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Short communication

Ultracapacitors for automotive applications

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Abstract

In response to a growing consensus in the auto industry that ultracapacitors can potentially play a key role in the modern vehicle power distribution network, a task force was created at the United States Advanced Battery Consortium (USABC) to tackle issues facing the fledging industry. The task force embarked on first developing and establishing standards for performance and abuse tolerance of ultracapacitors in collaboration with the U.S. Department of Energy and National Labs. Subsequently, potential applications in the automotive industry were identified and a consensus requirement specification was drawn as a development guide for the industry.

Keywords: Ultracapacitors; Test procedures; Automotive applications; Automotive specifications; United States Advanced Battery Consortium

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1. Introduction

This article highlights the activities of the USABC to help guide the ultracapacitor industry in developing products for the automotive applications. The initial part of the effort was focused on developing common standards for performance testing and abuse tolerance tests for automotive applications. The performance test procedures [1] were developed primarily in collaboration with Idaho National Laboratory (INL) and the abuse tolerance test procedures [2] developed in collaboration with Sandia National Laboratory (SNL).

In addition to developing standards that create a uniform basis for comparing various energy storage devices and makes, the task force also embarked on developing a set of requirements for utilization of ultracapacitors in the automotive applications.

A quick study of requirements for what is known today as “strong” hybrids, i.e., hybrid vehicles in which a significant portion of the driveline power is provided by the electric drive, reveals that ultracaps can meet or exceed all of the requirements competitively with the notable exception of required energy. For “micro-hybrids” on the other hand, where idle-stop and similar strategies such as providing transient power to assist better acceleration or deceleration or smooth shifting of gears are utilized, the amount of required energy is dramatically reduced. For such applications, ultracaps with the superior cycling and cold-temperature performance seem an ideal fit.

This paper summarizes the work performed by the USABC ultracapacitor task force, including an overview of the test procedures, specifications, and other issues of interest to the automotive industry.

2. Applications in automotive

The studies undertaken by the ultracapacitor task force in collaboration with National Renewable Energy Labs (NREL) and the Big 3 US automakers, lead in 2004 to the publishing of the USABC Specifications for three micro-hybrid application categories, as shown in Table 1.

The three categories identified, the12 V stop–start (TSS), 42 V stop–start (FSS), and 42 V transient power assist (TPA), represent increasing demands from the ultracapacitor bank, respectively.

One of the key attributes in the requirement specifications is the cold-cranking pulse power. This is set at 4.2 kW peak power at the low end (TPA) and 8 kW peak at the high end (FSS, TPA) with a minimum voltage identified in each case. The cold-cranking pulse consists of 3-2 s rectangular pulses separated by 10 s rest periods as shown in Fig. 1.

Another critical attribute, one often misunderstood by suppliers, is the available energy. Many suppliers interpret the available energy as the energy content of the ultracapacitor bank or the

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Table 1
USABC ultracapacitor end-of-life (EOL) requirements

System attributes	12 V start–stop (TSS)	42 V start–stop (FSS)	42 V transient power assist (TPA)
Discharge pulse	4.2 kW-2 s	6 kW-2 s	13 kW-2 s
Regenerative pulse	N/A	8 kW-2 s	
Cold cranking pulse at −30 °C	4.2 kW-7 V min	8 kW-21 V min	8 kW-21 V min
Available energy (CP at 1 kW)	15 Wh	30 Wh	60 Wh
Recharge rate (kW)	0.4	2.4	2.6
Cycle life/equiv. road miles	750k/150k miles	750k/150k miles	750k/150k miles
Cycle life profile	UC50	UC50	UC50
Calendar life (years)	15	15	15
Energy efficiency on UC50 (%)	95	95%	95%
Self discharge (72 h from max. V)	<4%	<4%	<4%
Maximum operating voltage (Vdc)	17	48	48
Minimum operating voltage (Vdc)	9	27	27
Operating temperature range (°C)	−30 to +52	−30 to +52	−30 to +52
Survival temperature range (°C)	−46 to +66	−46 to +66	−46 to +66
Maximum system weight (kg)	5	10	20
Maximum system volume (l)	4	8	16
Selling price (US$/system at 100k year^{-1})	40	80	130

energy exchanged during a complete voltage swing from $V_{\max}$ to $V_{\min}$. The available energy, per USABC definition, represents the window of device operation in which all requirements listed in the table above are simultaneously met. The operative word here is "simultaneously". So if a device manufacturer claims to have 15 Wh available energy for TSS, he has to make sure that this energy is available while (1) 4.2 kW-2 s pulse can be delivered, (2) 4.2 kW CC pulse with a voltage no less than 7 V can be delivered, (3) cycle life of 750k/150k is not compromised, (4) calendar life of 15 years is not compromised, and (5) operating voltage stays within 9–17 V specified range, etc.

The cycle life requirements of 750k cycles are set based on the number of charge/discharge cycles required to meet a 150,000 miles requirement. The cycle profile UC50 is devised such that 50% of the available charge to be cycled in and out in a four-step "discharge-rest–charge-rest" regime described in Table 2.

The C-rate terminology has been adopted from the battery industry to normalize the current rate based on the device size and nameplate rating. By definition, a $1C$ rate is the constant current rate at which the device is fully discharged in 1-h. So 8 s discharge at $225C$ rate will result in $8 \times 225/3600 = 1/2$ of the available charge to be removed (assuming available charge is not significantly affected by the rate of discharge). The total cycle takes about 24 s.

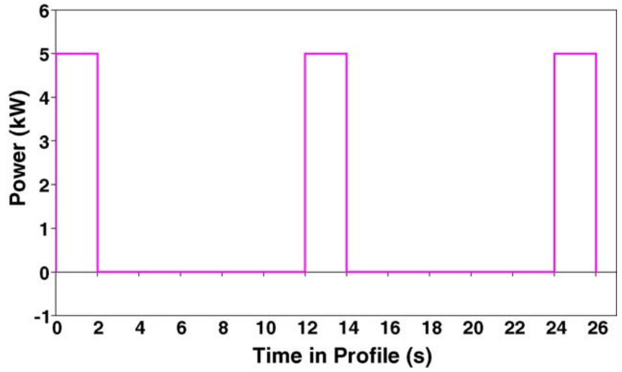

Fig. 1. A 5 kW cold-cranking cycle.

Another area of challenge is the self-discharge (SD). Self-discharge is defined as the energy lost from maximum voltage for 72 h at room temperature in an open-circuit condition as a percentage of the available energy. Although USABC test procedures allows the device manufacturers to define the conditions of the full charge prior to the open-circuit stand test, it is well known that the conditions of the charge prior to the open-circuit stand test dramatically affects the results. The SD test or open-circuit stand test is often confused with the leakage current test. In the leakage current test the device is clamped at the desired voltage (usually $V_{\max}$) and the current flow from the source to the device, required to sustain the voltage, is measured.

The two tests have different intended purposes and should be kept separate although they are obviously related. The SD is a measure of how much of the energy stored in the ultracap bank will be depleted when left on its own, disconnected from a source. The leakage current test measures how much of the external source (such as battery) energy will be depleted in the ultracap bank.

Another area of key interest in automotive applications is abuse tolerance. The abuse tolerance behavior of acetonitrile (ACN)-based ultracapacitors is not well understood and concerns exist on the potential release of toxic substances, specifically HCN, in the event of abusive electrical, thermal, or mechanical conditions. The use of acetonitrile as a solvent in Japan has been banned in favor of propylene carbonate (PC). In the US and Europe no conclusive decision has been reached yet. Although

Table 2
UC 50 cycle life profile

Step	Description	Duration	Current
1	Discharge	8	$225C$
2	Rest	4	
3	Charge	8 (Var.)	$225C$
4	Rest	4	

from the standpoint of abuse-tolerance, PC-based ultracaps are no-doubt superior, this advantage comes at the cost of lower performance in power, particularly at cold temperatures, energy, and even shorter cycle life.

The USABC test procedures for abuse tolerance, in collaboration with DOE Sandia National Laboratory, are now completed and published [2]. These procedures establish a common basis for assessment of abuse-tolerance of ultracapacitors. The USABC is now preparing to conduct independent tests at SNL on ACN and PC-based ultracaps starting later part of the 2005. Some data has been made public with regards to abuse tolerance of ACN-based ultracaps in recent years [3].

The other significant challenge in the ultracapacitors is the cost. Today the cost of a typical ultracapacitor is too high for automotive applications. Because large ultracapacitors are not designed for mass production at present, the material cost today does not constitute a significant portion of the system cost. As suppliers gear up for mass production, they will have to make critical decisions with respect to materials and processes and the trade-offs between cost, fabrication, performance and life. For example, it is known that phenolic-based activated-carbon with high specific capacitance, and good electrical conductivity and low impurities, generally make better ultracaps. They can be operated at higher voltages, result in better specific energy, power, and better life. But the price of activated carbon can range from US\$ 100 kg^{-1} at the high end to about US\$ 15 kg^{-1} at the low end. This price range would have a large impact on the cost of the ultracap system particularly when mass produced. Similar statements can be made about the other key components such as the electrolyte.

Recognizing cost is a major barrier for widespread automotive use, USABC has set cost targets for each class of applications. These are obviously stretch targets and selected with the entry-cost of the new technology in mind.

3. Ultracapacitors in combination with lead-acid battery

In considering ultracapacitors for applications in automotive, the energy limitation of ultracaps is a key factor. A 20-cell 3 kF ultracap bank has a total usable energy of about 39 Wh when the voltage of the bank allowed to drop from the peak of 50–25 V. This is about 2 Wh per cell in a 3 kF cell, and $3\frac{1}{4}$ for a 5 kF cell. To put this in perspective of requirements for automotive applications, we recall that a 1 kW load in 1 min consumes about 17 Wh of energy, roughly half of the total usable energy in a 3 kF, 20-cell bank of ultracaps. A typically stop at traffic in large cities and crowded highways could easily take up to 5 min. In addition, one cannot assume that each time energy is drawn from ultracap it is at its peak voltage. The charge and discharge are often opportunistic rather than planned events as the road and driver conditions are generally assumed unpredictable.

So for most start–stop applications, the energy content of the ultracapacitor bank is insufficient to supply power requirements during idle-stop. Similarly, as a reference, an 18 kW pulse of 8 s duration consumes 40 Wh s of energy, beyond what the example ultracap bank can supply. Since most traction related applications in automotive are energy intensive, it order to best utilize ultracapacitors, they need to be used in combination with an inexpensive, i.e., lead-acid, battery. The latter has the advantage of having been already tested and true technology in today's vehicles.

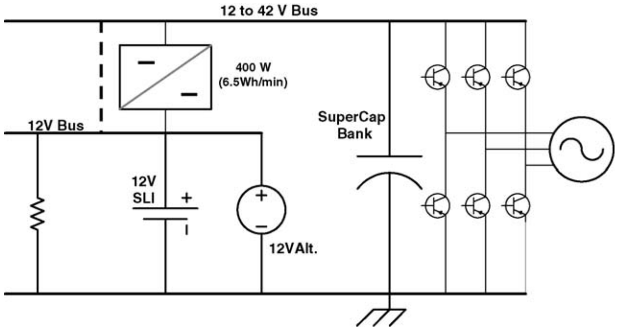

Fig. 2. A dual bus configuration separating loads between the battery and ultracapacitor bank.

Fig. 2 shows an example of how ultracapacitors can be used in the car power network in combination with the 12 V lead-acid battery.

In this bus configuration, the loads can be divided into two groups. The low power but energy intensive loads to be supplied by the lead-acid battery, but the burst of high power low energy loads such as those of cold-cranking, and hot restarts to be provided by the ultracapacitor bank.

Used in this manner, a typical specification is derived for the ultracapacitor bank as shown in Table 3. The lead-acid battery in Fig. 2 is charged by the 12 V alternator while a dc–dc converter is utilized to provide charge to the ultracapacitor bank. In order to make the ultracapacitor bank ready for hot restart at all times, it is necessary to keep it always at or near its peak voltage. One cannot always rely on the regenerative power supplied by the integrated starter–alternator to keep the ultracapacitor bank fully charged. The dc–dc converter ensures that the capacitor bank is kept at or near full SOC at all times. This dc–dc converter also presents a cost challenge, as the cost of the entire system

Table 3
Battery–ultracapacitor specifications

Attribute	SLI battery	UltraCap bank
Discharge pulse power		6 kW-2 s (3.3 Wh)
Regenerative pulse power		6 kW-2 s (3.3 Wh)
Engine-off accessory load	0.7 kW-2 min (23 Wh)	
Available energy	50 Wh at 700 W	10 Wh at 6 kW
Energy efficiency on load profile		90%
Cycle life on UC 10-5	100,000 at 23 Wh DOD	150,000
Cold-cranking power at −30 °C		6 kW at 7 V min
Calendar life (years)	5	15
Maximum operating voltage	17	17
Minimum operating voltage	8	8
Operating temperature range	−30 to 52 °C	−30 to 52 °C

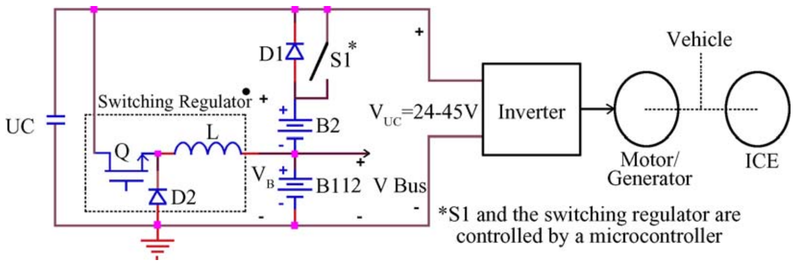

Fig. 3. A 24/45 V battery–ultracapacitor dual bus system.

at volumes of about 100,000 units per year should not exceed US$ 150–170 to be cost competitive. An alternative configuration directly connects the ultracapacitor bank across the 12 V battery (dotted line), but this configuration has technical disadvantag that it cannot separate loads and therefore the cycles are borne jointly by both the lead-acid and ultracapacitor bank.

Another implementation of a dual bus voltage 24/45 V is shown in Fig. 3. In this circuit configuration, the 12 V bus is supplied via battery B1 while a small switching regulator is used to supplement battery B1 so that it stays in balance with battery B2 [4].

4. Suppliers and technologies

There are a number of suppliers and a number of key technology differentiators in the ultracapacitor industry. Table 4 summarizes some of the key players and their respective technologies that were tested at INEEL.

A key distinguishing factor between ultracapacitors is their energy densities. Fig. 4 shows a comparison between specific energy of six different types of ultracapacitors. It is observed that ultracapacitors energy is by and large independent of discharge rates with the exception of the asymmetric ultracaps. The latter have significantly higher energy but their energy content, like batteries, shows an inverse relationship with the rate of discharge.

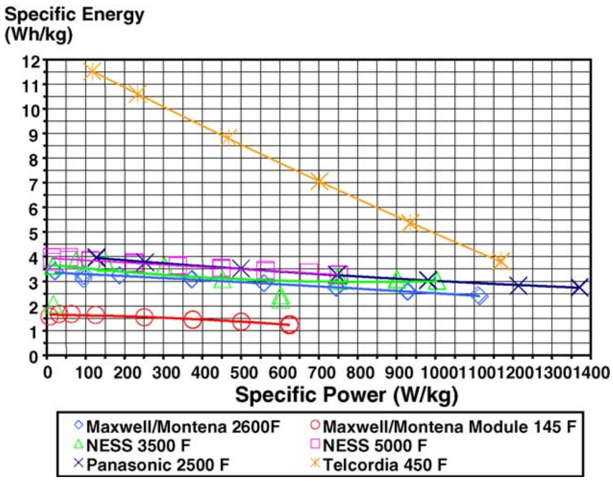

Fig. 4. Energy as a function of discharge rate for various symmetric and asymmetric ultracaps.

Indeed in comparing the constant current discharge behavior of symmetric and asymmetric ultracapacitors, more similarities can be observed between the asymmetric ultracaps and battery discharge behavior, just as expected (see Fig. 5).

The similarities between asymmetric ultracapacitors and batteries have some industry experts convinced that the advantages of EDLcapacitors, namely uniform power capability and energy capability over a wide range of temperatures, high efficiency

Table 4
Key suppliers and technology attributes

Capacitor	Rated capacitance (F), voltage range (V)	Electrodes and electrolyte system
Maxwell Technologies (USA) PC2500	2700, 0–2.7	Carbon/carbon, Et_4NBF_4 in acetonitrile
Maxwell Technologies (USA) BCAP0010	2600, 0–2.5	Carbon/carbon, Et_4NBF_4 in acetonitrile
Maxwell Technologies (USA) BMOD011501	145, 0–42 (18 cells in series)	Carbon/carbon, Et_4NBF_4 In acetonitrile
NESS Capacitor Co. Ltd. (Korea) NESSCAP3500F	3500, 0–2.7	Carbon/carbon, Et_4NBF_4 in acetonitrile
NESS Capacitor Co. Ltd. (Korea) NESSCAP5000F	5000, 0–2.7	Carbon/carbon, Et_4NBF_4 in acetonitrile
Panasonic (Japan) UP-CAP 2500F	2500, 0–2.3	Carbon/carbon, Et_4NBF_4 in acetonitrile
Telcordia Technologies (USA)	450, 1–2.8, Asymmetic	Carbon/$Li_4Ti_6O_{12}$, $LiBF_4$ in acetonitrile, in flex plastic pouch
ESMA (Russia) 30EC502H-130-45/22.5-0.011	175, 27–45, Asymmetric	Ni oxyhydroxide/carbon, aqueous KOH
EPCOS Capacitor Co. (Germany) BP-49400-L2366-Q000	3600, 0–2.5	Carbon/carbon, Et_4NBF_4 in acetonitrile
EPCOS Capacitor Co. (Germany) BP-49400-G2506-Q000	5000, 0–2.5	Carbon/carbon, Et_4NBF_4 in acetonitrile
EPCOS Capacitor Co. (Germany) OTC PN 3504763	112.5, 0–2.5	Carbon/carbon, Et_4NBF_4 in acetonitrile
Power Systems Co. Ltd. (Japan) EcaSS PMLF54-65	65, 0–54	Carbon/carbon, Et_4NBF_4 in propylene carbonate

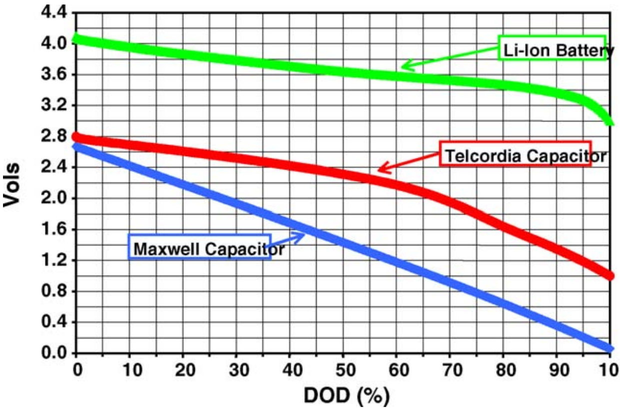

Fig. 5. The *C*/1 discharge behavior of asymmetric and symmetric ultracaps (25 °C).

at peak power, good cycle life, and low self discharge, can be compromised by using non-carbon electrodes. In fact the tests conducted so far at INEEL, provide some evidence to that point. For example, Fig. 6 compares the capacitances of various symmetric ultracaps and Telcordia's asymmetric ultracap with rate of discharge at 25 and −20 °C.

Fig. 7 subsequently shows the energy efficiency of various symmetric and asymmetric ultracaps at 25 °C and shows that the efficiency of asymmetrical ultracaps at high discharge rates could drop as low as 35% well below the target value of 90%.

Fig. 8 compares the self discharge rate of various capacitors at 25 °C over a period of 72 h stand time. The self discharge is calculated as the percentage of total energy loss over the stand period at open-circuit voltage and confirms that asymmetric Telcordia ultracap discharges much faster than its symmetrical counterparts to the tune of 20% over the 72 h stand period, much faster than its symmetrical counterparts.

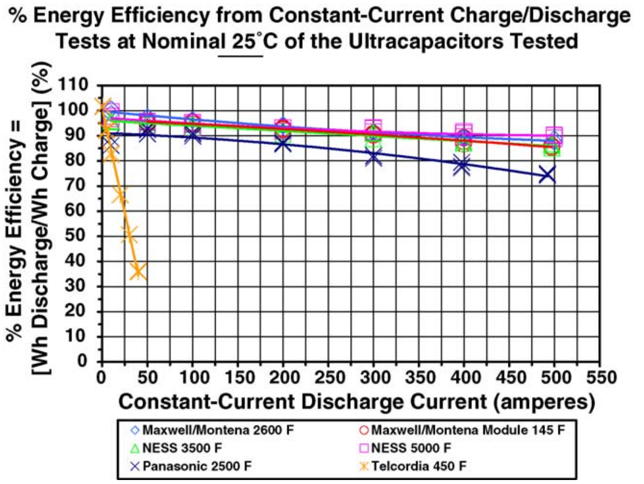

Fig. 7. Energy efficiency of various symmetric and asymmetric ultracaps at 25 °C.

5. Development of standards and test procedures

Effort has been under way in the United States to develop common standards and test procedures for ultracapacitors. The first ultracapacitor test manual was written by Andy Burke and John Miller and published in October 1994. This manual was subsequently revised by Randy Wright and John Miller based on the experience gained during several years of testing ultracaps at INEEL and released in October 2003. In November 2003, the manual was reviewed by the USABC task force on ultracaps and major revisions were recommended in the manual. The current manual, now released and available to the public for review and feedback, classifies the test procedures into four categories:

I Characterization tests: These tests are designed to establish device performance at the beginning of life (BOL).
II Life tests: The life tests subject the device to representative operating stresses in a time and/or temperature accelerated regimes and try to establish the life of the component in actual vehicle operation.
III Reference performance tests (RPT): RPT's are a subset of characterization tests performed at regular time/cycle intervals to establish performance degradation of the device over life.

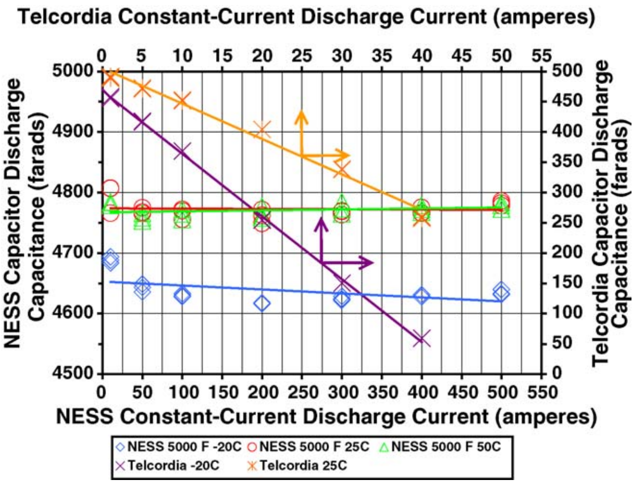

Fig. 6. Variation of capacitance with discharge rate at 25 and −20 °C.

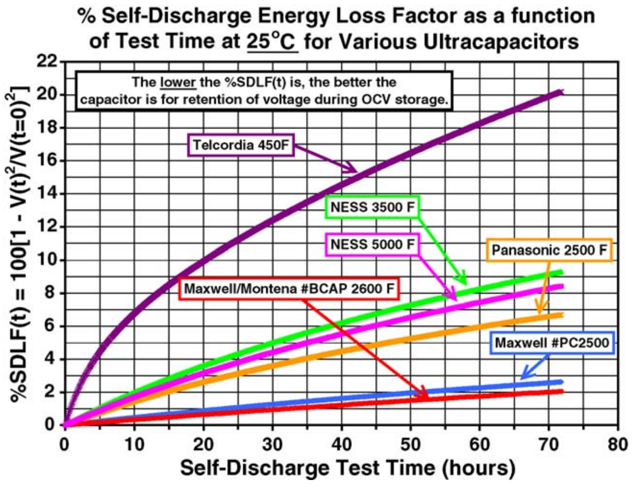

Fig. 8. Self discharge rate (%) of symmetric and asymmetric ultracaps at 25 °C.

IV Abuse tolerance tests: These tests subject the device to extreme electrical, thermal, and mechanical conditions to establish what happens during a failure that leads to the device operating outside its normal operating conditions.

The first draft of the ultracapacitors' test procedures is now available to the public at the USCAR web site http://uscar.org/consortia&teams/consortiahomepages/con-Usabc.htm. All interested parties are encouraged to download, review, and provide feedback. All feedbacks received by July 1, 2004, will be given due consideration for incorporation into the Version 1.0 of the manual due for release in August 2004. All feedbacks regarding performance tests (categories I–III) should be forwarded to Randy Wright RGW2@INEL.gov and feedbacks concerning abuse tolerance should be forwarded to Chris Crafts cccraft@sandia.gov.

Acknowledgements

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