steady run-up of the engine rotation rate.

rotational speed increases continuously to a peak value. This sequence is typical for starting of most internal combustion engines, the entire cranking process occurring over only approximately a second. The 30-second North American CCA standard used for batteries is hardly to the point for measuring cranking ability when a starting event lasts only a second or two.

Time. **Figure 2** shows the associated hypothetical engine rotation rate versus time for the same un-fueled internal combustion engine that is cranked with the Figure 1 starter (powered by an ideal voltage source). Note particularly that the engine RPM reaches a peak value at ~1.5 seconds after cranking is initiated and decreases thereafter. This is typical IC engine behavior and independent of the power source. Figure 1 and Figure 2 promise to be important in establishing standards for ECs to be used in engine cranking.
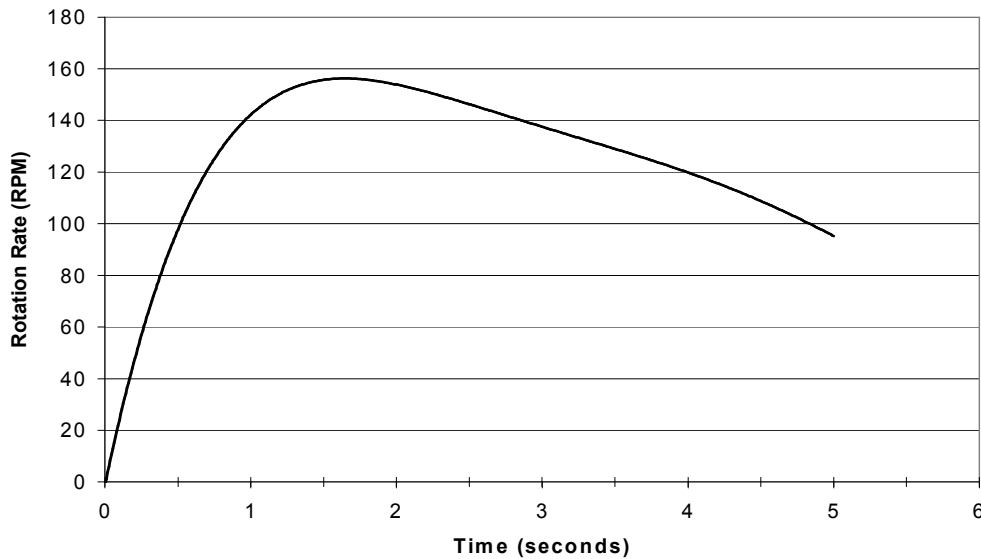

Figure 2: IC engine rotation rate (hypothetical) when powered by the starter in Figure 1 with an ideal voltage source. Note that maximum engine RPMs are reached in about 1.5 s after cranking initiation. This sort of behavior is typical for IC engine starting.

Summarizing, cranking a modern engine is an event that requires very high power but of very short duration, typically one second or less.

V. Outlining a New Approach

A more promising approach to developing standards for ECs used in engine cranking might start by considering capacitors at system-level, rather than at cell-level. In a 12 V battery system, for instance, standards have been established for the nominal 12 V battery and not for its individual 2-V cells. The reason why cell standards are not appropriate is that many ways exist for connecting them together, which clearly does affect achieved performance. Associated factors include the resistance of interconnects, as well as inclusion of any voltage balance electronics that will affect leakage current and voltage decay. So ratings on a cell-level basis fail to take these additional issues into account and are not suggested.

What appears to be needed are standards for the cranking capacitor system as an entity itself. They would focus strictly on its cranking performance and related operating issues. Details like form factor, terminal type and locations, weight, dimensions, and so on are certainly important but not part of these performance rating standards. (These issues, properly speaking, are a concern for manufacturers of capacitor products that are designed for use in particular applications.)

Any new standards should, of course, be accompanied by a "Recommended Practices" document that relates the capacitor rating standards to different engine types and sizes in various environments, like low temperature. For completeness in comparison with battery standards, temperatures should include -18° C (0° F), 0° C (32° F), and 80° F (27° C) as well. The recommended practice document will, of course, grow in size and breadth as experience is gained and as new engines come on the market. Ultimately, the industry itself will settle on issues like capacitor system shape and size, similar to the way that battery Groups have evolved.

In summary, certain assumptions will be implicit in the set of standards developed for capacitors used in IC engine cranking. They include the following:

⇒ Standards are developed for the capacitor cranking system itself, not for cells it is comprised of, nor for a string of cells without their usual and customary electronics.

⇒ Standards should be comprehensive such that the capacitor cranking system can be properly implemented as an isolated unit or in combination with an existing power source (battery).

⇒ Standards should not require exotic test equipment. A fixed-load (resistor) discharge tester should be relied on, for instance, rather than more complex constant-power discharge equipment.

⇒ Standards should be useful for most commonly encountered engine types and sizes, and in the most common environments (temperatures). Standards for exceptions can be developed later as needed.

⇒ Standards should allow easy determination of whether a capacitor is "good" or "bad" since testing is envisioned at most IC engine maintenance facilities. A portable EC tester is envisioned.

⇒ Standards should relate only to cranking performance and capacitor system durability, not EC form factor, physical size, electrical terminations, mounting hardware, etc.

⇒ Standards will need to be accompanied by a "Recommended Practice Guide" that relates the set of capacitor ratings to different engine types, sizes, operating environments, and uses.

VI. Proposed Rating Standards

The following standards were developed by the Committee and are proposed for IC engine cranking capacitors. They anticipate capacitor use in conjunction with a battery as well as capacitor use completely independent of a battery.

Rated voltage (RV), meaning thereby not the rated voltage of an EC cell itself or a string of cells, but rather the nominal voltage of the system as a whole. A nominal 12 V system would need to be compatible with an engine that has a 12 V battery, including its charging system that can produce voltages >14 V. Thus, the rated voltage of the cranking capacitor system would be the nominal system voltage, presently 12 or 24 V for lead acid batteries, and other appropriate

values for NiCd or nickel metal hybrid batteries sometimes found in stationary generator sets. The minimum operating or storage voltage must also be provided if it is different than 0 V.

Peak power (PP) measures the maximum instantaneous power that the capacitor can deliver at -18° C (0° F) and 0° C (32° F), the same low temperatures used in the battery standards. Units of peak power are kW. This standard, peak power, would be the maximum instantaneous value that could be delivered by the capacitor cranking system into whatever resistive load produces the highest value. The value at -18° C would be Cold Peak Power (CPP), and the value at 0° C would be Peak Power (PP), following the battery example CCA and CA. This parameter may prove to be very useful in helping to size the capacitor system to break loose the engine before the start of its rotation.

Cranking power (CP) is the maximum average power the capacitor system, either at -18° C or 0° C, can deliver during the first 1.5 seconds it is applied to a load. The load should be a resistor that is selected using an iterative process to identify the value that produces the maximum average power. Figure 2 above showed that the maximum RPMs are reached in about 1.5 s, so the average power for 1.5 s relates to the work performed in spinning the engine up to its maximum RPM value. Mathematically, this average is the integral of the current times the voltage during the first 1.5 s divided by 1.5 seconds. Units are again kW. So by analogy with the battery standards, there are two capacitor system standards, Cold Cranking Power (CCP) for the -18° C average maximum power and Cranking Power (CP) for the 0° C average maximum power. The resistive load used for these two standards may be different.

Leakage Current (LC) is the steady-state current drawn by the capacitor cranking system when installed. LC is measured at the worst-case environmental specification, 27º C (80º F). In actual fact this is the current necessary to maintain the capacitor at its rated voltage, which often takes many hours to reach steady-state conditions. Measurement after one hour on charge at 12.6 or 25.2 V and 27 C is proposed for this standard. Values would be in units of Amperes or mA, as appropriate. In capacitor engine cranking systems that are isolated from the starting system until operation, LC would be exactly zero.

Self-discharge time (SDT) measures the time the capacitor system can stand open-circuit and still perform an acceptable engine crank. The self-discharge time is defined as the time it takes for the system at 27° C to lose 10% of its average cranking power. In some capacitor systems this could be as long as hundreds of hours while in others it could be minutes. This standard is particularly important in determining the most appropriate installation for the capacitor system, in particular, whether it can be effectively isolated from the battery pack or power supply that may be present. The measurement temperature was selected to be the worst case situation, where a capacitor has the highest voltage decay rate.

Charging time (CT) measures the time needed to charge the capacitor to rated voltage using 100 A constant current. The initial state of the capacitor is 0 V, unless the capacitor has a different minimum voltage. This standard is useful for estimating the time needed to bring the capacitor to its operational state, important for a cranking capacitor not continuously maintained at its rated voltage. Units of charging time are seconds. Note that this standard allows calculation of system capacitance. In Farads, $C = 100 \cdot \tau/\Delta V$ where τ is the charging time in seconds and ΔV is the total voltage change in volts that occurs during the 100 A charging.

Operation designation relates to voltage application to the capacitor and is a "use" rating for the capacitor, as specified by the manufacturer. Here, the capacitor would be designated as suitable for "continuous" or "intermittent" rated voltage application. This standard relates directly to system durability. Some capacitor systems are designed to be maintained continuously at their nominal rated voltage while others are designed to have rated voltage applied just before engine cranking.

Eventually an accelerated aging protocol must be developed and validated for the engine cranking capacitor, which can be used to demonstrate acceptable life (durability) in a reasonable period of time (for either continuous or intermittent operation, as designated by the manufacturer). This ultimately should lead to the establishment of a capacitor reliability standard.

In review, the eight proposed engine cranking standards for electrochemical capacitors, and their units, are listed in Table I.

Table I: Proposed IC engine cranking standards for electrochemical capacitors.

Standard	Measured in	Environmental Condition
RV (Rated Voltage)	Volts	All rated temperatures
PP (Peak Power)	kW	-18° C (0° F), 0° C (32° F)
CP (Cranking Power)	kW	0° C (32° F)
CCP (Cold Cranking Power)	kW	-18° C (0° F)
LC (Leakage Current)	Amperes	80° F (27° C)
SDT (Self-Discharge Time)	Days or Hours	80°F (27° C)
CT (Charging Time)	Seconds	80°F (27° C)
Operation Designation	Continuous? Y or N	All rated temperatures

Summarizing, the proposed standards for IC engine cranking capacitors use analogous environmental conditions to battery standards but much different functional performance measurements, selected to mimic needed operation in the intended application. Capacitor standards would include a nominal voltage rating, essentially that of the electrical system in which it is installed. They would include a PP rating in kW showing the ability to overcome static friction of an engine, a CP or CCP rating in kW that describes average power values over the first 1.5 s of cranking (related to the amount of work the capacitor performs to reach the maximum engine rotation rate at ~1.5 s), an LC rating in A that describes the additional leakage current that the capacitor may add to the overall starting system, and an SDT rating that describes the length of time the capacitor system remains capable of cranking an engine after being removed from charge, a CT that describes the length of time needed to charge the capacitor system at 100 A to its nominal voltage rating, and an operation designation (by the manufacturer) concerning voltage application.

The CCP (and CP) standard relates to the work the capacitor can perform to spin up the engine to running conditions. A question arises about the sensitivity of this parameter to capacitor products developed for the engine starting application. Will the parameter sufficiently differentiate performance of available capacitor products? This question is addressed next.

VII. Sensitivity Examination of CP and CCP Standard

The sensitivity of the CP and CCP standards to details of capacitor performance can be examined using circuit simulations. Consider the capacitor as a series-RC circuit, as shown in **Figure 3**. The series resistance is the equivalent series resistance (ESR). This model assumes that the capacitor is ideal. In actual fact most electrochemical capacitors are not well represented by a single-time-constant model due to their use of porous electrode materials. Nevertheless, this first-order model is useful for examining general capacitor behavior. **Figure 3** also shows the load used to measure the cranking power--a resistor with resistance value R. In the simulation, the capacitor is initially charged at 12.6 V then connected at zero time to the resistor load. Power dissipated in the load is the product of its current times its voltage. Thus, the average power dissipated in the load from time 0 to time τ is the time integral of the power divided by τ.
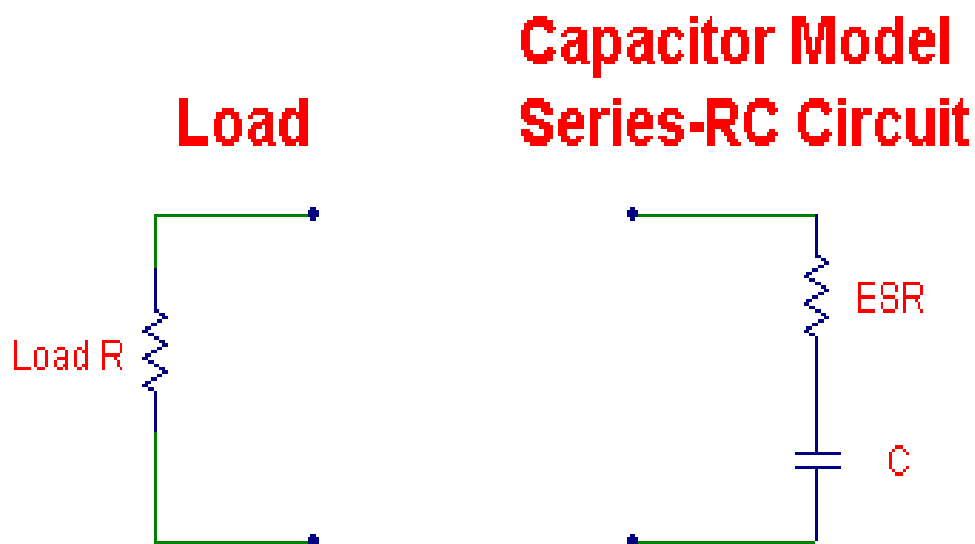

Figure 3: Circuit models for the capacitor (series-RC circuit) and load (resistor) used in performance simulations. The capacitor is initially charged to 12.6 V, then connected to and discharged by the load. The time constant of the capacitor model is equal to the ESR-C product.

Simulations can be performed either analytically or numerically. **Figure 4** shows numerical solutions of the average power delivered by a 900 F capacitor with an ESR of 1.11 mΩ to five different loads, which are resistances of 1 to 5 mΩ in increments of 1 mΩ. The RC product of this capacitor is 1.0 s. First, note that the average power is a monotonic decreasing function of time, as expected for a discharging capacitor. Second, note that the smallest resistor dissipates the highest average power at times less than ~0.6 s. At longer times, the 2 mΩ load dissipates higher average power, out to ~2.3 s, at which time the 3 mΩ load has the highest average power, and so on. The so called "matched load" for a capacitor is not a fixed value, but rather depends on the time used to calculate the average delivered power. This is in contrast with a constant-voltage source such as a battery, where maximum delivered power is obtained using a resistance load with a value equal to the equivalent series resistance of the voltage source.
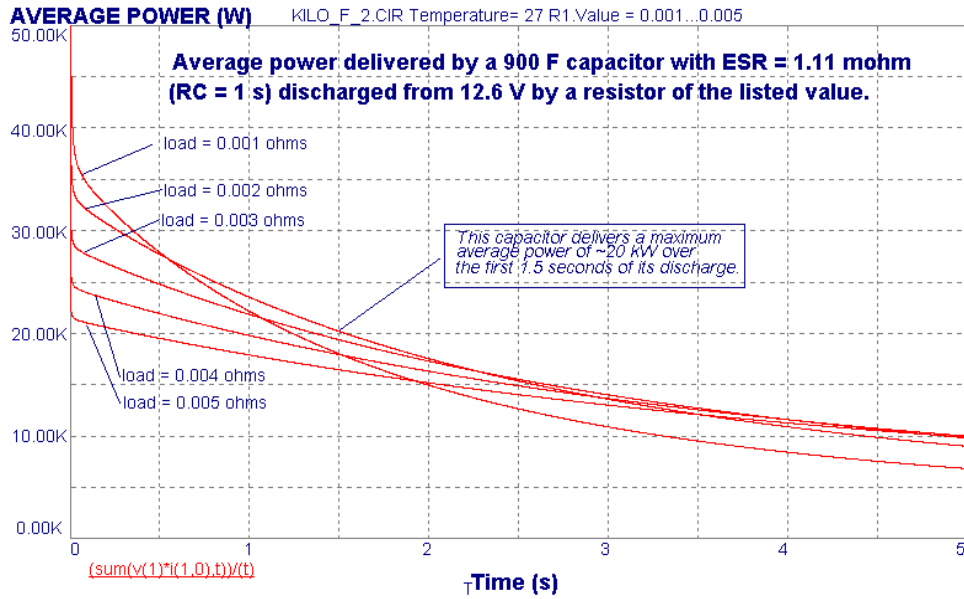
Figure 4: Average power dissipated by resistor loads versus discharge time from discharging a series-RC circuit initially at 12.6 V. The capacitor was 900 F and its ESR=1.11 mohms, yielding RC=1.0 s. Note that at 1.5 s, the maximum average power for a resistor load was ~20 kW.

The highest average power dissipated in the load for times from 0 to 1.5 s by the Figure 4 capacitor is with a 2 mΩ load. Larger or smaller resistance values dissipate less average power during the first 1.5 s period. This relationship between the value of the load resistance and the average dissipated power over the first 1.5 s of the discharge is shown in **Figure 5** for the 900 F capacitor along with three other capacitors. The maximum average power the 900 F capacitor can deliver over 1.5 s is ~20 kW.
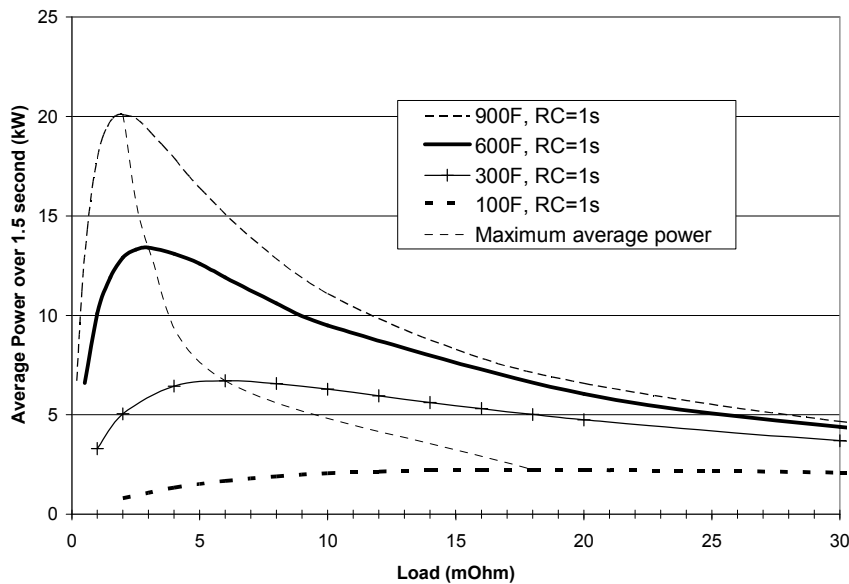

Figure 5: Average power dissipated by various resistor loads at 1.5 s for four different size capacitors, with ESR*C=1.0 s. The 900 F curve was derived using the Figure 4 simulations with R= 1 to 5 mΩ.

Page 10 of 16

The other capacitors shown in Figure 5 have the same RC product, i.e. RC=1.0 s, consistent with examining different 12.6 V capacitors of the same technology. (Parallel or series connecting cells of a given technology will not affect the response time.) During the first 1.5 s, the maximum average power delivered by the 600 F capacitor is ~13 kW, for the 300 F capacitor it is 6.7 kW, and for the 100 F capacitor it is ~2.2 kW. These peak values are the values proposed for the capacitor cranking standard, "Cranking Power".

Simulations as shown in Figure 4 were performed with capacitors having different response times to examine this sensitivity. Results for RC=0.3 s are shown in **Figure 6**. As shown, the maximum average power values at 1.5 s are greater than with the capacitor having RC=1 s. For example, the peak value for the 900 F capacitor is 33 kW instead of 20 kW--this capacitor with RC=0.3 s has 50% higher Cranking Power than the 900 F capacitor with RC=1.0 s.
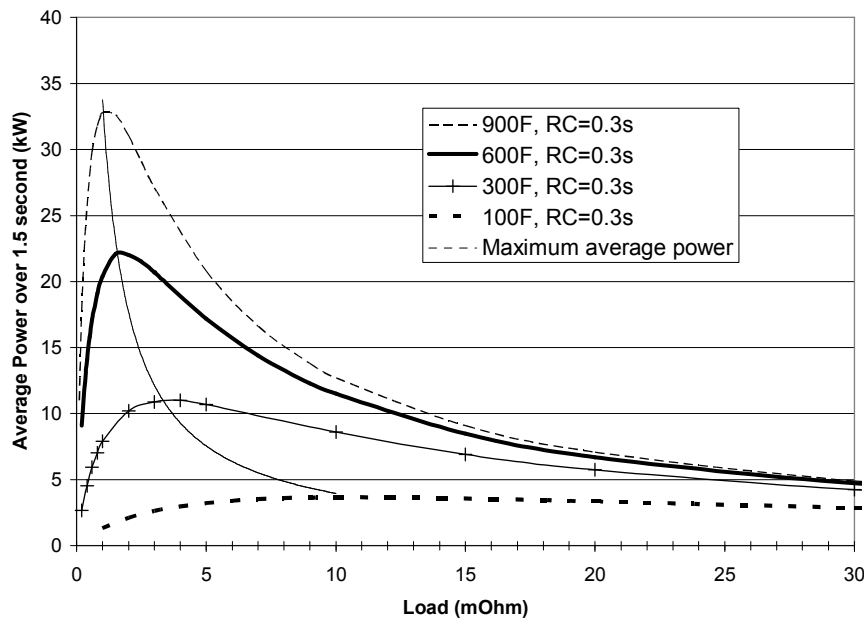

Figure 6: Average power dissipated in resistor loads after 1.5 s for four different size capacitors, with ESR*C=0.3 s. The maximum average power (peaks) represent the standard "Cranking Power".

Figure 7 shows simulation results for the same four capacitors sizes, but this time with RC=3.0 s. Cranking Power values are 9.5, 6.3, 3.2, and 1.1 kW, much lower than the Cranking Power values in the previous two simulations performed using faster response capacitors, i.e. capacitors with smaller RC-products. Thus, the response time of the capacitor enters implicitly into the determination of the Cranking Power value.

Response time simulation results are summarized in **Figure 8**, which plots Cranking Power versus capacitor size for the four different size capacitors with each RC-product. The results have linear behavior for each response time--Cranking Power is proportional to the capacitor size, with the proportionality constant dependent on the RC-product of the capacitor. Thus from this figure, a 137 F-0.3 s time constant, a 224 F-1 s time constant, and a 476 F-3 s time constant capacitor each has the same Cranking Power, 5 kW.
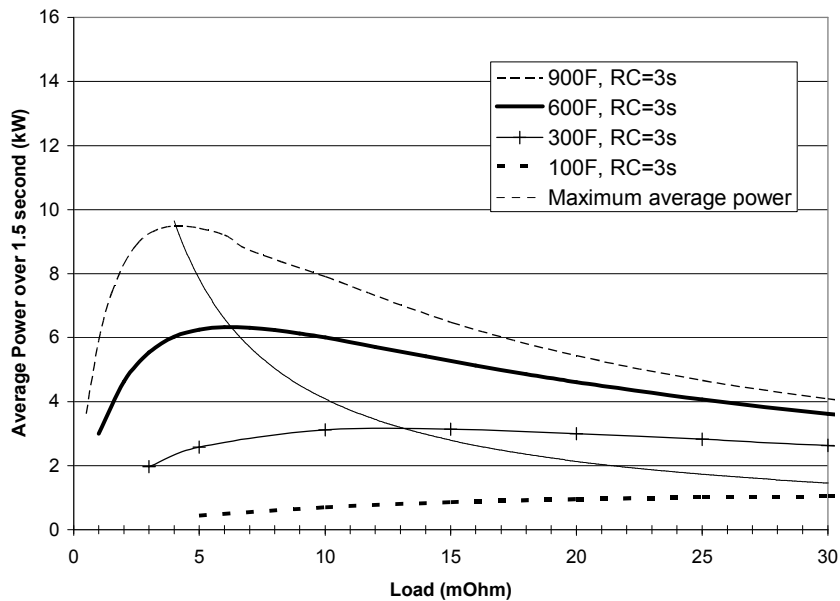
Figure 7: Average power dissipated in resistor loads after 1.5 s for four different size capacitors, with ESR*C=3.0 s. The maximum average power (peak) is the specified Cranking Power standard.
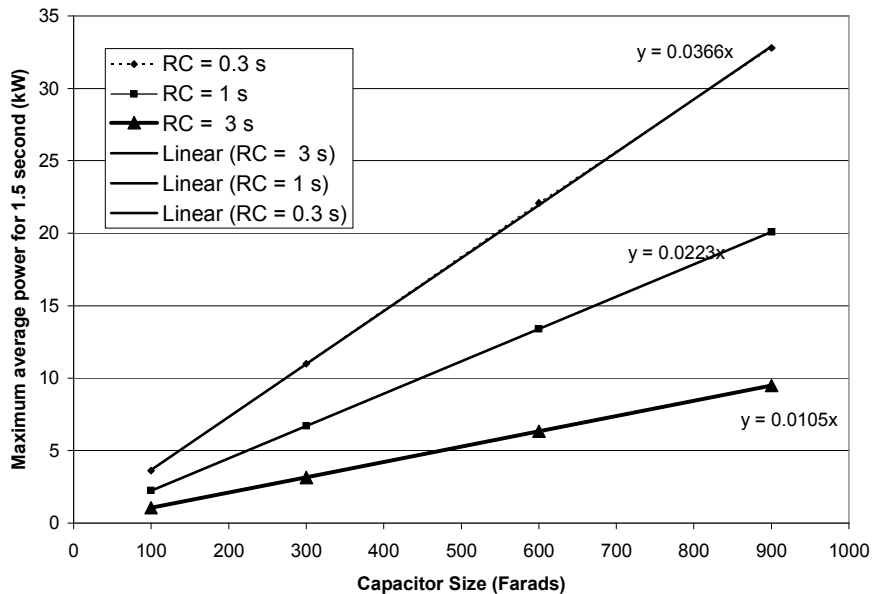

Figure 8: Maximum average power values (Cranking Power) versus capacitor size from the three previous figures. Note the linear behavior. As shown, a 137 F, 224 F, and 476 F capacitors each have 5 kW Cranking Power values. Respective capacitor time constants are 0.3, 1 and 3 s.

The Cranking Power equivalence of the 137 F, 224 F and 476 F capacitors is predicated on using the 1.5 s average power value. Is 1.5 s the best time to use? Perhaps 1.0 s or 3.0 s is better. This can be examined again using simulations. **Figure 9** shows the average power dissipated when a 300 F capacitor is discharged into a resistor load having the same resistance value as the

capacitor's ESR. Note that at time >3 s there is little differentiation between the four different response time capacitors. Thus sensitivity is totally lost when times are equal to or greater than 3 s--all capacitors with a given amount of stored energy appear to provide the same maximum average power value**.** Consequently, the selected time of 1.5 s appears to provide adequate differentiation among equal capacity but different response-time capacitors, as needed. Or stated differently, power capability of a capacitor does influence the Cranking Power standard.
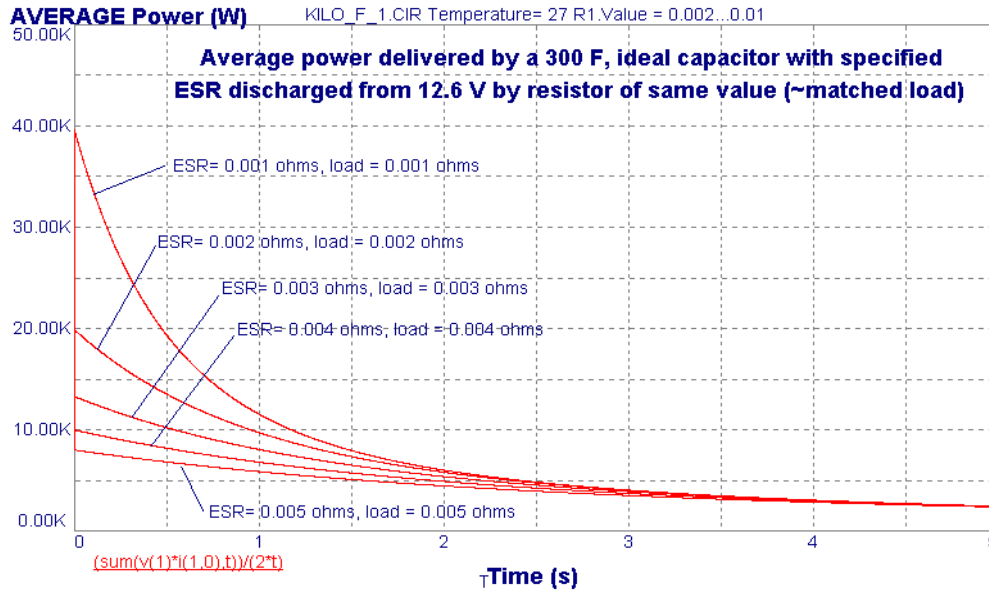

Figure 9: Average power delivered by a 300 F series-RC circuit (charged to 12.6 V) that is discharged into resistor loads of the same resistance value. ESR*C time constants range from 0.3 to 1.5 s. Note that all curves converge at ~3 s, showing essentially no differences at longer times.

VII. Engine Start Time

The Cranking Power standard generated the most discussion among members of the KFI Standards Committee, compared with the other standards listed in Table I. The heart of the issue revolved around the 1.5 s time used to measure Cranking Power, and the prior experience of some Committee members where cranking times of 2, 3, 4, or more seconds were needed to start large diesel engines at very low temperatures. Thus, there was justified concern as to whether the Cranking Power standard should use a longer time. Remember that sensitivity to capacitor power decreases at long times. The resolution of this dilemma was found by examining the IC engine cranking process in detail, as next described.

Klementov investigated the theoretical and practical requirements of IC engine starting and demonstrated that a diesel combustion-ignition engine at low temperatures could be started directly, i.e., in less than 2 s, provided that it was cranked with adequate power.[2] The key is to quickly spin up the engine to an RPM level that supports continued engine running. Then energy lost to engine friction during cranking is at a minimum. Alternatively, the engine can be started at a lower power level (which means lower rotation rate) provided that it is cranked for a sufficient length of time to warm it up, thus reducing the RPM value required to sustain operation. Unfortunately, longer cranking time means that more energy is lost to engine friction during

starting, generally an amount that is approximately proportional to the cranking time. Consequently, an under-powered crank that necessitates 4 s of engine rotation for a successful start will use at least two-times more energy than a more powerful crank that starts the engine in under two seconds.

With capacitor technology <u>we can and therefore we must</u> demand a direct engine start. Otherwise, one ends up substituting the much more expensive capacitor technology for the cheap, energy-rich battery technology. This is a losing proposition. Without doubt, electrochemical capacitor technology can and must evoke a paradigm shift in engine starting for its successful commercialization in this emerging application. This whole issue can be summed up by declaring that "battery thinking" should not be used with this new power source.

There is one other capacitor characteristic that can and should be exploited to advantage-- cyclability. At an extremely low temperature condition (well below the design temperature for a first-crank start), the capacitor can be recharged for a second-attempt start, and a third if needed since a capacitor can be recharged/discharged over and over again with good results. (This is not true with a battery, which looses both energy and power with each additional try.) The capacitor is warmed by each cranking attempt, then recharged to the same voltage, and thus delivers even higher power the next try. Each subsequent start attempt will reach a higher peak rpm value because the capacitor is more powerful and the engine is warmer, thus increasing the probability of a successful start Consequently, allowing infrequent second and third start attempts at unusually low temperatures may be the optimum design when system costs are considered. The capacitor would be sized to provide first-attempt starts under selected design conditions, then rely on second-try cranking when outside the design conditions.

IX. Measurements Using Proposed Standards

All of the standards listed in Table I, except for operation designation, can be measured using commonly available test equipment, which includes a voltmeter, voltage source, current source, assortment of high-power dump resistors, calibrated shunt resistor, stopwatch, and a two-channel oscilloscope. Instantaneous power is easily measured, and as shown in the Figure 4 simulation, its maximum value can be easily determined. The maximum initial value would be the Peak Power standard provided the temperature were correct. The PP value in Figure 4 was ~40 kW.

Cranking Power, which is the major capacitor performance standard used for engine starting, is measured using the assortment of dump resistors with two channels of the scope (recording resistor voltage and resistor current (voltage across the shunt resistor)). **Figure 10** shows the maximum average power delivered in 1.5 s by a 30 kJ, 24 V nominal capacitor discharged by resistors. The peak value is the Cranking Power, provided that the capacitor is at the proper temperature. The peak was found using an iterative process. Sufficient time is needed between resistor discharges to allow the capacitor to equilibrate to the specified temperature, since it will warm during each discharge. Thus, depending on measurement temperature, the CCP or CP for this capacitor would be 11.5 kW.
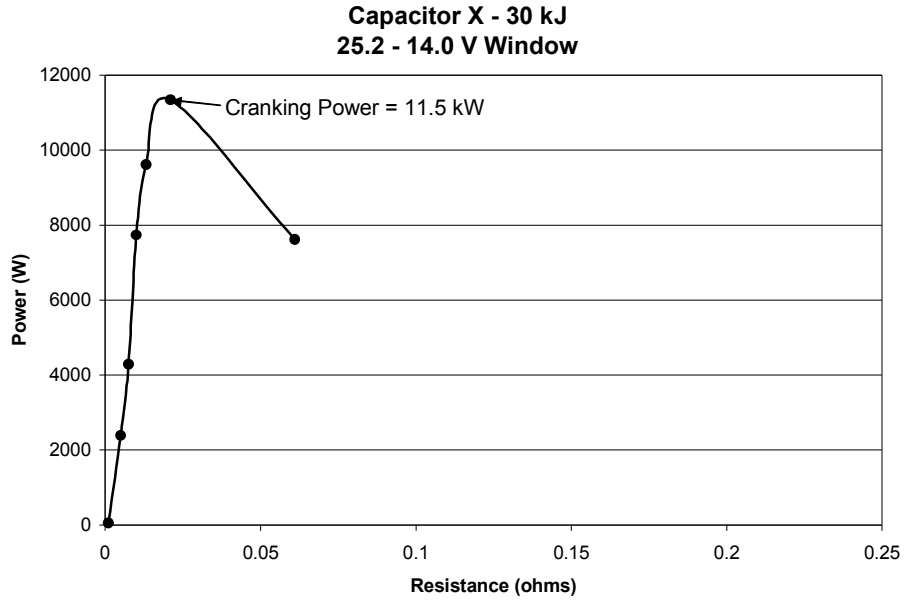
Capacitor X - 30 kJ
25.2 - 14.0 V Window

Cranking Power = 11.5 kW

(Plot: Power (W) vs Resistance (ohms))

Figure 10: Average power delivered during 1.5 s into resistor loads by a 30 kJ commercial capacitor. The peak of this curve is the Cranking Power, or Cold Cranking Power, depending on measurement temperature. This example was measured at room temperature.

A second example of Cranking Power measurements is shown in **Figure 11.** Here the capacitor has a nominal 12 V rating. This capacitor stored 60 kJ of energy, twice the value of the previous example. The peak value is found again using an iterative process and it is easily determined without any ambiguity. The CP value is 7.3 kW. Note that this Cranking Power value is only 64% of the previous value even though this capacitor stores twice the energy, which is a clear demonstration that a capacitor's stored energy value is unreliable for gauging its engine cranking ability.
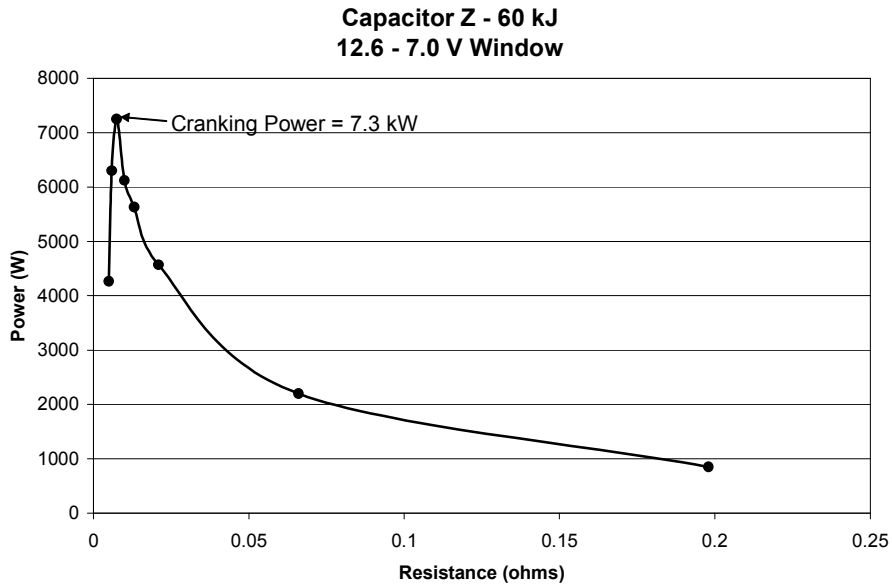
Capacitor Z - 60 kJ
12.6 - 7.0 V Window

Cranking Power = 7.3 kW

(Plot: Power (W) vs Resistance (ohms))

Figure 11: Average power delivered during 1.5 s discharge into resistor loads by a 60 kJ commercial capacitor. The peak of this curve (at 7.3 kW) is the Cranking Power, or Cold Cranking Power of the capacitor, depending on measurement temperature. This example was measured at room temperature.

X. Summary

This report outlined the common rationale for the work of the KFI Standards Committee in developing engine cranking standards. Results were presented in the form of a draft standard for capacitors used to crank internal combustion engines. Due to its exceptional power performance, capacitor technology can and therefore must deliver an immediate engine start to be competitive with alternative power sources. Second-try cranks should be part of the design at the lowest temperatures to help make capacitor costs acceptable--the ability to provide repeated cranks is one of the most attractive features of capacitor. They can deliver comparable or higher power cranks with each subsequent try. Cranking Power, defined as the maximum average power that a capacitor at 0 or -18 $^{\circ}$C can deliver to a resistive load during the first 1.5 s is a key standard. Numerical simulations were used to examine sensitivity of this parameter to capacitor differences--good sensitivity was observed. Cranking Power measurements were demonstrated for two different capacitor technologies (at room temperature) using common test equipment. The next task of the Committee, after Cranking Standard adoption, is to prepare a "Recommended Practices Guide" that suggests standards values for popular IC engines at several temperatures.

XI. References

(1) see WWW.kilofarad.com for more information about this organization.
(2) "Theoretical and Practical Aspects of Internal Combustion Engine Starting with Capacitors", Arkadiy D. Klementov, 15th Int. Seminar on Double Layer Capacitors and Hybrid Energy Storage Devices, Deerfield Beach, FL. (Dec. 5-7, 2005)

XII. Bibliography: IC Engine Starting using Capacitors

Y. Tsuchiya, A. Shirata, and H. Moroboshi, "Low discharge capacitor motor starting system", US Patent no. 5,146,095 (Sept. 8, 1992).

A. Beliakov, "Russian Supercapacitors to Start Engines," Battery International, p102, (April 1993).

A. Ivanov, A. Gerasimov, and A. Vishnevshy, "ECOND Double-Layer Super-High-Energy Capacitor for Pulse Power Applications," Proc. 3rd Int. Seminar on Double Layer Capacitors and Similar Energy Storage Devices, Deerfield Beach, FL (Dec. 6-8, 1993).`

A.I. Beliakov, "Investigation and Developing of Double Layer Capacitors for Start of Internal Combustion Engines and of Accelerating Systems of Hybrid Electric Drive," Proc. 6th Int. Seminar on Double Layer Capacitors and Similar Energy Storage Devices, Deerfield Beach, FL (Dec. 9-11, 1996).

J.R. Miller, J. Burgel, H. Catherino, F. Krestik, J. Monroe, and J.R. Stafford, "Truck Starting Using Electrochemical Capacitors," SAE Technical Paper 982794, Int. Truck and Bus Meeting and Exposition, Indianapolis, IN (Nov. 16-18, 1998).

J.R. Miller, "Engineering Battery-Capacitor Combinations in High Power Applications: Diesel Engine Starting", 9th Int. Seminar on Double Layer Capacitors and Similar Energy Devices, Deerfield Beach, FL (Dec.6-8,1999).`

W. Ong and R. Johnston, "Electrochemical Capacitors and Their Potential Application to Heavy Duty Vehicles", SAE Technical Paper 200-01-3495, Truck and Bus Meeting and Exposition, Portland, OR (Dec. 4-6, 2000).

J.R. Miller and S. Butler, "Diesel Engine Starting Using Battery-Capacitor Combinations", Electronics for Trucks and Buses 2001 (SP-1653), Paper 2001-01-2714, SAE Int. Truck and Bus Meeting and Exposition, Chicago, IL (Nov. 12-14, 2001).

R. Capps and J. Burke, "Ultracapacitors in Practical Applications: Starting Diesel Engines," Advanced Capacitor World Summit 2003, Washington, DC (August 11-13, 2003).

A. Beliakov, "Starting of Locomotive Diesel Engines Using ECs," Advanced Capacitor World Summit 2003, Washington, DC (August 11-13, 2003).

A. Klementov, "Capacitor Assisted Starting of Internal Combustion Engines," Advanced Capacitor World Summit 2004, Washington, DC (July 14-16, 2004).

A.D. Klementov, "Theoretical and Practical Aspects of Internal Combustion Engine Starting with Capacitors", 15th Int. Seminar Double Layer Capacitors and Hybrid Energy Storage Devices, Deerfield Beach, FL. (Dec.5-7,2005).