APPENDIX J

DETAILED PROCEDURES

Procedures Included in Appendix J

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Peak Power Test

1.0 PURPOSE

The purpose of this test is to determine the maximum sustained power capability of a battery for 30 second discharge pulses at various depths of discharge (DOD). The value calculated at 80% DOD is particularly important because this is the point at which the USABC power goal is defined, and the technology performance at this point is compared with this goal. This procedure does **not** measure the actual peak power of the battery; rather it infers (calculates) a predicted peak power performance from measurements taken at high currents which are nonetheless lower than the rated peak power.

2.0 PREREQUISITES

2.1 A battery test plan or other test requirements document is required for testing using this procedure. The test plan specifies certain values to be used for this test. These values include the manufacturer's rated peak power at 80% DOD, minimum discharge voltage, maximum rated current (if any), rated A•h capacity, and test temperature limitations, along with safety precautions and any special handling/testing instructions specified for the battery by the manufacturer and/or the USABC.

2.2 Prior to the performance of this procedure, USABC Test Procedures No. 1A, Battery Pre Test Preparation, and No. 1B, Readiness Review, should normally have been completed. These activities are not a part of this procedure. This procedure may be executed as a stand-alone test activity or as part of a sequence of tests (e.g. periodic testing during a life-cycle test regime) provided that the information required by 2.1 above is available.

3.0 TEST EQUIPMENT

The equipment required to perform the peak power test consists of (a) a suitable charger for the battery; (b) a battery discharge tester capable of achieving the currents defined in 4.1.2 and 4.1.3; and (c) a data system capable of acquiring the data specified in Section 6.0 at intervals of 1 second or less. The maximum permissible transition time between current steps is 1 second or less. The transition times are included in the overall profile length (i.e. a High Test Current Step is always 30 seconds long.)

4.0 DETERMINATION OF TEST CONDITIONS

4.1 Calculate the Test Currents for the test as follows. (An example of these calculations is contained in the box following.) **Note: all current, power and ampere-hour values in calculations for this procedure use the convention that current (and thus power) out of the battery is negative.**

4.1.1 **Rated Peak Current** = Rated Peak Power (at 80% DOD) divided by 2/3 of the Open Circuit Voltage (at 80% DOD at beginning of life.)

4.1.2 **High Test Current** = the lesser [in magnitude] of (a) the manufacturer's Maximum Rated Current for the battery or (b) 80% of Rated Peak Current.

4.1.3 **Base Discharge Rate** = that current which, combined with a High Test Current 30 second pulse every 10% DOD, gives an average discharge current equivalent to the C/3 discharge rate. This can be calculated as follows:

$$I_{base\ discharge} = (12 \bullet C_{rated} - \text{High Test Current}) \div 35.$$

Note: If the capacity of the battery is so small that the Base Discharge Current would be zero or less (i.e. the pulse alone is 10% DOD or more), the test cannot be performed without modifying this procedure.

Example: Suppose Maximum Rated Current (for 30 s) = -250 A
Rated Peak Power at 80% DOD = -16.0 kW
Open Circuit Voltage (OCV) at 80% DOD=120V
C/3 Rated Capacity = -120 Ah

Then:

Rated Peak Current = -16.0 kW ÷ (2/3 of 120 V) = -200 A

High Test Current = the lesser (in magnitude) of
a. -250 A
b. 80% of -200 A

High Test Current = -160 A

Base Discharge Rate = (12 * -120 - (-160)) ÷ 35
Base Discharge Rate = -36.57 A

Since 10% DOD should require 3 hours ÷ 10 = 1080 seconds, at an average current of 120 A•h ÷ 3 hr = 40 A, this is 43,200 A-s per 10% DOD. During each 10% DOD, there is one 30 second pulse at the High Test Current of 160 A. This accounts for (30 * 160) = 4800 A-seconds, leaving 38,400 A-seconds for the Base Discharge Rate over the remaining 1050 seconds. 38,400 A-s ÷ 1050 s = 36.57 A.

4.2 Establish the **Discharge Voltage Limit** for the battery as the greater of (a) the manufacturer's minimum voltage limit, or (b) 2/3 OCV at 80% DOD at beginning of life. If this value is not supplied by the manufacturer, it can be measured using a C/3 discharge terminated at 80% of rated capacity; the battery voltage at 1 hour after it is placed on open circuit at this condition will be considered the OCV.

5.0 PROCEDURE STEPS

5.1 Charge the battery in accordance with the test plan.

5.2 Conduct the Discharge

5.2.1 Discharge the battery at the Base Discharge Rate for 30 seconds.

5.2.2 Discharge the battery at the High Test Current for 30 seconds.

5.2.3 Continue to discharge the battery at the Base Discharge Rate until a 10% increment of the rated capacity (in A-h) has been removed, including the pulse in Step 5.2.3 (i.e. the capacity removed in the pulse plus the additional discharge at the Base Discharge Rate should be 10% DOD.)

5.2.4 Repeat 5.2.2 and 5.2.3 for each 10% DOD increment until 90% DOD is reached. When the 30 second discharge pulse is performed at 90% DOD, the Base Discharge Rate should continue for the remaining capacity of the battery.

5.3 Recharge the battery in accordance with the Test Plan.

5.4 Calculate the Peak Power capability of the battery at each 10% DOD increment.

5.4.1 Using the voltage and current measured (1) near the end of each High Test Current step and (2) just prior to the beginning of that step, calculate the battery resistance as the quotient of the voltage change and the current change between these two points:

Resistance R =)V ÷)I

5.4.2 Calculate the battery IR-free voltage (i.e. open-circuit voltage at this depth-of-discharge) from the voltage and current measured near the end of the High Test Current step:

Battery IR_{Free} Voltage: $V_{IRFree} = V - IR$

5.4.3 Calculate the Peak Power capability at this depth-of-discharge as the minimum value of the following three equations:

(1) Peak Power Capability = $-(2/9) \bullet (V_{IRFree}{}^2) \div R$

or

(2) Peak Power Capability = - DVL • (VIRFree - DVL) ÷ R

where DVL is the Discharge Voltage Limit or

(3) Peak Power Capability = $I_{MAX} \bullet (V_{IRFree} + R \bullet I_{MAX})$

where I_{MAX} is the Manufacturer's Maximum Rated Current (if defined, otherwise ignore this calculation)

See the example which follows for more information.

Example: (based on earlier example battery at 80% DOD)

Suppose Current near end of High Test Current step = -160 A
Voltage near end of High Test Current step = 88 V

Current 30 seconds earlier (Base Current) = -35 A
Voltage 30 seconds earlier (Base Current) = 113 V

Then **R** =)V ÷)I = (88-113) ÷ (-160-(-35)) = **0.2 ohms**

$\mathbf{V_{IRFree}}$ = 88 - (-160 * 0.2) = **120 Volts**

Equation 1: Peak Power = -(2/9) * $(120)^2$ ÷ 0.2 = -16,000 W

NOTE: negative sign on discharge current is required for correct result

Equation 2:DVL = 2/3 OCV at 80% DOD = 120 • 2/3 = 80V

Peak power = -80 • (120-80) ÷ 0.2 = -16,000 W

Equation 3: Peak Power = (-250 A) * (120 V + 0.2 S * -250 A)
= -17,500 W

Thus

Peak Power Capability = -16,000 Watts

5.4.4 If voltage or current limiting (due to minimum voltage or maximum current limits) was encountered during a High Test Current step, the Peak Power Capability is still calculated as above. However, if the actual power at the end of a 30 second step (where voltage or current limiting occurs)is less than the value calculated, this lower actual power must be reported as the Peak Power Capability. The High Test Current for subsequent steps during this discharge may (depending on equipment capabilities) be reduced to a value that will permit the step to be done at constant current (i.e. a value that does not result in further voltage limiting.)

5.4.5 If the Base Discharge Rate cannot be achieved at any point during the discharge without dropping below the Discharge Voltage Limit, the discharge is terminated.

6.0 DATA ACQUISITION

6.1 Current Step Data

Battery current and voltage measurements must be taken at 1 second intervals for the period from 30 seconds before the start of each High Test Current step to 30 seconds after the completion of each High Test Current step. This is an interval of 90 seconds during each 10% DOD. These measurements should be preserved for subsequent analysis; and the 90 seconds of data nearest 80% DOD should be reviewed graphically to assure that the test results are valid.

6.2 Base Discharge Data

During the remainder of the discharge at the Base Discharge Rate, all measurements (voltage, current, temperature, module voltages if any etc.) must be recorded at intervals not exceeding 10 minutes or whenever any parameter (including % DOD) changes by 2% or more from the previous recorded value.

6.3 Data Averaging for Calculation

The two voltage-current measurement pairs used for calculating the peak power capability at each 10% DOD are normally obtained by (1) averaging three successive current and voltage measurements near the end of the High Test Current step and (2) averaging three successive current and voltage measurements just prior to the start of the step.

7.0 REPORTING

The calculated peak power capability at each 10% DOD interval should be reported and graphed against the actual (not nominal) depth of discharge corresponding to the end of the High Test Current step. A plot of current and voltage during the step closest to 80% DOD should also be provided.

FUDS Cycle Test

1.0 PURPOSE

For simulated driving cycle testing of USABC batteries, a variable power discharge cycle based on the Federal Urban Driving Schedule (FUDS) may be applied to the battery. The USABC FUDS is scaled to a percentage of the maximum rated power or USABC power goal for a given technology. In general the FUDS maximum power is likely to be 80% of the USABC peak power goal for a technology; however, the specific value to be used in this procedure is specified (in watts or kilowatts) in the test plan.

Figure 5A-1 shows a graphical representation of the USABC FUDS 1372 second test profile, which is applied repetitively over a complete battery discharge. Table 5A-1 is the tabular listing of the USABC FUDS power profile; this listing may be obtained in computer readable form from the Idaho National Engineering Laboratory (208-526-1847).

Note: All references to the term 'battery' in this procedure refer to the unit to be tested, which may be a single cell, a multi-cell module, a battery pack, or a complete battery system.

2.0 PREREQUISITES

2.1 A Battery Test Plan or other test requirements document is required for testing using this procedure. The test plan specifies the values to be used for the FUDS. These values include battery A•h ratings, peak discharge power to be applied during FUDS testing, charge/discharge termination criteria, charging procedure, test temperature limitations, safety precautions, and any special handling/testing instructions specified by the manufacturer and/or the USABC.

2.2 Prior to the performance of this procedure, USABC Test Procedures No. 1A, Battery Pre Test Preparation, and No. 1B, Readiness Review, should normally have been completed. These activities are not a part of this procedure. This procedure may be executed as a stand-alone test activity or as part of a sequence of tests (e.g. a life-cycle test regime) provided that the information required by 2.1 above is available.

3.0 TEST EQUIPMENT

The equipment required to perform the FUDS consists of (a) a battery charge-discharge tester capable of achieving the scaled power-time profile shown in Figure 5A-1; and (b) a data system capable of acquiring the data specified in Section 6.0 at intervals of 1 second or less. The steps in this profile are only 1 second long, and the maximum permissible transition time between power steps is thus 1 second or less. The transition times are included in the overall profile length (i.e. a FUDS profile is always 1372 seconds long.)

4.0 DETERMINATION OF TEST CONDITIONS

4.1 Determine the **power levels** to be applied **for each step** of this FUDS procedure. The maximum power level (as specified in the test plan or other test requirements document) is the 100% level shown in Figure 5A-1, which occurs in Step 195 in Table 5A-1. The power levels of the remaining steps are then calculated using the percentage values in Table 5A-1.

4.2 Determine (from the test plan) the **ampere-hour capacity** to be used for this FUDS procedure. In general the FUDS is performed to 100% of the battery's rated capacity. However, some lesser value such as 80% of this capacity may be established for life cycle testing. The battery capacity to be used for discharge is based on <u>net</u> capacity removed (total A•h less regeneration A•h).

4.3 Establish the **battery limits** to be observed during the test. These should be specified in the test plan and will normally consist of some set of voltage, current, power and/or temperature limits which should not be exceeded for the battery. The tester should be programmed such that these limits are not permitted to be exceeded during the test.

A FUDS discharge will terminate whenever the specified power cannot be achieved for a given step without exceeding one of the battery limits. (If specifically required by the test plan, this condition may be violated by permitting, for example, reduced regen power under some conditions during a discharge. However, this will affect the reporting requirements of Section 7.0.)

5.0 PROCEDURE STEPS

5.1 <u>Charging</u> - Fully charge the battery in accordance with instructions given in the test plan.

5.2 <u>Open Circuit After Charge</u> - With the battery on open circuit, stabilize the battery temperature or other initial conditions as specified in the test plan.

5.3 <u>Discharge</u> - Discharge the battery using the FUDS power profile. Repeat the 1372 second FUDS segments end-to-end (i.e. with no rest period between profiles) until a termination condition is reached.

5.4 <u>Termination</u> - The discharge should terminate when either of the following conditions is reached: (a) the power achievable on any step (without violating any battery limits) is less than the specified value for that step; or (b) the specified net ampere-hour capacity of the battery is removed.

5.5 <u>Recharge</u> - Recharge the battery in accordance with the test plan.

6.0 DATA ACQUISITION

6.1 Acquisition Rates

Overall battery voltage, current and power are required to be measured at intervals not exceeding 1 second during the entire FUDS discharge, and net ampacity (ampere-hours) and net energy (watt-hours) should be accumulated based on at least this frequency of data acquisition. Other measurements required by the test plan (e.g. battery temperatures, the voltages of modules or cells within a multi-cell/module battery etc.) must be measured at least once per minute, including during the maximum discharge and maximum regen steps, unless termination criteria are based on their values, in which case they must also be measured at 1 second intervals.

6.2 Data Retention

6.2.1 Performance Testing

For a FUDS test conducted as a battery performance test, overall voltage, current, power, ampacity (ampere-hour) and energy (kilowatt-hour) values must be recorded and retained at 1 second intervals for the entire discharge. The value of all measured parameters must be recorded and retained at least once during the maximum discharge and maximum regen steps in each profile. (See Data Acquisition and Retention requirements section of the USABC procedures manual.)

6.2.2 Life Cycle Testing

If the FUDS is used as a repetitive life cycle test, the data required by 6.2.1 must be retained between successive executions of the Reference Performance Tests, until permission is received from the USABC Program Manager to discard it.

7.0 REPORTING

In addition to the summary information required from all USABC tests, the following specific information shall be reported for any FUDS discharge conducted as a performance test:

a. The peak power to which the test was scaled
b. Measured capacity of the battery
c. If any limitations were placed on the discharge by battery limits in the test plan (e.g. regen current limits), the capacity achieved both with and without such limits in effect shall be reported
d. The current, power and voltage during the first 300 seconds of the complete profile nearest to 80% DOD shall be graphed

For FUDS discharges conducted as part of a life-cycle test series, the capacities in (b) and (c) above shall be graphed as a function of cycle number over the course of the life test series. Periodic (i.e. monthly) progress reporting shall include the capacities at the start of life testing, the number of cycles performed to date, and the present capacities.

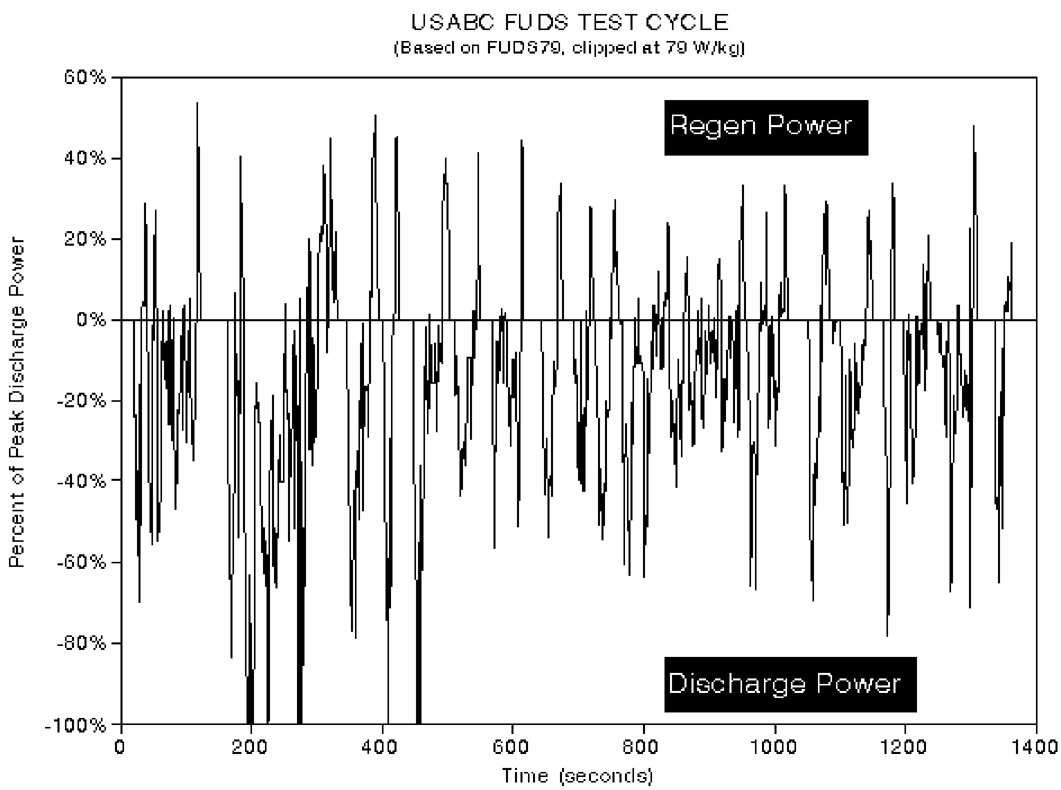

Figure 5A-1

Table 5A-1
USABC FUDS POWER PROFILE
TIME (seconds) vs POWER (Fraction of Peak)

Time	Power
0	0
1	0
2	0
3	0
4	0
5	0
6	0
7	0
8	0
9	0
10	0
11	0
12	0
13	0
14	0
15	0
16	0
17	0
18	0
19	0
20	0
21	-0.24051
22	-0.23671
23	-0.38354
24	-0.46835
25	-0.52911
26	-0.58481
27	-0.15949
28	-0.23291
29	-0.6962
30	-0.32911
31	-0.26582
32	-0.11519
33	0.021519
34	0.044304
35	0.044304
36	0.031646
37	0.041772
38	0.287342
39	0.179747
40	-0.04557
41	-0.11519
42	-0.11772
43	-0.1519
44	-0.30127
45	-0.5038
46	-0.55823
47	-0.51392
48	-0.13544
49	-0.01392
50	-0.0481
51	0.144304
52	0.268354
53	0.183544
54	0.103797
55	-0.04937
56	-0.4443
57	-0.54557
58	-0.52152
59	-0.52658
60	-0.38228
61	-0.21519
62	-0.18481
63	-0.13291
64	0.018987
65	-0.0557
66	-0.14937
67	-0.13165
68	-0.05696
69	-0.0557
70	-0.09367
71	-0.25443
72	-0.25949
73	-0.13797
74	0.006329
75	0.032911
76	-0.13291
77	-0.22405
78	-0.3
79	-0.10253
80	0.005063
81	-0.23165
82	-0.29241
83	-0.3557
84	-0.46709
85	-0.3481
86	-0.29747
87	-0.22532
88	-0.22785
89	-0.23165
90	-0.12785
91	-0.04051
92	-0.08228
93	-0.08228
94	-0.16835
95	-0.27089
96	0.018987
97	0.035443
98	0.018987
99	-0.22152
100	-0.3038
101	-0.26962
102	-0.19367
103	-0.17342
104	-0.08608
105	0.035443
106	0.053165
107	-0.16456
108	-0.22532
109	-0.30886
110	-0.31519
111	-0.34684
112	-0.28861
113	-0.20886
114	-0.0481
115	0.035443
116	0.535443
117	0.489873
118	0.459494
119	0.389873
120	0.311392
121	0.229114
122	0
123	0
124	0
125	0
126	0
127	0
128	0
129	0
130	0
131	0
132	0
133	0
134	0
135	0
136	0
137	0
138	0
139	0
140	0
141	0
142	0
143	0
144	0
145	0
146	0
147	0
148	0
149	0
150	0
151	0
152	0
153	0
154	0
155	0
156	0
157	0
158	0
159	0
160	0

161	0
162	0
163	0
164	-0.26329
165	-0.36203
166	-0.45949
167	-0.57089
168	-0.71646
169	-0.83671
170	-0.73165
171	-0.70633
172	-0.55949
173	-0.30506
174	0.068354
175	0.046835
176	0.018987
177	-0.18608
178	-0.15443
179	-0.1557
180	-0.22785
181	-0.53797
182	0.06962
183	0.351899
184	0.153165
185	0.403797
186	0.174684
187	0.026582
188	-0.2557
189	-0.16962
190	-0.39241
191	-0.66962
192	-0.77215
193	-1
194	-1
195	-1
196	-1
197	-0.63291
198	-1
199	-0.75443
200	-1
201	-0.95823
202	-1
203	-0.73038
204	-0.68734
205	-0.6481
206	-0.26329
207	-0.16076
208	-0.21899
209	-0.15696
210	-0.25696
211	-0.25696
212	-0.25696
213	-0.25696
214	-0.37089
215	-0.37342
216	-0.54557
217	-0.61266
218	-0.62532
219	-0.51899
220	-0.58734
221	-0.65823
222	-0.5481
223	-0.61772
224	-0.75443
225	-1
226	-0.98987
227	-0.69367
228	-0.57089
229	-0.43924
230	-0.31013
231	-0.18734
232	-0.36835
233	-0.49873
234	-0.57595
235	-0.64937
236	-0.51772
237	-0.66329
238	-0.52911
239	-0.60886
240	-0.47215
241	-0.40633
242	-0.28608
243	-0.40253
244	-0.40253
245	-0.40253
246	-0.40253
247	-0.40253
248	-0.33544
249	-0.21013
250	-0.20633
251	0.039241
252	-0.05443
253	-0.11646
254	-0.2443
255	-0.17468
256	-0.28987
257	-0.55063
258	-0.42152
259	-0.42278
260	-0.35949
261	-0.17595
262	-0.10506
263	-0.1038
264	-0.09873
265	-0.02658
266	-0.51899
267	-0.09114
268	-0.26709
269	-0.21772
270	-0.21392
271	-0.38354
272	-0.27848
273	-1
274	0.053165
275	-1
276	-0.34937
277	-0.67975
278	-1
279	-0.71266
280	-0.51519
281	-0.66076
282	-0.39367
283	-0.27342
284	0.002532
285	0.043038
286	0.118987
287	0.198734
288	0.165823
289	-0.32152
290	-0.32152
291	-0.08101
292	0.168354
293	-0.25696
294	-0.35823
295	-0.25696
296	-0.06456
297	-0.24937
298	-0.29114
299	-0.29114
300	-0.05949
301	0.003797
302	0.005063
303	0.13038
304	0.201266
305	0.2
306	0.229114
307	0.226582
308	0.196203
309	0.221519
310	0.381013
311	0.292405
312	0.355696
313	0.250633
314	0.21519
315	0.140506
316	0.117722
317	-0.08354
318	0.035443
319	0.132911
320	0.225316
321	0.394937
322	0.446835
323	0.149367
324	0.094937
325	0.040506
326	0.131646
327	0.120253
328	0.213924
329	0.096203
330	0
331	0
332	0
333	0
334	0

335	0	393	0.155696	451	-0.57089
336	0	394	0	452	-0.71646
337	0	395	0	453	-0.83671
338	0	396	0	454	-1
339	0	397	0	455	-1
340	0	398	0	456	-0.5519
341	0	399	0	457	-0.54557
342	0	400	0	458	-1
343	0	401	0	459	-0.71139
344	0	402	0	460	-0.36203
345	0	403	-0.20886	461	-0.62152
346	0	404	-0.26709	462	-0.27215
347	-0.08354	405	-0.42658	463	-0.36456
348	-0.26582	406	-0.58101	464	-0.37215
349	-0.41772	407	-0.68481	465	-0.11646
350	-0.50633	408	-0.80633	466	-0.19494
351	-0.61519	409	-1	467	-0.1962
352	-0.70633	410	-0.89114	468	-0.06835
353	-0.6962	411	-0.29494	469	-0.01772
354	-0.76962	412	-0.71013	470	-0.28228
355	-0.42278	413	-0.61392	471	-0.16456
356	-0.5443	414	-0.46709	472	0.013924
357	-0.52532	415	-0.16582	473	-0.11266
358	-0.59241	416	-0.07975	474	-0.11139
359	-0.78734	417	0.002532	475	-0.06329
360	-0.40633	418	0.018987	476	-0.15823
361	-0.42025	419	0.035443	477	-0.15823
362	-0.32785	420	0.093671	478	-0.15823
363	-0.4	421	0.443038	479	-0.15823
364	-0.44051	422	0.453165	480	-0.15823
365	-0.4962	423	0.383544	481	-0.06203
366	-0.19873	424	0.305063	482	-0.2038
367	-0.26962	425	0.224051	483	-0.20506
368	-0.10759	426	0	484	-0.27722
369	-0.01266	427	0	485	-0.01519
370	-0.22532	428	0	486	-0.06203
371	-0.47342	429	0	487	-0.1557
372	-0.37089	430	0	488	-0.1557
373	-0.16456	431	0	489	-0.06076
374	-0.16456	432	0	490	-0.05949
375	-0.16456	433	0	491	-0.10506
376	-0.16456	434	0	492	0.150633
377	-0.16456	435	0	493	0.255696
378	-0.19494	436	0	494	0.329114
379	-0.28734	437	0	495	0.346835
380	-0.19873	438	0	496	0.372152
381	-0.12025	439	0	497	0.4
382	0.012658	440	0	498	0.332911
383	0.13038	441	0	499	0.332911
384	0.151899	442	0	500	0.268354
385	0.056962	443	0	501	0.170886
386	0.382278	444	0	502	0
387	0.416456	445	0	503	0
388	0.503797	446	0	504	0
389	0.368354	447	0	505	0
390	0.340506	448	-0.26329	506	0
391	0.307595	449	-0.36203	507	0
392	0.265823	450	-0.45949	508	0

509	0	567	0	625	0
510	0	568	0	626	0
511	-0.1	569	-0.26329	627	0
512	-0.18861	570	-0.36203	628	0
513	-0.16709	571	-0.45949	629	0
514	-0.09114	572	-0.56456	630	0
515	-0.28608	573	-0.33291	631	0
516	-0.17848	574	-0.32658	632	0
517	-0.16582	575	-0.27595	633	0
518	-0.25823	576	-0.05443	634	0
519	-0.39747	577	-0.05443	635	0
520	-0.43671	578	-0.15823	636	0
521	-0.40886	579	-0.1038	637	0
522	-0.34937	580	-0.05443	638	0
523	-0.33797	581	-0.0038	639	0
524	-0.30127	582	0.026582	640	0
525	-0.33418	583	-0.02911	641	0
526	-0.36203	584	0.007595	642	0
527	-0.31519	585	-0.15696	643	0
528	-0.29494	586	-0.08101	644	0
529	-0.21772	587	-0.02911	645	0
530	-0.13291	588	0.016456	646	-0.16203
531	-0.0962	589	-0.02785	647	-0.20506
532	-0.0962	590	-0.0519	648	-0.42911
533	-0.0962	591	-0.07722	649	-0.3481
534	-0.0962	592	-0.15696	650	-0.41139
535	-0.0962	593	-0.18228	651	-0.30127
536	-0.29494	594	-0.26203	652	-0.29241
537	-0.15949	595	-0.22405	653	-0.50127
538	-0.16076	596	-0.31392	654	-0.54051
539	0.018987	597	-0.27468	655	-0.41392
540	0.018987	598	-0.09873	656	-0.39367
541	-0.02025	599	-0.1	657	-0.38734
542	-0.0962	600	-0.19367	658	-0.43924
543	-0.0962	601	-0.18861	659	-0.33797
544	0.04557	602	-0.19241	660	-0.19114
545	0.155696	603	-0.11519	661	-0.23038
546	0.412658	604	-0.08101	662	-0.14177
547	0.332911	605	-0.08101	663	-0.14304
548	0.268354	606	-0.13418	664	-0.1038
549	0	607	-0.37468	665	-0.16456
550	0	608	-0.51266	666	-0.1443
551	0	609	-0.38228	667	-0.10506
552	0	610	-0.27089	668	0.032911
553	0	611	-0.26203	669	0.032911
554	0	612	0.1	670	0.25443
555	0	613	0.443038	671	0.281013
556	0	614	0.406329	672	0.335443
557	0	615	0.327848	673	0.197468
558	0	616	0.244304	674	0.156962
559	0	617	0	675	0.192405
560	0	618	0	676	0
561	0	619	0	677	0
562	0	620	0	678	0
563	0	621	0	679	0
564	0	622	0	680	0
565	0	623	0	681	0
566	0	624	0	682	0

683	0	741	-0.42405	799	-0.14557
684	0	742	-0.29747	800	-0.23924
685	0	743	-0.26962	801	-0.28101
686	0	744	-0.20253	802	-0.63797
687	0	745	-0.24177	803	-0.48481
688	0	746	-0.21013	804	-0.49494
689	0	747	-0.11266	805	-0.51392
690	0	748	0.003797	806	-0.14557
691	0	749	-0.06962	807	-0.36203
692	0	750	-0.02911	808	-0.30127
693	0	751	0.035443	809	-0.26329
694	-0.11519	752	0.065823	810	-0.1038
695	-0.15696	753	0.16962	811	-0.0557
696	-0.09747	754	0.26962	812	-0.1481
697	-0.17468	755	0.253165	813	-0.10127
698	-0.35063	756	0.293671	814	-0.00886
699	-0.34177	757	0.246835	815	0.035443
700	-0.4	758	0.131646	816	-0.1
701	-0.2557	759	0.168354	817	0.035443
702	-0.40759	760	0	818	0.035443
703	-0.12785	761	0	819	-0.09241
704	-0.00253	762	0	820	-0.00127
705	-0.0519	763	0	821	-0.08987
706	-0.42152	764	-0.01266	822	0.117722
707	-0.29747	765	0	823	0.053165
708	-0.28734	766	0	824	-0.07975
709	-0.42405	767	-0.24051	825	-0.12152
710	-0.35316	768	-0.26709	826	-0.12152
711	-0.08101	769	-0.44557	827	-0.12152
712	0.021519	770	-0.6	828	0.002532
713	-0.2557	771	-0.60506	829	-0.07722
714	-0.26329	772	-0.4038	830	-0.11899
715	-0.14051	773	-0.26076	831	-0.03418
716	0.102532	774	-0.32658	832	0.018987
717	0.091139	775	-0.35696	833	0.068354
718	0.113924	776	-0.3962	834	0.035443
719	0.278481	777	-0.41392	835	0.067089
720	0.274684	778	-0.63291	836	0.201266
721	0.205063	779	-0.57595	837	0.240506
722	0	780	-0.42152	838	0.220253
723	0	781	-0.27468	839	0.165823
724	0	782	-0.20633	840	0.131646
725	0	783	-0.30759	841	-0.06076
726	0	784	-0.11519	842	-0.28734
727	0	785	-0.11519	843	-0.27342
728	-0.01139	786	-0.07342	844	-0.19873
729	-0.21772	787	0.003797	845	-0.22532
730	-0.26709	788	-0.03038	846	-0.25443
731	-0.41646	789	-0.11013	847	-0.26203
732	-0.51013	790	-0.11013	848	-0.31899
733	-0.30127	791	-0.06962	849	-0.39747
734	-0.43671	792	0.051899	850	-0.41519
735	-0.47342	793	-0.06709	851	-0.29114
736	-0.43165	794	-0.10506	852	-0.1
737	-0.5443	795	-0.10506	853	-0.15823
738	-0.52405	796	-0.10506	854	-0.15949
739	-0.5	797	-0.10506	855	-0.16203
740	-0.40633	798	-0.10506	856	-0.29241

857	-0.20506	915	0.120253	973	-0.47975
858	-0.34051	916	0.149367	974	-0.2962
859	-0.1557	917	0.044304	975	-0.20759
860	-0.15696	918	-0.07215	976	-0.1519
861	-0.15696	919	-0.09873	977	-0.11266
862	-0.07468	920	-0.32658	978	-0.11266
863	0.111392	921	-0.31013	979	0.092405
864	0.051899	922	-0.27342	980	-0.02785
865	0.035443	923	-0.14557	981	0.005063
866	0.15443	924	-0.14684	982	0.020253
867	0.082278	925	-0.2519	983	0.005063
868	0.032911	926	-0.15316	984	0.032911
869	-0.18354	927	-0.13418	985	0.005063
870	-0.18734	928	-0.13544	986	0.032911
871	-0.22532	929	-0.15696	987	0.14557
872	-0.15823	930	0.006329	988	0.265823
873	-0.26709	931	-0.02025	989	0.032911
874	-0.31392	932	-0.0962	990	-0.07089
875	-0.28861	933	-0.0962	991	-0.15823
876	-0.20127	934	0.006329	992	-0.26835
877	-0.3	935	-0.01899	993	-0.22911
878	-0.30886	936	-0.01899	994	-0.01392
879	-0.17848	937	-0.09114	995	-0.08228
880	-0.07468	938	-0.1481	996	-0.13671
881	-0.07468	939	-0.25316	997	0.007595
882	-0.07342	940	-0.0962	998	-0.08228
883	0.020253	941	0.018987	999	-0.08228
884	0.020253	942	-0.09367	1000	-0.31139
885	-0.06962	943	0.032911	1001	-0.24051
886	-0.10886	944	-0.21392	1002	-0.28101
887	0.020253	945	-0.28734	1003	-0.15063
888	0.020253	946	-0.25949	1004	-0.18734
889	0.050633	947	0.032911	1005	-0.22532
890	-0.22785	948	0.122785	1006	-0.13797
891	-0.26835	949	0.265823	1007	-0.06076
892	-0.20127	950	0.224051	1008	0.032911
893	-0.16835	951	0.33038	1009	0.093671
894	-0.02911	952	0.263291	1010	0.018987
895	-0.16835	953	0.183544	1011	0.031646
896	-0.10886	954	0	1012	0.007595
897	-0.10886	955	0	1013	0.018987
898	0.003797	956	0	1014	0.034177
899	0.005063	957	0	1015	0.020253
900	0.035443	958	0	1016	0.113924
901	0.005063	959	0	1017	0.33038
902	-0.06582	960	-0.16203	1018	0.287342
903	-0.10506	961	-0.24304	1019	0.207595
904	-0.10506	962	-0.51392	1020	0
905	-0.02532	963	-0.55316	1021	0
906	-0.06329	964	-0.65823	1022	0
907	-0.1038	965	-0.52152	1023	0
908	0.005063	966	-0.31139	1024	0
909	0.005063	967	-0.39241	1025	0
910	-0.09873	968	-0.33924	1026	0
911	-0.19494	969	-0.30633	1027	0
912	-0.06203	970	-0.36203	1028	0
913	0.006329	971	-0.52785	1029	0
914	0.096203	972	-0.66835	1030	0

1031	0	1089	-0.01519	1147	0.124051
1032	0	1090	-0.0557	1148	0.160759
1033	0	1091	-0.05696	1149	0.191139
1034	0	1092	0	1150	0
1035	0	1093	-0.01519	1151	0
1036	0	1094	0	1152	0
1037	0	1095	0	1153	0
1038	0	1096	0	1154	0
1039	0	1097	0	1155	0
1040	0	1098	0	1156	0
1041	0	1099	0	1157	0
1042	0	1100	0	1158	0
1043	0	1101	-0.01139	1159	0
1044	0	1102	-0.04557	1160	0
1045	0	1103	-0.08608	1161	0
1046	0	1104	-0.16582	1162	0
1047	0	1105	-0.37848	1163	0
1048	0	1106	-0.43291	1164	0
1049	0	1107	-0.50633	1165	0
1050	0	1108	-0.2481	1166	0
1051	0	1109	-0.13671	1167	0
1052	0	1110	-0.34684	1168	0
1053	-0.1	1111	-0.49747	1169	-0.16962
1054	-0.22658	1112	-0.5038	1170	-0.26709
1055	-0.40127	1113	-0.32785	1171	-0.4038
1056	-0.49241	1114	-0.13038	1172	-0.55823
1057	-0.60127	1115	-0.1	1173	-0.66329
1058	-0.69367	1116	-0.10127	1174	-0.78481
1059	-0.38354	1117	-0.15696	1175	-0.68481
1060	-0.41646	1118	-0.2962	1176	-0.60633
1061	-0.51899	1119	-0.22911	1177	-0.23418
1062	-0.41013	1120	-0.31519	1178	0.031646
1063	-0.37975	1121	-0.29494	1179	0.031646
1064	-0.33038	1122	-0.25316	1180	0.308861
1065	-0.34304	1123	-0.05823	1181	0.336709
1066	-0.39114	1124	-0.05696	1182	0.272152
1067	-0.19241	1125	-0.1519	1183	0.179747
1068	-0.28734	1126	-0.22405	1184	0
1069	-0.27342	1127	-0.22785	1185	0
1070	-0.24177	1128	-0.16076	1186	0
1071	0.003797	1129	-0.23418	1187	0
1072	0.035443	1130	-0.15696	1188	0
1073	0.035443	1131	-0.19367	1189	0
1074	-0.10253	1132	-0.14051	1190	0
1075	0.06962	1133	-0.10253	1191	0
1076	0.246835	1134	-0.10253	1192	0
1077	0.259494	1135	-0.06329	1193	0
1078	0.105063	1136	-0.06329	1194	0
1079	0.087342	1137	-0.10127	1195	0
1080	0.291139	1138	0.005063	1196	0
1081	0.274684	1139	-0.06456	1197	-0.02025
1082	0.187342	1140	0.018987	1198	-0.10886
1083	0.062025	1141	0.032911	1199	-0.16582
1084	0.016456	1142	0.096203	1200	-0.2443
1085	0	1143	0.120253	1201	-0.45443
1086	0	1144	0.253165	1202	-0.37975
1087	0	1145	0.162025	1203	-0.20506
1088	0	1146	0.272152	1204	-0.06456

1205	0.012658
1206	-0.08354
1207	-0.09873
1208	-0.03924
1209	-0.20633
1210	-0.33544
1211	-0.36835
1212	-0.40886
1213	-0.33038
1214	-0.38861
1215	-0.2
1216	-0.15823
1217	-0.06962
1218	0.007595
1219	0.007595
1220	-0.16203
1221	-0.15823
1222	-0.12911
1223	-0.04051
1224	-0.01013
1225	-0.01013
1226	-0.07089
1227	-0.04051
1228	0.136709
1229	0.041772
1230	0.008861
1231	-0.17342
1232	-0.11899
1233	-0.12025
1234	0.03038
1235	0.208861
1236	0.177215
1237	0.182278
1238	0
1239	0
1240	0
1241	0
1242	0
1243	0
1244	0
1245	0
1246	0
1247	0
1248	0
1249	0
1250	0
1251	0
1252	-0.08354
1253	-0.01266
1254	-0.01266
1255	-0.01266
1256	-0.01266
1257	-0.05696
1258	-0.11899
1259	-0.08987
1260	-0.08987
1261	-0.11392
1262	-0.23797
1263	-0.28861
1264	-0.10506
1265	0
1266	0
1267	0
1268	-0.16582
1269	-0.34684
1270	-0.5519
1271	-0.67215
1272	-0.63165
1273	-0.43924
1274	-0.27722
1275	-0.18987
1276	-0.3038
1277	-0.26709
1278	-0.24177
1279	-0.21392
1280	-0.09241
1281	0.032911
1282	0.031646
1283	-0.08734
1284	-0.08734
1285	-0.08734
1286	-0.08734
1287	-0.08734
1288	-0.24051
1289	-0.12658
1290	-0.21392
1291	-0.14937
1292	-0.18608
1293	-0.22405
1294	-0.15696
1295	-0.13797
1296	-0.19494
1297	-0.16203
1298	-0.3481
1299	-0.71266
1300	0.224051
1301	-0.68354
1302	-0.15696
1303	-0.07468
1304	0.129114
1305	0.478481
1306	0.444304
1307	0.378481
1308	0.3
1309	0.217722
1310	0
1311	0
1312	0
1313	0
1314	0
1315	0
1316	0
1317	0
1318	0
1319	0
1320	0
1321	0
1322	0
1323	0
1324	0
1325	0
1326	0
1327	0
1328	0
1329	0
1330	0
1331	0
1332	0
1333	0
1334	0
1335	0
1336	0
1337	0
1338	-0.12278
1339	-0.26582
1340	-0.44557
1341	-0.46709
1342	-0.41392
1343	-0.37595
1344	-0.23924
1345	-0.65316
1346	-0.17722
1347	-0.35316
1348	-0.27848
1349	-0.07089
1350	-0.51899
1351	0.031646
1352	0.021519
1353	0.020253
1354	0.031646
1355	0.043038
1356	0.031646
1357	0.018987
1358	0.103797
1359	0.087342
1360	0.078481
1361	0.073418
1362	0.108861
1363	0.188608
1364	0
1365	0
1366	0
1367	0
1368	0
1369	0
1370	0
1371	0
1372	0

Dynamic Stress Test (DST)

1.0 PURPOSE

For simulated driving cycle testing of USABC batteries, a variable power discharge cycle called the Dynamic Stress Test (DST) will be applied to the battery. The DST is scaled to a percentage of the maximum rated power or USABC power goal for a given technology and requires higher regeneration levels than previous similar test cycles such as the Simplified Federal Urban Driving Schedule (SFUDS). In general the DST maximum power is intended to be 80% of the USABC peak power goal for a technology; however, the specific value to be used by this procedure is specified (in watts or kilowatts) as an input to this procedure.

Figure 5B-1 shows a graphical representation of the DST 360 second test profile, which is applied repetitively over a complete battery discharge. Table 5B-1 is the tabular listing of the DST power profile.

Note: All references to the term 'battery' in this procedure refer to the unit to be tested, which may be a single cell, a multi-cell module, a battery pack, or a complete battery system.

2.0 PREREQUISITES

2.1 A Battery Test Plan or other test requirements document is required for testing using this procedure. The test plan specifies the values to be used for the DST. These values include battery A•h ratings, peak discharge power to be applied during DST testing, charge/discharge termination criteria, charging procedure, test temperature limitations, safety precautions, and any special handling/testing instructions specified by the manufacturer and/or the USABC.

2.2 Prior to the performance of this procedure, USABC Test Procedures No. 1A, Battery Pre Test Preparation, and No. 1B, Readiness Review, should normally have been completed. These activities are not a part of this procedure. This procedure may be executed as a stand-alone test activity or as part of a sequence of tests (e.g. a life-cycle test regime) provided that the information required by 2.1 above is available.

3.0 TEST EQUIPMENT

The equipment required to perform the DST consists of (a) a battery charge-discharge tester capable of achieving the scaled power-time profile shown in Figure 5B-1; and (b) a data system capable of acquiring the data specified in Section 6.0 at intervals of 1 second or less. The maximum permissible transition time between power steps in this profile is 1 second, and these transition times are included in the overall profile length (i.e. a DST profile is always 360 seconds long.)

4.0 DETERMINATION OF TEST CONDITIONS

4.1 Determine the **power levels** to be applied **for each step** of this DST profile. The maximum power level (as specified in the test plan or other test requirements document) is the 100% level shown in Figure 5B-1, which occurs in Step 15 in Table 5B-1. The power levels of the remaining steps are then calculated using the percentage values in Table 5B-1.

4.2 Determine (from the test plan) the **ampere-hour capacity** to be used for this DST procedure. In general the DST is performed to 100% of the battery's rated capacity. However, some lesser value such as 80% of this capacity may be established for life cycle testing. The battery capacity to be used for discharge is based on <u>net</u> capacity removed (total A•h less regeneration A•h).

4.3 Establish the **battery limits** to be observed during the test. These should be specified in the test plan and will normally consist of some set of voltage, current, power and/or temperature limits which should not be exceeded for the battery. The tester should be programmed such that these limits are not permitted to be exceeded during the test. In the test plan does not include a manufacturer-specified minimum discharge voltage, the Discharge Voltage Limit shall be set to 2/3 of the open circuit voltage at 80% DOD (at beginning of battery life.) Voltage during any DST discharge step shall not be allowed to fall below the Discharge Voltage Limit.

A DST discharge will terminate whenever the specified power cannot be achieved for a given step without exceeding one of the battery limits. (If specifically required by the test plan, this condition may be violated by permitting, for example, reduced regen power at the beginning of a discharge. However, this will affect the reporting requirements of Section 7.0.)

5.0 PROCEDURE STEPS

5.1 <u>Charging</u> - Fully charge the battery in accordance with instructions given in the test plan.

5.2 <u>Open Circuit After Charge</u> - With the battery on open circuit, stabilize the battery temperature or other initial conditions as specified in the test plan.

5.3 <u>Discharge</u> - Discharge the battery using the DST power profile. Repeat the 360 second DST segments end-to-end (i.e. with no rest period between profiles) until a termination condition is reached.

5.4 <u>Termination</u> - The discharge should terminate when either of the following conditions is reached: (a) the power achievable on any step (without violating any battery limiting conditions) is less than the specified value for that step; or (b) the specified net ampere-hour capacity of the battery is removed.

5.5 Recharge - Charge the battery in accordance with the test plan.

6.0 DATA ACQUISITION

6.1 Acquisition Rates

Overall battery voltage, current and power are required to be measured at intervals not exceeding 1 second during the entire DST discharge, and net ampacity (ampere-hours) and net energy (watt-hours) should be accumulated based on at least this frequency of data acquisition. Other measurements required by the test plan (e.g. battery temperatures, the voltages of modules or cells within a multi-cell/module battery etc.) must be measured at least twice per DST profile during the maximum discharge and maximum regen steps (Steps 15 and 19 in Table 5B-1), unless termination criteria are based on their values, in which case they must also be measured at 1 second intervals.

6.2 Data Retention

6.2.1 Performance Testing

For a DST conducted as a battery performance test, overall voltage, current, power, ampacity (ampere-hour) and energy (kilowatt-hour) values must be recorded and retained for at least 2 points per step in each DST profile for the entire discharge, once near the beginning and once near the end of each step. The value of all measured parameters must be recorded and retained at least once during the maximum discharge and maximum regen steps in each profile. (See Data Acquisition and Retention requirements section of the USABC procedures manual.)

6.2.2 Life Cycle Testing

If the DST is used as a repetitive life cycle test, the data required by 6.2.1 must be retained between successive execution of the Reference Performance Tests, until permission is received from the USABC Program Manager to discard it.

7.0 REPORTING

In addition to the summary information required from all USABC tests, the following specific information should be reported for any DST discharge conducted as a performance test or a Reference Performance Test during life cycling:

a. The peak power to which the test was scaled
b. Measured capacity of the battery
c. If any limitations were placed on the discharge by battery limits in the test plan (e.g. regen current limits), the capacity achieved both with and without such limits in

effect should be reported

d. The current, power and voltage during the complete profile nearest to 80% DOD should be graphed.

For DST discharges conducted as part of a life-cycle test series, the capacities in (b) and (c) above should be graphed as a function of cycle number over the course of the life test series. Periodic (i.e. monthly) progress reporting should include the capacities at the start of life testing, the number of cycles performed to date, and the present capacities.

TABLE 5B-1
DST POWER PROFILE TABULAR LISTING

Step No.	Duration (Seconds)	Discharge Power (%)	Step No.	Duration (Seconds)	Discharge Power (%)
1	16	0.0	11	12	-25.0
2	28	-12.5	12	8	+12.5
3	12	-25.0	13	16	0.0
4	8	+12.5	14	36	-12.5
5	16	0.0	15	8	-100.0
6	24	-12.5	16	24	-62.5
7	12	-25.0	17	8	+25.0
8	8	+12.5	18	32	-25.0
9	16	0.0	19	8	+50.0
10	24	-12.5	20	44	0.0

Note: Negative values represent discharge; positive values are regen.

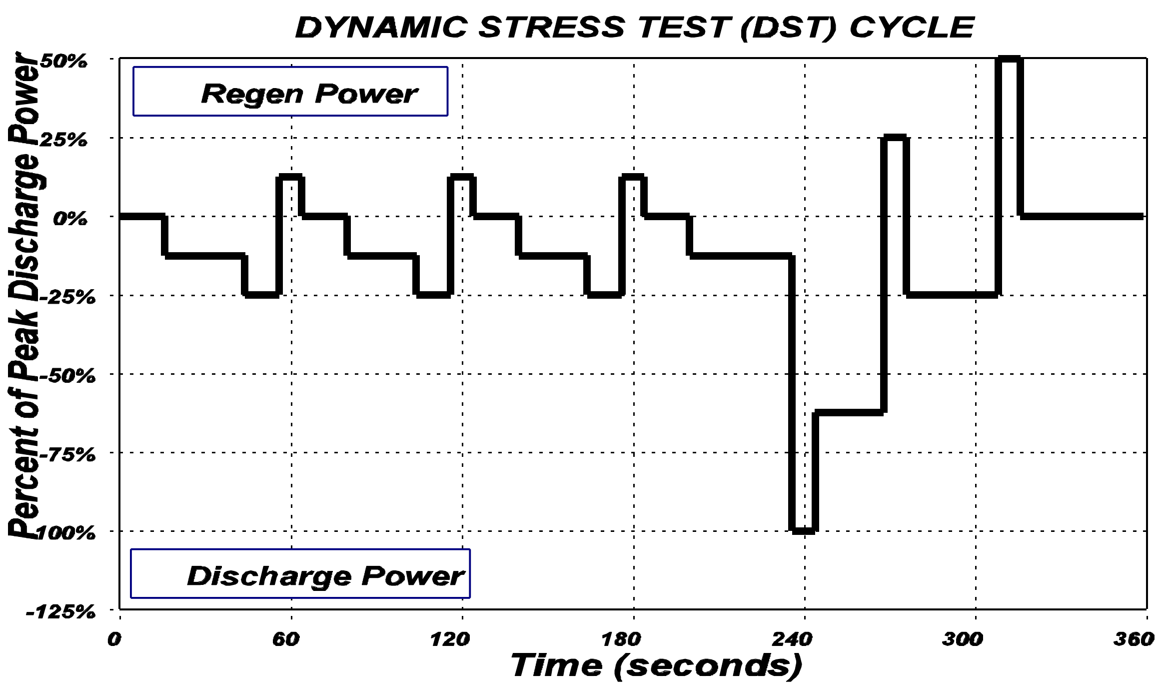

Figure 5B-1. DST Profile in Relative Power Units

Partial Discharge Test

1.0 PURPOSE

The purpose of this test is to measure the response of the battery to a series of partial discharges, identify any resulting capacity loss, and verify proper charging with partial depth-of-discharge (DOD) operation.

This test may be used either to determine the rate of capacity loss from a period of partial discharge operation or to verify that the loss is within acceptable USABC limits.

2.0 PREREQUISITES

2.1 A battery test plan or other test requirements document is required for testing using this procedure. The test plan specifies certain values to be used for this test. These values may include the number and type of partial discharges and the discharge termination conditions, along with safety precautions and any special handling/testing instructions specified for the battery by the manufacturer and/or the USABC.

2.2 Prior to the performance of this procedure, USABC Test Procedures No. 1A, Battery Pre Test Preparation, and No. 1B, Readiness Review, should normally have been completed. These activities are not a part of this procedure. This procedure may be executed as a stand-alone test activity or as part of a sequence of tests provided that the information required by 2.1 above is available.

3.0 TEST EQUIPMENT

The only equipment required for this procedure consists of a charge/discharge tester and data system capable of performing a constant-current (or other) discharge test as specified by the test plan.

4.0 DETERMINATION OF TEST CONDITIONS

4.1 Unless otherwise specified by the test plan, this test is performed at normal ambient temperature (~23°C $\pm$ 2°C).

4.2 Discharge termination conditions are generally the same as those for normal discharge tests. However, this test may be performed in two fundamentally different ways depending on the test plan objective.

4.2.1 The normal test method determines the **actual** capacity loss (if any) resulting from partial discharges. Using this method, the capacity must be measured to a predetermined condition (e.g. cutoff voltage) both before and after the partial discharge test series. In this case, the test plan should specify that testing is to be done to 100% of actual deliverable (not rated) capacity.

4.2.2 The alternate test method uses reference constant current discharges to 100% of the **rated** capacity of the battery, i.e. discharge terminates when the rated capacity has been removed even if no other discharge limiting condition has been reached. If this is done, no battery capacity loss will be observed unless the battery capacity drops below its rated value after the partial discharge tests. This method is used only to determine that an unacceptable capacity loss does not result from partial discharges.

4.3 This procedure is based on the use of C/3 constant current discharges for both the full and partial discharge portions of this test series. Use of another test profile such as the DST for the partial discharge cycles is permissible if specified in the test plan.

5.0 PROCEDURE STEPS

5.1 Fully charge the battery in accordance with manufacturer's recommendations or as specified in the test plan.

5.2 Discharge the battery fully using a C/3 constant current discharge as defined in USABC Procedure 2, using the specified termination conditions as defined in 4.2 above.

5.3 Fully charge the battery as in 5.1 above.

5.4 Repeat 5.1 through 5.3 twice (i.e. total of 3 full constant current discharge cycles.)

5.5 Perform a predetermined number of partial discharge cycles, normally 10 unless otherwise specified in the test plan.

5.5.1 Discharge the battery for a predetermined fraction of its capacity (normally 50%, or as specified in the test plan) using a C/3 constant current discharge.

5.5.2 Recharge the battery fully using the manufacturer's recommended procedure or as specified in the test plan. Battery current and voltage data acquired during recharge should be examined to determine that proper end-of-charge conditions are being achieved.

5.5.3 Allow a stand interval of approximately one hour after each discharge and charge cycle.

5.6 Repeat the reference discharge test sequence 5.2 through 5.4 above to determine whether a capacity loss has occurred.

5.7 If a capacity loss (i.e. capacity in 5.2 minus capacity in 5.6) greater than 1% is observed, discharge the battery for additional cycles as necessary to achieve a stable capacity.

6.0 DATA ACQUISITION

There are no specific data acquisition requirements beyond those for normal constant current discharge tests. However, data acquisition rates during recharge should be adequate to allow analysis of the charge procedure with partial discharge operation.

7.0 REPORTING

7.1 In addition to the normal data reported for constant-current discharge tests, the immediate measured loss of capacity shall be reported. Because of the variability inherent in repeated discharge tests of the same type, a capacity loss (averaged over 3 cycles) of less than 1% may be reported as "less than 1%" rather than attempting to attach any significance to very low values.

7.2 Any permanent or long-term loss in capacity (i.e. persisting beyond the three cycles in 5.6) should also be noted. In this event the full-discharge capacity vs cycle should be reported so that the capacity recovery can be evaluated.

7.3 End-of-charge and end-of-discharge voltages vs cycle should be reported graphically for the entire test series encompassed by this procedure.

7.4 Reported results should specify whether the test was performed based on rated or deliverable capacity.

Stand Test

1.0 PURPOSE

The purpose of this test is to measure battery capacity loss when the battery is not used for an extended period of time, analogous to the situation that occurs when a vehicle is not driven for such a period and the battery is not placed on charge. This loss, if it occurs, may be due to self-discharge, which is normally temporary, or to other mechanisms that could produce permanent or semi-permanent loss of capacity. If significant stand loss is measured, additional testing may be required to determine the cause of this behavior.

This test may be used either to determine the rate of capacity loss on stand or to verify that the loss is within acceptable USABC limits.

2.0 PREREQUISITES

2.1 A battery test plan or other test requirements document is required for testing using this procedure. The test plan specifies certain values to be used for this test. These values may include the length of the stand period and the discharge termination conditions, along with safety precautions and any special handling/testing instructions specified for the battery by the manufacturer and/or the USABC.

2.2 Prior to the performance of this procedure, USABC Test Procedures No. 1A, Battery Pre Test Preparation, and No. 1B, Readiness Review, should normally have been completed. These activities are not a part of this procedure. This procedure may be executed as a stand-alone test activity or as part of a sequence of tests provided that the information required by 2.1 above is available.

3.0 TEST EQUIPMENT

The only equipment required for this procedure consists of a charge/discharge tester and data system capable of performing a constant-current discharge test in accordance with USABC Procedure 2.

4.0 DETERMINATION OF TEST CONDITIONS

4.1 Unless otherwise specified by the test plan, this test is performed at normal ambient temperature (~23°C $\pm$ 2°C).

4.2 Discharge termination conditions are generally the same as those for normal constant current discharge tests. However, this test may be performed in two fundamentally different ways depending on the test plan objective.

4.2.1 The normal test method determines the **actual** capacity loss rate on stand. Using this method, the battery must be discharged to a predetermined condition (e.g. cutoff voltage) both before and after the stand time. In this case, the test plan should specify that testing is to be done to 100% of actual deliverable (not rated) capacity.

4.2.2 The alternate test method uses constant current discharges to 100% of the **rated** capacity of the battery, i.e. discharge terminates when the rated capacity has been removed even if no other discharge limiting condition has been reached. If this is done, no battery capacity loss will be observed unless the loss causes the battery capacity to drop below its rated value. This method is used only to determine that the stand loss does not result in unacceptable capacity loss during the stand period.

5.0 PROCEDURE STEPS

5.1 Fully charge the battery in accordance with manufacturer's recommendations or as specified in the test plan.

5.2 Discharge the battery using a C/3 constant current discharge as defined in USABC Procedure 2, using the specified termination conditions as defined in 4.2 above.

5.3 Fully charge the battery as in 5.1 above.

5.4 Allow the battery to stand at ambient temperature (or as specified in the test plan) for a period of 48 hours for midterm battery technologies or 30 days for long term technologies, or as specified in the test plan. Any external sources of parasitic energy losses during the stand period must be eliminated to the extent possible, including disconnection of measurement circuitry if leakage energy could be significant compared to the losses expected. If battery control systems or other external hardware must be powered during the stand period, this power should be provided from sources external to the battery; the energy consumed by such hardware over the stand period should be measured and reported separately.

5.5 At the end of the stand period, immediately discharge the battery using a C/3 constant current discharge under the same conditions as 5.2 above.

5.6 Recharge the battery as in 5.1 above.

5.7 If a capacity loss (i.e. capacity in 5.2 minus capacity in 5.5) greater than 2% is observed, discharge the battery for two additional cycles or as necessary to achieve a stable capacity.

6.0 DATA ACQUISITION

Data acquisition requirements are the same as those for normal constant current discharge tests, except that monitoring of parasitic energy losses during the stand period may be required for external hardware such as battery controllers or thermal management systems.

7.0 REPORTING

7.1 In addition to the normal data reported for constant-current discharge tests, the immediate measured loss of capacity shall be reported. Because of the variability inherent in repeated discharge tests of the same type, a capacity loss of less than 2% may be reported as "less than 2%" rather than attempting to attach any significance to very low values.

7.2 Any permanent or long-term loss in capacity (i.e. persisting beyond three cycles after the stand period) should also be noted. In this event the full-discharge capacity vs cycle should be reported so that the capacity recovery can be evaluated.

7.3 Parasitic energy losses (if any) measured during the stand period should be reported.

7.4 Reported results should specify whether the test was performed based on rated or deliverable capacity.

Thermal Performance Test

1.0 PURPOSE

The purpose of this test procedure is to characterize the effects of ambient temperature variation on battery performance. It can also be used to determine the need for thermal management or the allowable operating temperature range for a battery that may later incorporate thermal management.

This procedure is appropriate for determining ambient temperature effects on batteries without thermal management systems. Additional information may be required for systems-level testing.

2.0 PREREQUISITES

2.1 A battery test plan or other test requirements document is required for testing using this procedure. The test plan specifies certain values to be used for this test. These values may include the specific charge and discharge tests/procedures to be used, the temperature(s) at which charging and discharging are to be performed, and any limiting test conditions for the battery, along with safety precautions and any special handling/testing instructions specified by the manufacturer and/or the USABC.

2.2 Prior to the performance of this procedure, USABC Test Procedures No. 1A, Battery Pre Test Preparation, and No. 1B, Readiness Review, should normally have been completed. These activities are not a part of this procedure. This procedure may be executed as a stand-alone test activity or as part of a sequence of tests provided that the information required by 2.1 above is available.

3.0 TEST EQUIPMENT

Equipment required for the performance of this testing includes the following:

3.1 A battery charge-discharge tester capable of performing the specified discharge tests
3.2 An appropriate battery charger (which may be the tester itself)
3.3 An environmental chamber capable of heating and/or cooling the battery to the temperatures specified in the test plan
3.4 A data acquisition system capable of acquiring the data required for the specific discharge tests at the appropriate rate. (See the corresponding USABC procedure for these discharge tests for more information.)

4.0 DETERMINATION OF TEST CONDITIONS

4.1 References

4.1.1 USABC Test Procedure 2, Constant Current Tests
4.1.2 USABC Test Procedure 3, Peak Power Test
4.1.3 USABC Test Procedure 5B, Dynamic Stress Test

4.2 Discharge Conditions

This procedure is written to characterize battery performance based on the DST and the Peak Power Test; however, other discharge cycles may be used in addition to or in place of these two. In such cases the test plan must specify the discharge regime(s) to be used. The USABC procedure for the specific type(s) of discharge to be performed (e.g. FUDS, DST, constant current, constant power etc.) is used to determine the discharge conditions and limits (other than temperature) to be observed during this testing. Unless otherwise specified, the same termination conditions will be used at all temperatures.

4.3 Charge Conditions

The manufacturer's recommended charge method is to be used in conjunction with this procedure whenever possible. If the test plan requires charging to be done at high or low temperatures, rather than ambient temperature as specified in this procedure, the manufacturer should be consulted regarding modifications to the normal charge algorithm.

4.2 Temperature Conditions

The values specified in this procedure are selected based on the USABC performance requirements. If other values are to be used based on the development status of a technology, they must be specified directly in the test plan, including the temperatures to be used for charging and discharging, and the sequence of charge/discharge cycles to be performed at each temperature.

If the battery to be tested includes control or thermal management hardware, the test plan should specify whether this equipment is to be subjected to the same temperature regime as the battery itself.

5.0 PROCEDURE STEPS

5.1 At the nominal ambient temperature of ~23°C, perform a sequence of Reference Performance Test discharges to a predetermined termination condition, using a C/3 constant current discharge (Reference 4.1.1), 100% DOD DST discharge (Reference 4.1.2) and peak power test (Reference 4.1.3) in that order.

5.2 Repeat 5.1 at the lowest specified temperature (normally -30°C.) Each discharge should be performed at the specified temperature, and the battery should then be returned to ambient temperature to be recharged (unless otherwise specified in the test plan.)

5.3 Repeat 5.1 at 0°C.

5.4 Repeat 5.1 at the highest specified temperature (normally 65°C.)

5.5 Repeat 5.1 at ambient temperature to determine whether off-normal temperature testing resulted in any change in battery performance at normal ambient temperature.

5.6 If a change of more than 5% in battery capacity or peak power capability is observed in between the results of 5.1 and 5.5, the Reference Performance Tests should be repeated two additional times (3 total) at ambient temperature or as necessary to re-establish a stable capacity.

6.0 DATA ACQUISITION

In general the data acquisition requirements for this testing are the same as those for the same discharge tests conducted at ambient temperature.

6.1 Battery temperature sensors should be insulated from ambient air so that they will indicate the temperature of the battery component on which they are mounted.

6.2 Additional temperature measurements (beyond those used for ambient temperature testing) may be specified in the test plan, especially if a thermal management system is used.

6.3 If an active thermal managment system is used, its power consumption must be monitored under charge, discharge and stand conditions at all test temperatures.

7.0 REPORTING

7.1 The normal data for the type of discharge(s) performed shall be provided.

7.2 Battery temperature shall be reported graphically as a function of time during discharge (and charge, if charging is done at other than normal ambient temperature) for each set of temperature conditions.

7.3 Any thermal management power consumption data acquired under 6.3 shall be reported as a function of temperature.

7.4 Any changes from the temperatures or discharge tests specified in this procedure should be specifically noted.

Battery Vibration Test

1.0 PURPOSE

This test is intended to characterize the effect of long-term, road-induced vibration and shock on the performance and service life of candidate batteries. Depending on the maturity of the battery, the intent of the procedure is either (a) to qualify the vibration durability of the battery or (b) to identify design deficiencies that must be corrected. Either swept sine wave vibration or random vibration can be used for the performance of this procedure, and separate sections are included for these alternatives.

For testing efficiency, a time-compressed vibration regime is specified to allow completion of the test in just over 24 hours of exposure per test article for swept sine wave excitation. For random excitation, the test regime requires a minimum of 13.6 hours and a maximum of 92.6 hours of testing, depending on the type of shaker table available and the choice of acceleration levels. The procedure has been synthesized from rough-road measurements at locations appropriate for mounting of traction batteries in EVs. The data were analyzed to determine an appropriate cumulative number of occurrences of shock pulses at any given G-level over the life of the vehicle. The envelopes shown in Figure 10-1 of the USABC Manual summary of this procedure (page 25, not repeated here) correspond to approximately 100,000 miles of usage at the 90th percentile. The vibration spectra contained in this procedure have been designed to approximate this cumulative exposure envelope.

This procedure describes the performance testing of a single test unit (battery, module or cell). For statistical purposes, multiple samples would normally be subjected to this testing. Additionally, some test units may be subjected to life cycle testing (either after or during vibration testing) to determine the effects of vibration on battery life. Such life testing is not described in this procedure.

2.0 PREREQUISITES

2.1 A battery test plan or other test requirements document is required for testing using this procedure. The test plan specifies the appropriate test conditions for the Reference Performance Tests and certain vibration frequencies to be used, along with safety precautions and any special handling/testing instructions specified for the battery by the manufacturer and/or the USABC.

2.2 Prior to the performance of this procedure, USABC Test Procedures No. 1A, Battery Pre Test Preparation, and No. 1B, Readiness Review, should normally have been completed. These activities are not a part of this procedure. This procedure may be executed as a stand-alone test activity or as part of a sequence of tests provided that the information required by 2.1 above is available.

2.3 Performance of the Reference Performance Tests specified in USABC Procedure 14C is required before and after the conduct of vibration testing. For completeness these are itemized within the procedure steps in Sections 5 and 6.

2.4 Unless otherwise specified, the test unit shall be tested early in its life (i.e. prior to the performance of any life cycle testing.)

3.0 TEST EQUIPMENT

3.1 A. Performance of the swept sine wave version of this procedure requires a single-axis shaker table capable of producing a peak acceleration of 5G within the range of 10 to 30 Hz, as well as G-loadings at the values and within the frequency ranges shown in Tables 1 and 2 following. (Note: if the unit to be tested can only be vibrated while in a particular physical orientation due to leakage or other constraints, a multi-axis table will be required.)

B. Performance of the random vibration version of the procedure requires a one- to three-axis table capable of producing accelerations up to 1.9G over the vibration spectra detailed in Figure 2, extending from 10 to approximately 200 Hz. If the unit to be tested can only be vibrated while in a particular physical orientation, a multi-axis table will be required. Additionally, the time required to perform the test can be significantly reduced if the longitudinal and lateral axis vibration (or all three axes) can be performed concurrently.

3.2 Test fixtures are required to properly secure the test unit to the shaker table. The exact nature of these fixtures depends on the type of table used, the test unit itself, and any restrictions on physical orientation of the test unit.

3.3 Special instrumentation hookups capable of withstanding the vibration are required so that important battery conditions can be monitored during testing. (See Section 7.)

4.0 DETERMINATION OF TEST CONDITIONS AND TEST TERMINATION

4.1 Electrical test conditions are determined according to Procedure 14C, Reference Performance Tests.

4.2 The states-of-charge to be used for each vibration test regimes in Section 5 should be reviewed and adjusted for each specific battery technology (if necessary) to assure that a worst-case state-of-charge is used for each vibration regime.

4.3 The specific vibration frequencies for maximum vibration steps 5.3.2 and 5.5.2 should be specified in the test plan. If these are not specified, the vertical and longitudinal testing of 5.3.2 and 5.5.2 will be done at 15 and 12 Hz respectively. Other vibration test conditions are specified in the procedure steps in Sections 5 and 6.

4.4 Vibration testing shall be suspended or terminated if any observed component degradation threatens safe operation of the battery as specified by the manufacturer. Conditions to be monitored are defined in Section 7.

5.0 PROCEDURE STEPS FOR SWEPT SINE WAVE VIBRATION TESTING

5.1 Perform USABC Reference Performance Tests using Procedure 14C. This sequence includes a C/3 Constant Current discharge, a DST discharge to 100% of rated capacity, and a Peak Power discharge.

5.2 Charge the battery fully using the manufacturer's recommended charge method.

5.3 Vertical Axis Vibration (First Half at Full Charge)

5.3.1 Mount the test unit so that it will be subjected to vibration in the vertical axis, based on the manufacturer's recommended physical orientation.

5.3.2 Subject the test unit to 2000 sinusoidal cycles at 5 G peak acceleration, applied at a frequency to be specified in the test plan within the range from 10 Hz to 30 Hz.

5.3.3 Subject the test unit to 60 sine sweeps from 10 Hz up to 190 Hz and back to 10 Hz, to be conducted at a sweep rate of 1 Hz/s for a total testing duration of 6 hours. The following profile of G-levels shall be used:

Table 1. Frequency and G-Values for Vertical Axis

Frequency Range (Hz)	Peak Acceleration (G)
10-20	3.0
20-40	2.0
40-90	1.5
90-140	1.0
140-190	0.75

5.4 Discharge the battery to approximately a 40% depth-of-discharge at the C/3 rate.

5.5 Longitudinal Axis Vibration (at 40% DOD)

5.5.1 Mount the battery so that it will be subjected to vibration in the longitudinal axis, based on the manufacturer's recommended physical orientation.

5.5.2 Subject the test unit to 4000 sinusoidal cycles at 3.5 G peak acceleration, applied at a frequency to be specified in the test plan within the range from 10 Hz to 30 Hz.

5.5.3 Subject the test unit to 60 sine sweeps from 10 Hz up to 190 Hz and back to 10 Hz, to be conducted at a sweep rate of 1 Hz/s for a total test duration of 6 hours. The following profile of G-levels shall be used:

Table 2. Frequency and G-Values for Longitudinal Axis

Frequency Range (Hz)	Peak Acceleration (G)
10-15	2.5
15-30	1.75
30-60	1.25
60-110	1.0
110-190	0.75

5.6 Lateral Axis Vibration (at 40% DOD)

5.6.1 Mount the battery so that it will be subjected to vibration in the lateral axis (assumed to be orthogonal to the longitudinal axis), based on the manufacturer's recommended physical orientation.

5.6.2 Repeat 5.5.2 and 5.5.3 with the test unit mounted in this configuration.

5.7 Discharge the battery to approximately an 80% depth-of-discharge at the C/3 rate.

5.8 Vertical Axis Vibration (Second Half at 80% DOD)

5.8.1 Repeat 5.3.1 through 5.3.3 with the test unit at this reduced state of charge.

5.9 Repeat the USABC Reference Performance Tests using Procedure 14C. This sequence includes a C/3 Constant Current discharge, a DST discharge to 100% of rated capacity, and a Peak Power discharge.

6.0 PROCEDURE STEPS FOR RANDOM VIBRATION TESTING

6.1 Perform USABC Reference Performance Tests using Procedure 14C. This sequence includes a C/3 Constant Current discharge, a DST discharge to 100% of rated capacity, and a Peak Power discharge.

6.2 Charge the battery fully using the manufacturer's recommended charge method.

6.3 For each of the vertical, longitudinal and lateral axes of the battery, select either the normal or alternative G-levels from Table 3 and program the shaker table appropriately. This choice will determine the vibration time required for each axis, also in accordance with Table 3. (The vibration spectra, shown in Figure 1 following, are expressed in G^2/Hz, so they can be scaled for either set of G-levels.)

Table 3. Vibration Schedule for Random Vibration Test

TEST CONDITIONS		NORMAL TEST			ALTERNATIVE TEST		
VIBRATION SPECTRUM	SOC (%)	Accel (g rms)	Time (h)	Cumul Time, h	Accel (g rms)	Time (h)	Cumul Time, h
Vertical Axis Vibration:							
Vertical 1 spectrum	100	1.9	0.15	0.15	1.9	0.15	0.15
Vertical 1 spectrum	100	0.75	5.25	5.4	0.95	3.5	3.65
Vertical 2 spectrum	100	1.9	0.15	5.55	1.9	0.15	3.8
Vertical 2 spectrum	100	0.75	5.25	10.8	0.95	3.5	7.3
Vertical 3 spectrum	20	1.9	0.15	10.95	1.9	0.15	7.45
Vertical 3 spectrum	20	0.75	5.25	16.2	0.95	3.5	10.95
Longitudinal Axis Vibration:							
Longitudinal spectrum	60	1.5	0.09	16.29	1.5	0.09	11.04
Longitudinal spectrum	60	0.4	19.0	35.29	0.75	6.7	17.74
Longitudinal spectrum	60	1.5	0.09	35.38	1.5	0.09	17.83
Longitudinal spectrum	60	0.4	19.0	54.38	0.75	6.7	24.53
Lateral Axis Vibration:							
Longitudinal spectrum	60	1.5	0.09	54.47[1]	1.5	0.09	24.62[1]
Longitudinal spectrum	60	0.4	19.0	73.47[1]	0.75	6.7	31.32[1]
Longitudinal spectrum	60	1.5	0.09	73.56[1]	1.5	0.09	31.41[1]
Longitudinal spectrum	60	0.4	19.0	92.56[1]	0.75	6.7	38.11[1]

Note 1: These cumulative times apply only if all three axes are done separately.

6.4 Mount the test unit so that it will be subjected to vibration along the appropriate axes, based on the manufacturer's recommended physical orientation. This procedure permits the required vibration to be performed in one, two or all three axial directions simultaneously depending on the capabilities of the shaker table used (but see 6.4 for other considerations.)

6.5 Perform the programmed vibration for the required times, while battery depth-of-discharge is varied from 0% (full charge) to 80% (minimal charge) over the course of the vibration testing of a given battery. Two approaches are permitted to accomplish this:

(a) if a one- or two-axis vibration table is used, approximately half of the vertical axis testing should be done at full charge, followed by the longitudinal and lateral vibration at 40% DOD, and then the remaining vertical axis vibration at 80% DOD.

(b) If a three-axis table is used to perform all vibration regimes simultaneously, the total testing period can be divided into three intervals of roughly equal length. The first interval should be performed with the battery fully charged, the second interval with the battery at 40% DOD, and the third interval at 80% DOD.

6.6 Between each pair of the three intervals of vibration specified in 6.5, the battery should be discharged at a C/3 constant current rate for 40% of the rated capacity of the battery. Following the third vibration interval, the battery should be fully recharged.

6.7 Repeat the USABC Reference Performance Tests using Procedure 14C. This sequence includes a C/3 Constant Current discharge, a DST discharge to 100% of rated capacity, and a Peak Power discharge.

7.0 SAFETY CONSIDERATIONS FOR TESTING

During the application of the vibration regimes, the test unit shall be instrumented to determine the presence of any of the following conditions:

7.1 Loss of electrical isolation between the battery positive connection and the battery case and/or test equipment ground. The degree of isolation shall be verified regularly, e.g. daily, during any period of vibration testing to be within the USABC trial criterion of 0.5 MS or greater isolation (1.0 mA or less leakage at 500V DC).

7.2 Abnormal battery voltages indicating the presence of open- or short-circuit conditions.

7.3 Unexpected resonance conditions within the battery, indicating failure of mechanical tie-down components.

7.4 Abnormal temperature conditions indicating possible damage to battery cells or thermal management system components.

Detection of any of the conditions listed in 7.1 through 7.4 shall cause testing to be suspended until the condition has been evaluated and a determination has been made that either it is safe to proceed or the testing should be terminated.

8.0 DATA ACQUISITION AND REPORTING

8.1 Data to be acquired during the Reference Performance Tests of Sections 5 or 6 shall be as required for the normal conduct of those tests. Data from these measurements (other than summary results) need not be retained if no anomalous behavior is observed during testing.

8.2 The general reporting requirements for USABC testing are given in Section 4 of Appendix B, Reporting and Data

Acquisition Outline, of this manual.

8.3 A report shall be prepared detailing the actual vibration regimes applied, a compilation and interpretation of all data acquired, any results of detailed component failure analyses, and any recommendations for improvements in battery design, installation procedures, or test methods. Also, the pre- and post-vibration electrical performance data that confirms the adequacy of the battery design to withstand the vibration environments shall be summarized as required by 8.1.

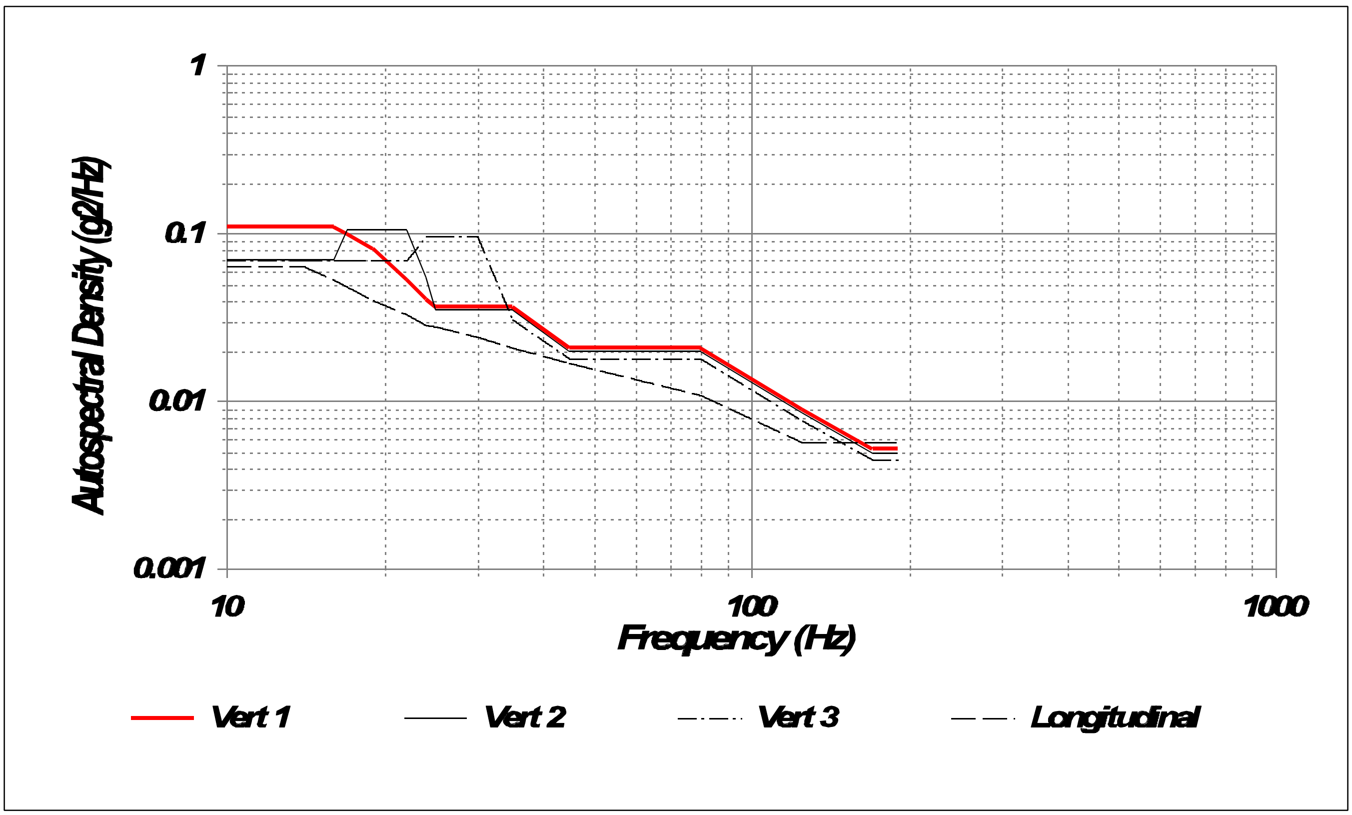

Figure 1. Vibration Spectra for Random Vibration Test