INTERIM PROCEDURE FOR TYPE APPROVAL OF 406 MHz BEACONS EQUIPPED WITH LI-ION RECHARGEABLE BATTERIES
C/S IP (LIRB) - Revision 3
October 2013

The following procedure shall be used by the Cospas-Sarsat Secretariat for the review of type approval applications for 406 MHz beacons equipped with Li-ion rechargeable batteries. Because of the limited experience available and the limitations which may affect beacons equipped with rechargeable batteries, 406 MHz beacons equipped with Li-ion rechargeable batteries successfully tested in accordance with this Interim Procedure will receive a Letter of Compatibility in lieu of a full Cospas-Sarsat Type Approval Certificate. All C/S T.007 requirements are applicable for type approval testing of beacons equipped with Li-ion rechargeable batteries, except when otherwise stated in this document.

This procedure only applies to rechargeable batteries where lithium ions move from the anode (negative electrode) to the cathode (positive electrode) during discharge and the reverse direction when undergoing charge and where the anode is made from insertion material (hard carbon, graphite, etc.), the cathode is a metal oxide, and the electrolyte is a lithium salt in an organic solvent.

1. DEFINITIONS APPLICABLE TO LITHIUM-ION RECHARGEABLE BATTERIES

1.1 Beacon Modes

1.1.1 Beacon Storage Mode: No circuits are powered by the primary battery[1].

1.1.2 Beacon Stand-By Mode: The beacon 406 MHz transmitter and other ancillary devices are not activated; automatic internal checks are performed from time to time by the beacon resulting in a current drain from the primary battery.

1.1.3 Beacon Self-Test Mode: Some beacon circuits are powered during the self-test of the beacon, which results in specific power drain from the primary battery.

1.1.4 Beacon Active Mode: The 406 MHz transmitter is active and/or other ancillary devices powered by the primary battery are active.

1.2 Time Between Recommended Charges (TBRC)

The Time Between Recommended Charges (TBRC) at ambient temperature, for this procedure, is the time recommended by the beacon manufacturer between battery recharges when the beacon is in stand-by mode. The TBRC determined by the manufacturer must take into account the power drain which would result from recommended periodic self-tests during TBRC. The TBRC must be clearly indicated on the beacon.

TBRC is temperature dependent; the beacon manufacturer shall inform the user that prolonged storage at high temperature will require recharging the beacon more often than stated.

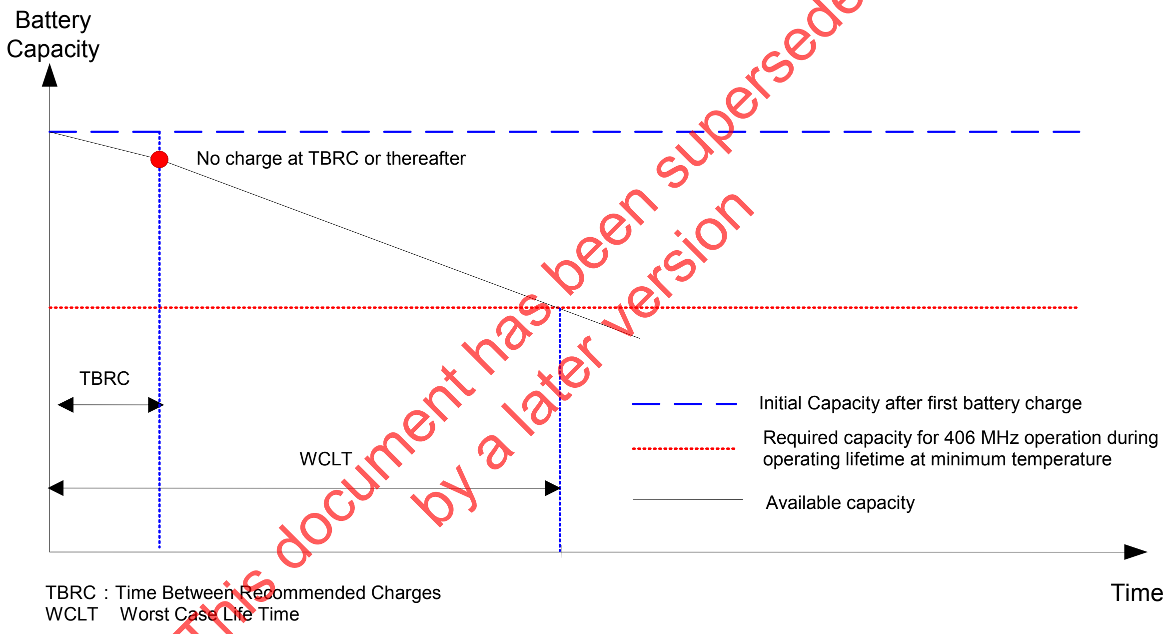
[1] The primary battery is the non-rechargeable or rechargeable battery which is powering the 406 MHz function

1.3 Worst Case Life Time (WCLT)

In a worst case configuration, the user might not recharge[2] the battery after the initial full charge. In this configuration, the “Worst Case Life Time” (WCLT) is the time in beacon stand-by mode when the available capacity remains greater or equal to the capacity required to meet the declared operating life time at minimum temperature.

The Worst Case Life-Time is determined by the beacon manufacturer. The WCLT definition assumes no irreversible losses due to beacon storage prior to the first battery charge that initiates the beacon stand-by mode. The definition also assumes that no self-tests are performed during WCLT. If self-tests are recommended by the manufacturer during TBRC, separate from the recharge process, the corresponding current drain would also have to be considered for the determination of WCLT.

Figure 1: Illustration of Battery Capacity and Worst Case Life Time



1.4 Battery Replacement Life Time

The Battery Replacement Life Time is determined by the beacon manufacturer from the sum of the following losses and current drains:

a) irreversible capacity loss over the replacement life time and maximum storage time (including the 1.65 safety factor),

b) reversible capacity loss during TBRC (including the 1.65 safety factor),

c) average current drain resulting from constant operation of the beacon circuits in stand-by mode,

d) current drain from any device powered by the beacon battery prior to beacon activation, during TBRC (including the 1.65 safety factor), and

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2 It is assumed that the initial charge of the battery has been done by the user in accordance with the user manual procedure.

e) current drain due to maximum number of self-tests carried out during TBRC as recommended by the beacon manufacturer.

The battery replacement life time assumes a maximum two year storage time (battery storage and beacon storage mode) prior to the first charge of the new battery by the end-user.

1.5 Maximum Storage Time

The maximum storage time includes the battery storage time prior to its installation in the beacon and the beacon storage time before the first full charge of the battery assumed to be performed by the end-user after purchasing the beacon.

A maximum storage time of two year shall be used for the determination of the battery replacement date.

1.6 Battery Replacement Date

The battery replacement date is the date at which the rechargeable battery installed in the beacon must be replaced. The battery replacement date shall be clearly indicated on the beacon together with the TBRC. The replacement date is determined by the beacon manufacturer using:

- the date the batch of new batteries was manufactured,
- up to two year's storage time at the manufacturer's recommended state of charge and prior to the first full charge by the user, and
- the specific battery replacement life time determined by the manufacturer for the beacon model.

The battery replacement date is given by the expression:

Replacement Date = Date of Manufacture + Two Year Storage + Battery Replacement Life Time

On the battery replacement date, the beacon shall meet the declared operating life time at minimum temperature.

2. PROCEDURES FOR TESTING BEACONS WITH LITHIUM-ION RECHARGEABLE BATTERIES

2.1 General Requirements

All C/S T.007 requirements are applicable for type approval testing of beacons equipped with Li-ion rechargeable batteries, except when otherwise stated in the this document.

2.2 Test Conditions

In addition to provisions of section 4.4 of document C/S T.007, and at the discretion of the test authority, the manufacturer may be required to replace or recharge the LIRBs between tests. However, no other modifications to the beacon will be allowed during the test period without a full re-test.

2.3 Technical Data (section 5 of C/S T.007)

In addition to the technical data submitted to the Cospas-Sarsat Secretariat, the manufacturer shall submit supplementary technical information related to the LIRB, in accordance with Attachment A of this document.

2.4 Changes to Type Approved Beacons

The manufacturer must advise the Cospas-Sarsat Secretariat (see C/S T.007 Annex H) of any changes to the design or production of the beacon, ~~or~~ power source or charger for beacons using Li-ion rechargeable batteries, which might affect beacon electrical performance.

2.5 Operating Lifetime at Minimum Temperature

In addition to the requirements described in section A.2.5 of document C/S T.007, for calculation of the pre-test battery discharge for beacons equipped with LIRBs, the following factors shall be accounted for:

i. the reversible and irreversible losses[3] of battery capacity;

ii. the average current drain resulting from constant operation of the circuits powered from the beacon battery prior to beacon activation, over the Time Between Recommended Charges (TBRC) ;

iii. the number of self-tests, as recommended by the beacon manufacturer and, when the function is included, the maximum number and maximum duration of GNSS self-test transmissions, over the rated life of the battery pack (the beacon manufacturer shall substantiate the method(s) used to determine the corresponding current drain(s);

iv. the worst case depletion in battery power due to current draw that cannot be replicated during the lifetime test, for example, to account for a difference between the actual output power setting of the test unit homer transmitter and the maximum output power of the homer transmitter, as declared by the beacon manufacturer in Annex G;

v. a correction coefficient of 1.65 applied to item (ii) and item (iii) to account for differences between battery to battery, beacon to beacon and the possibility of exceeding the battery replacement time; and

vi. a correction coefficient of 1.65 applied to item (i) to account for differences between battery to battery and the possibility of not recharging the battery at the required time.

2.6 Self-Test Mode

For beacons using LIRBs, the battery status should be tested during the self-test. If the battery is not in “normal battery mode” as defined in section 3.1, the self-test result should indicate ”Failure”.

[3] The terms are defined in section 3.1.

Design data shall be provided on protection against repetitive self-test mode transmissions.

3. Procedures for Evaluation of Li-ion Rechargeable Batteries Performance

3.1 Definitions

3.1.1 Normal Battery Mode

The beacon manufacturer shall state the Time Between Recommended Charges (TBRC). The beacon shall automatically check the battery condition at defined intervals ($T_{wake\text{-}up}$), which shall not be longer than one fourth of TBRC. At the end of each $T_{wake\text{-}up}$ interval, the beacon shall check the time since the last charge and the battery condition.

- If the time since the last charge is less than TBRC and if the battery condition is good, the battery is considered to be in "Normal Battery Mode" and the beacon may go back to standby mode until the end of the next $T_{wake\text{-}up}$ interval.
- If the above conditions are not fulfilled, the user shall be warned that the battery must be recharged (see section 3.2).

3.1.2 Irreversible Capacity Loss

The irreversible capacity loss is the loss of the battery capacity which cannot be recovered by subsequent recharges of the battery. There are two components to the total irreversible capacity loss:

(i) during battery and beacon storage, and
(ii) during the battery replacement life time while the beacon is in standby mode.

3.1.3 Reversible Capacity Loss

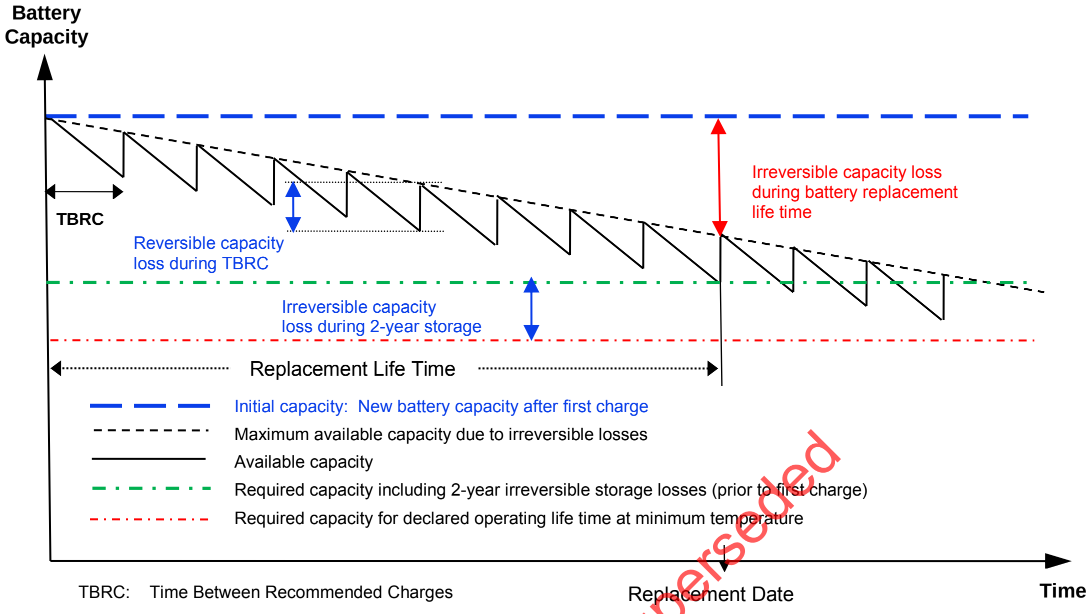
The reversible capacity loss is the loss of the battery capacity which can be recovered by subsequent recharges of the battery. This reversible capacity loss is also known as "self discharge".

3.1.4 Determination of the Battery Replacement Life Time

Figure 2 illustrates the determination of the battery replacement life time. The diagram of available battery capacity assumes that, initially, the new battery installed in the beacon is fully charged and is not affected by any irreversible storage loss. To take irreversible storage losses into consideration, the battery capacity required to meet the specified performance during the declared operating life time at minimum temperature is augmented by the irreversible storage loss assuming a maximum two year storage time (battery storage and beacon storage mode).

The operating life time at minimum temperature performance of the beacon on the battery replacement date shall be verified using the procedure described in section A.2.3 of the document C/S T.007.

Figure 2: Determination of Battery Replacement Life *Time*



3.1.5 Worst Case Life Time (WCLT)

In a worst case configuration, the user might forget to recharge the beacon battery, the "Worst Case Life Time" (WCLT) is the time in beacon stand-by mode when the available capacity remains greater or equal to the capacity required to meet the declared operating life time at minimum temperature. The WCLT shall be a minimum of 1 month greater than the beacon manufacturers declared TBRC.

3.2 Charge Indication

Beacons using rechargeable batteries shall provide a clear indication when the battery has to be recharged. This should be made either by visual (e.g. LED, display) and/or audio indicator (e.g. buzzer). Beacon manufacturers may choose to indicate:

a) either that the battery is in "normal battery mode" (for example by activating a green LED); or

b) that the battery is no more in "normal battery mode" (for example by flashing a red LED).

The charge indication shall be shown on the beacon and shall be fully documented in the user manual.

3.3 Measurement of Remaining Battery Capacity at the Replacement Date

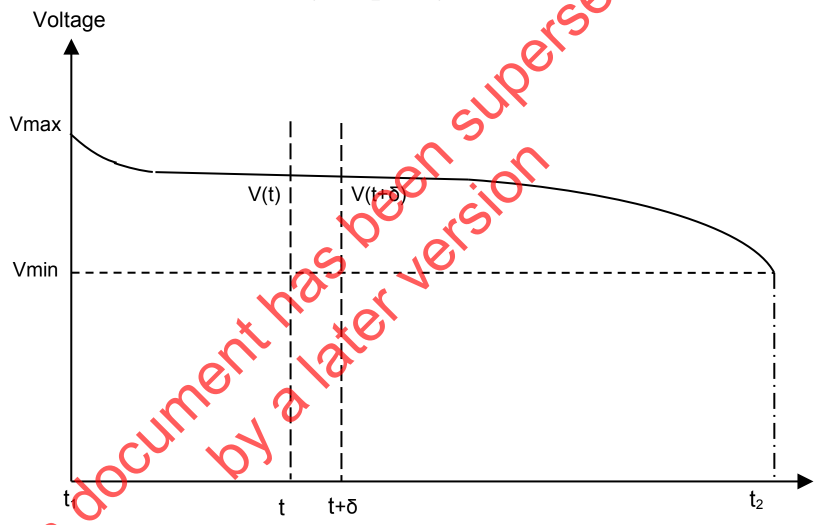
3.3.1 Battery Capacity Measurement

The capacity of the battery can be defined as $C = \int_{t_1}^{t_2} I(t) \cdot dt$

The measurement of the battery capacity shall be made using the following procedure:

- a complete charge process is made on the battery (at time t_1 in Figure 3 the battery is fully charged);
- a discharge of the battery is made using a well known resistor $R_{discharge}$ until the battery is fully discharged, the voltage goes down to zero[4] (at time t_2 in Figure 3 the battery is "empty"); and
- the voltage is monitored every δt.

Figure 3: Battery Capacity Measurement Procedure



The capacity is calculated as follows:

$$C = \int_{Fully\text{-}charged}^{Empty\text{-}Battery} I(t) \cdot dt = \frac{1}{R_{discharge}} \sum_{t_1}^{t_2} \left(\frac{V(t+\delta t) + V(t)}{2} \cdot \delta t \right)$$

$R_{discharge}$ is chosen in order to provide an equivalent discharge current equal to the maximum charge current of the charger when the battery is at its maximum (i.e. fully charged at Vmax in Figure 3 above).[5]

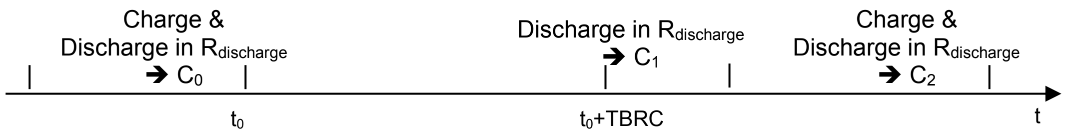
The value of the resistor $R_{discharge}$ has to be known to an accuracy better than 1%.

3.3.2 Measurement of Reversible Capacity Loss at Room Temperature

The measurement is performed by the beacon manufacturer. In this section, when a battery is recharged, the charger to be used shall be as described in section 3.6 of this document.

The measurement is performed using a batch of 10 batteries. The batteries shall be initially fully charged ($V_{charge\_final} = V_{max}$). The first capacity measurement shall be made at room temperature at time t_0 on each battery of the batch (as detailed in section 3.3.1 of this document). The average C_{0_mean} is then calculated.

Figure 4: Time Line for Capacity Loss Measurements during TBRC



The batteries are then fully recharged, disconnected and left unconnected during TBRC.

At t_0+TBRC, a voltage measurement is made on each battery to provide the battery voltage after TBRC. The average $V_{partial\_discharge\_mean}$ is calculated[4].

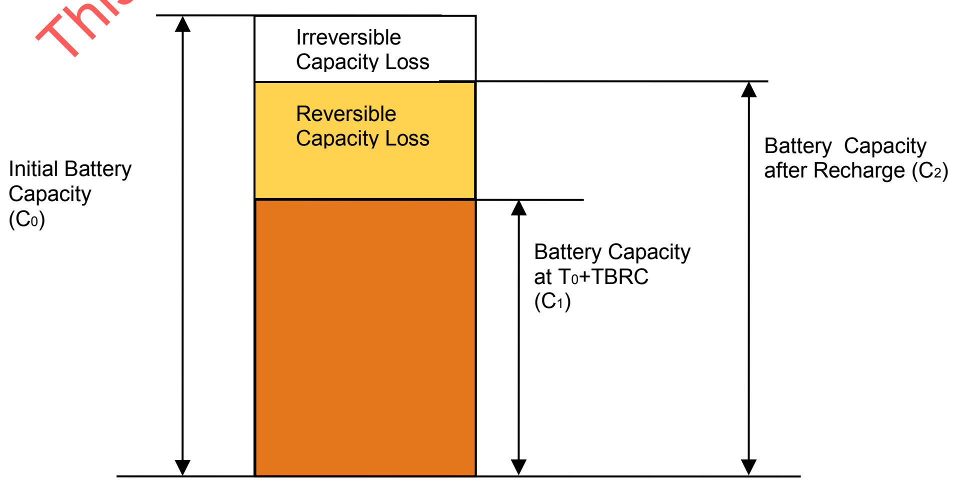
A second capacity[5] measurement is made on each battery at room temperature at t_0 + TBRC. The average $C_{1\_mean\_TBRC}$ is calculated.

Based on the dispersion of the individual measurements of $C_{reversible\_losses\_during\_TBRC}$, the manufacturer determines a $C_{maximum\_reversible\_losses\_during\_TBRC}$.

Based on the dispersion of the individual measurements of $C_{irreversible\_losses\_during\_TBRC}$, the manufacturer determines a $C_{maximum\_irreversible\_losses\_during\_TBRC}$.

After the capacity measurement at t_0+TBRC, a complete recharge of all batteries is performed. A third capacity measurement is made on each battery at room temperature and the average $C_{2\_mean\_TBRC}$ is calculated.

Figure 5: Illustration of Battery Capacity and Losses



4 This information is important to take into account the impact of multiple charge-discharge processes on irreversible capacity losses as described in section 3.3.3(ii)of this document.

5 The second capacity measurement is made before performing any recharge.

The reversible battery capacity loss during TBRC (after the first recharge) is then:

$$C_{reversible\_loss} = C_{2\_mean\_TBRC} - C_{1\_mean\_TBRC}$$

The irreversible battery capacity loss during TBRC is also calculated as follow:

$$C_{irreversible\_losses\_during\_TBRC} = C_{0\_mean\_TBRC} - C_{2\_mean\_TBRC}.$$

3.3.3 Evaluation of Irreversible Capacity Losses: Accelerated Aging

This evaluation is performed by the beacon manufacturer.

The Arrhenius equation states that the dependence of the rate constant k of chemical reactions to the temperature T (in Kelvin) and activation energy Ea is given by the following equation:

$$\lambda = A \cdot e^{-\frac{E_a}{RT}}$$

Where: λ : rate of capacity fade
A : pre exponential factor
E_a: activation energy as measured in section 3.9of this document (in J·mol^{-1})
R : 8.31 J·mol^{-1}·K^{-1}
T : temperature (in Kelvin)

In order to simulate the ageing of batteries within a reasonable test time, the batteries are placed at a higher temperature in a climatic chamber. The equivalent ageing of the capacity of the battery follows the Arrhenius law whereby an accelerated ageing of the battery can be achieved.

The activation energy is dependent upon the selected battery chemistry and cell construction (i.e. the chosen Anode-Cathode-Electrolyte chemistry), the beacon manufacturer has to measure this parameter as described in section 3.9 of this document.

The accelerated ageing factor is then calculated according to the expression:

$$\frac{t_1}{t_2} = e^{\frac{E_a}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)}$$ with:

- t_1 : time of the test at ambient temperature
- T_1 : ambient temperature 293°K (i.e. equal to 20°C±1°C)
- t_2 : time of the test at elevated temperature ($t_1 > t_2$)
- T_2 : climatic chamber temperature in °K (±1°K) ($T_2 > T_1$)

The selected test temperature shall correspond to a test period greater than 6 months and shall not exceed 55°C so as to avoid a distortion of ageing results.

(i) Estimation of Irreversible Capacity Loss during Storage

This test is performed using a batch of 10 new batteries. These batteries are to be supplied by the battery manufacturer as they will be supplied in production (i.e. most of the time they will not be fully charged).

At time t_0, C_0 capacity measurements are made at room temperature on a set of five batteries using the procedure described in section 3.3.1 of this document. These five batteries are not used for the remainder of the test. The average C_{0_mean} is calculated from the measurements obtained for these five batteries.

The other set of five batteries is left unconnected and not charged. The batteries are placed in a climatic chamber at the selected temperature during the test period equivalent to the maximum storage period at ambient temperature, as described above. The batteries are then removed from the climatic chamber. A complete charge is performed on these batteries and capacity measurements are made on all five batteries at room temperature to provide the average $C_{2\_mean\_storage}$.

The irreversible capacity loss due to storage is calculated as follow:

$$C_{irreversible\_loss\_in\_storage} = C_{0\_mean} - C_{2\_mean\_storage}$$

(ii) Estimation of Irreversible Capacity Loss During Beacon Standby Mode

This test is performed using a batch of 10 new batteries, as supplied by the manufacturer.

At time t_0, C_0 capacity measurements are made at room temperature on a set of five batteries using the procedure described in section 3.3.1 of this document. These five batteries are not used for the remainder of the test. The average C_{0_mean} is calculated from the measurements obtained for these five batteries.

The other set of five batteries is charged and placed in a climatic chamber at the selected temperature for the test period equivalent to the battery replacement life time at ambient temperature, as described above.

At time t_0 + test period, the five batteries are taken out from the climatic chamber. To take into account the aging linked to the repetitive charge-discharge process, N successive charge-discharge cycles are performed as follows.

The charge process is made using the charger as described in section 3.6 of this document and the discharge process is made from V_{charge_final}[6] to $V_{partial\_discharge\_mean}$ in $R_{discharge}$[7]. This step is repeated N times on all five batteries, with N defined as the ratio: Battery Replacement Life Time / TBRC, rounded down to the nearest integer.

Finally a charge process is applied on all five batteries and new capacity measurements C_2 are made. The average $C_{2\_mean\_Standby}$ is calculated.

The irreversible capacity loss in standby mode during the battery replacement life time, including the partial discharge/recharge cycles applied in beacon standby mode, is calculated as follow:

$$C_{irreversible\_loss\_in\_Stand\text{-}by\_mode} = C_{0\_mean} - C_{2\_mean\_Standby}$$

(iii) Estimation of Total Irreversible Losses

The total irreversible losses, which include storage loss and loss during normal mode, are:

[6] See definitions in 3.6.2 of this document and Figure 7. V_{charge_final} = battery voltage at end-of-charge.

[7] See definitions in section 3.3.2 of this document.

$$C_{irreversible\_losses} = C_{irreversible\_loss\_in\_storage} + C_{irreversible\_loss\_in\_Standby\_mode}$$

An additional safety factor of 1.65 is to be applied to this value when performing the operating life time at minimum temperature test per section A.2.3 of document C/S T.007.

3.4 Verification of Reversible and Irreversible Capacity Losses

In order to partially verify the results provided by the beacon manufacturer, the following measurements shall be performed at a Cospas-Sarsat accepted test laboratory.

The measurements are performed on a batch of 5 batteries. The batteries are initially fully charged. At time t_0, the first capacity measurement is made at room temperature on each battery of the batch. The average $C_{0\_mean\_lab}$ is calculated.

The batteries are recharged, disconnected and left unconnected during TBRC.

At time t_0+TBRC, a second capacity measurement is made at room temperature. The C_{1i} capacity is measured for each battery. After this capacity measurement, the batteries are recharged. A third capacity measurement is then made at room temperature. The C_{2i} capacity is measured for each battery.

The following battery capacity losses are derived from the above measurements:

(i) Reversible loss between successive charges = C_{2i}-C_{1i}
Each value has to be smaller than $C_{maximum_reversible_losses_during_}$TBRC provided by the beacon manufacturer as described in section 3.3.2 of this document

(ii) Irreversible loss between successive charges = C_{0i}-C_{2i}
Each value has to be smaller than $C_{maximum\_irreversible\_losses\_during\_TBRC}$ provided by the beacon manufacturer as described in section 3.3.2 of this document.

3.5 Verification of Worst Case Life Time

This test is performed by the beacon manufacturer using two complete beacons.

At time t_0, the batteries of the beacons are charged. After the charge, the beacons in stand-by mode are placed in a climatic chamber at a specific temperature (T_{wclt}) for a duration equivalent to the declared Worst Case Life Time (WCLT) at ambient temperature. As described in section 3.3.3 of this document, the accelerated ageing factor λ_{wclt} is a function of E_a and T_{wclt}:

$$\lambda_{wclt} = e^{\frac{E_a}{R}\left(\frac{1}{T_1}-\frac{1}{T_{wclt}}\right)}$$

The equivalent WCLT duration is the WCLT divided by the factor λ_{wclt} .

At the end of the test period the beacons are removed and kept at ambient temperature for at least 2 hours. Then the beacons are put in a climatic chamber at their minimum operating temperature and, after at least 2 hours, the beacons are turned on. An operating life time test at minimum temperature is then carried out on both beacons as described in C/S T.007

section A.2.3, but without any further pre-conditioning of the battery. If the operating life-time test is successful for both beacons (i.e. the beacons meet Cospas-Sarsat requirements for the declared operating lifetime at minimum temperature), the declared Worst Case Life Time is deemed to be confirmed by the test.

3.6 Battery Charger

3.6.1 Charger Information

The electric diagram of the charger shall be provided and the charge process shall be described. For CCCV (Constant Current and Constant Voltage) charge, the following information shall be provided:

a) charge current during constant current phase (this value could be provided as a function of the battery capacity[8]),

b) charge voltage and tolerance during constant voltage phase (for example 4.2V for most Li-ion cells),

c) current limit below which the charging process is ended,

d) estimated time to fully recharge a battery, and

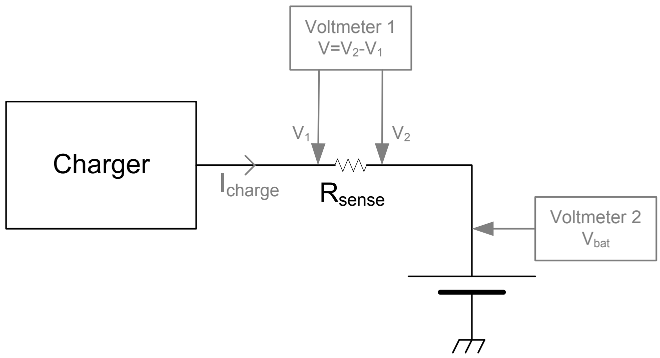
e) confirmation that the charger is compliant with national safety/EMC requirements.

3.6.2 Charger Test Procedure for CCCV Charge Process

These tests can be made by the beacon manufacturer and verified by a test laboratory accepted by Cospas-Sarsat.

a) Test set-up

Figure 6: Diagram of Beacon charger Test Set-up



Two voltmeters are necessary, one for differential measurement (image of the charge current), the second for monitoring the voltage of the battery.

8 For example, for a 2000 mAH battery, a charge at C/5 would mean a charge current of 2000/5=400 mA.

$$I_{charge} = \frac{V_2 - V_1}{R_{sense}}$$

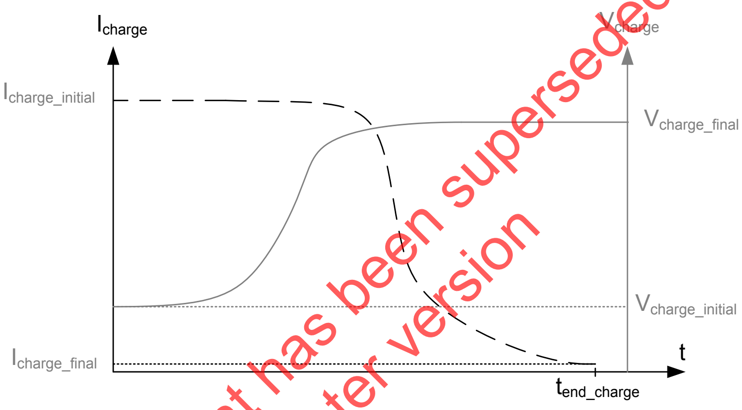
R_{sense}=0.1 Ohms (with accuracy lower or equal to 1%)

b) Test result

In a first step, the battery has to be fully discharged in a defined resistor as described in section 3.3.1 of this document. The battery is then charged and I_{charge} and V_{charge} are monitored.

At least 50 values (I_{charge} and V_{charge}) are to be provided and the time between two measurements shall not be longer than 1 minute.

Figure 7: Voltage and Current Intensity Measurements during Battery Charge



The charge applied to the battery shall then be calculated. The applied charge shall be equal or greater than the battery capacity measured in section 3.3.1 of this document.

Indications of on-going charge and end of charge shall be provided to the user.

3.7 Interaction between Charge Process and Self-Test

A self-test should be automatically started after each charge process. This would generate a self-test at least every TBRC.

The battery mode should be tested as described in section A.3.6 of document C/S T.007, during the self-test. If the battery is not in normal mode, the self-test result is FAILED.

3.8 Data to be Provided by Beacon Manufacturers

All information specific to the use of rechargeable batteries is documented in Attachment A to this document.

3.9 Measurement Method of the Activation Energy

The Arrhenius law applied to batteries is $C_{residual} = C_0 \cdot e^{-\lambda t}$ with $\lambda = \lambda_0 \cdot e^{-\frac{E_a}{RT}}$

Measurements are made:

- at 4 different temperatures,
- during 3 different time periods, and
- using 5 batteries for each measurement (in time and temperature).

A total of 60 batteries are needed for the test.

(i) Definition of the different temperatures

The four recommended temperatures[9] are:

- $T_1 = 20°C$
- $T_2 = 30.8°C$
- $T_3 = 42.4°C$
- $T_4 = 55°C$

(ii) Definition of the different measurement times

In order to define the measurement steps, a first "estimation" of the activation energy is needed. The first estimated "proposed value" is $E_a = 40$ kJ.mol^{-1}. The associated accelerated ageing factor is:

$$\frac{t_1}{t_2} = e^{\frac{E_a}{R}\left(\frac{1}{T_1} - \frac{1}{T_4}\right)} = e^{\frac{40.10^3}{8.31}\left(\frac{1}{273+20} - \frac{1}{273+55}\right)} = 5.7$$

The duration of the test is then defined by:

$$t_{Ea\_test} = \frac{\text{period equivalent to the replacement life time}}{5.7}$$

If the calculated value is below 6 months, the test is then defined to last 6 months.

The three recommended time periods are:

- $\tau_1 = t_{Ea\_test} \cdot 1/3$
- $\tau_2 = t_{Ea\_test} \cdot 2/3$
- $\tau_3 = t_{Ea\_test}$

(iii) E_a measurement

At the beginning of the test,

- 15 batteries are placed in a climatic chamber at T_1=20°C
- 15 batteries are placed in a climatic chamber at T_2=30.8°C
- 15 batteries are placed in a climatic chamber at T_3= 42.4°C
- 15 batteries are placed in a climatic chamber at T_4=55°C

After a period $\tau_1 = t_{Ea\_test} \cdot 1/3$, a set of 5 batteries is extracted from each climatic chamber and their remaining capacity is measured.

- For the 1st group stored at T_1, 5 capacities are measured:
  $C_{residual\_1}(\tau_1;T_1)$; $C_{residual\_2}(\tau_1;T_1)$; $C_{residual\_3}(\tau_1;T_1)$; $C_{residual\_4}(\tau_1;T_1)$; $C_{residual\_5}(\tau_1;T_1)$.
- For the 2nd group stored at T_2, 5 capacities are measured:
  $C_{residual\_1}(\tau_1;T_2)$; $C_{residual\_2}(\tau_1;T_2)$; $C_{residual\_3}(\tau_1;T_2)$; $C_{residual\_4}(\tau_1;T_2)$; $C_{residual\_5}(\tau_1;T_2)$.

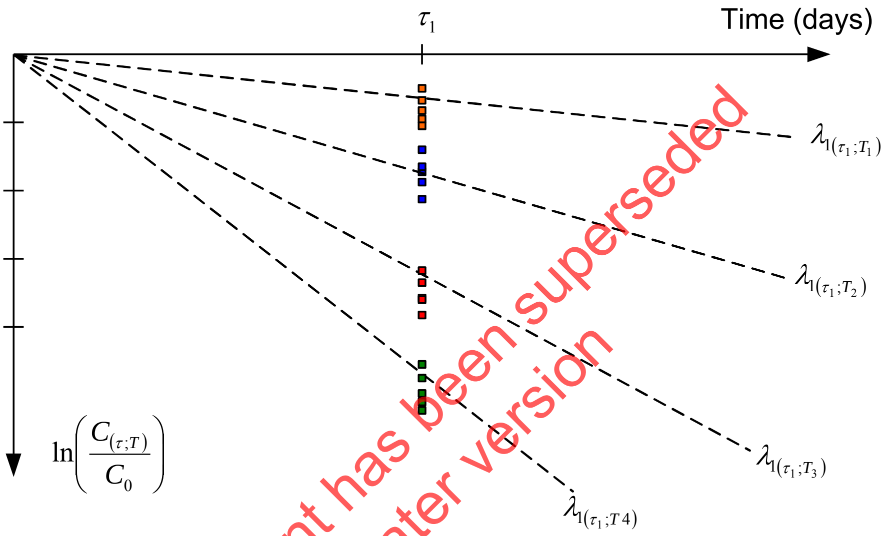
[9] T2 & T3 are chosen to have 3 regular steps on the curve in 1/T (T in °K) between T_1 & T_4

- For the 3rd group stored at T_3, 5 capacities are measured: $C_{residual\_1}(\tau_1;T_3)$; $C_{residual\_2}(\tau_1;T_3)$; $C_{residual\_3}(\tau_1;T_3)$; $C_{residual\_4}(\tau_1;T_3)$; $C_{residual\_5}(\tau_1;T_3)$.
- For the 4th group stored at T_4, 5 capacities are measured: $C_{residual\_1}(\tau_1;T_4)$; $C_{residual\_2}(\tau_1;T_4)$; $C_{residual\_3}(\tau_1;T_4)$; $C_{residual\_4}(\tau_1;T_4)$; $C_{residual\_5}(\tau_1;T_4)$.

According to: $C_{residual} = C_0 \cdot e^{-\lambda t}$, $\ln\left(\frac{C_{residual}}{C_0}\right) = -\lambda t$

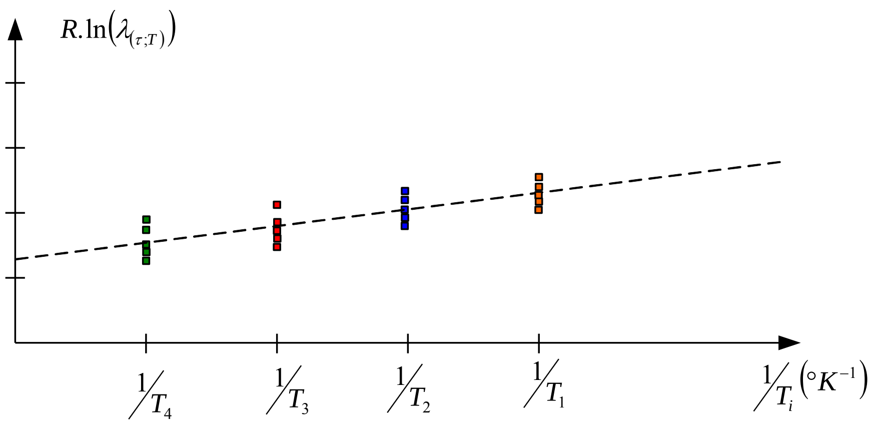
The measured values are incorporated in the graph below (Figure 8).

Figure 8: Capacity Versus Time at τ_1



Note: In Figure 8, only 1 of the 5 lines corresponding to the 5 measured values are depicted. For each measurement, 5 batteries are used as defined in the 1st paragraph of section 3.9 of this document. The slopes of the lines in Figure 8 provide different values of $\lambda_k(\tau_1;T_i)$, which are depicted in Figure 9. At τ_1, 20 values are to be reported on Figure 8, corresponding to 20 data point on Figure 9 (i.e. 5 at $1/T_4$, 5 at $1/T_3$, 5 at $1/T_2$ and 5 at $1/T_1$).

Figure 9: Accelerated Ageing Factor Versus Temperature at τ_1



The measured activation energy (E_{a_meas}) is the slope of the best fit straight line shown in Figure 9. The accelerated ageing factor shall be recalculated according to the expression:

$$\lambda = e^{\frac{E_a\_meas}{R}\left(\frac{1}{T_1}-\frac{1}{T_4}\right)}$$

The duration of the test is then recalculated as:

$$t_{Ea\_test} = \frac{period\ equivalent\ to\ the\ replacement\ life\ time}{\lambda}$$

At time $\tau_2 = 2/3 \cdot t_{Ea\_test}$ a set of 5 batteries is extracted from each climatic chamber and their remaining capacity is measured.

- For the 1st group stored at T_1, 5 capacities are measured: $C_{residual\_1}(\tau_2;T_1)$; $C_{residual\_2}(\tau_2;T_1)$; $C_{residual\_3}(\tau_2;T_1)$; $C_{residual\_4}(\tau_2;T_1)$; $C_{residual\_5}(\tau_2;T_1)$.
- For the 2nd group stored at T_2, 5 capacities are measured: $C_{residual\_1}(\tau_2;T_2)$; $C_{residual\_2}(\tau_2;T_2)$; $C_{residual\_3}(\tau_2;T_2)$); $C_{residual\_4}(\tau_2;T_2)$; $C_{residual\_5}(\tau_2;T_2)$.
- For the 3rd group stored at T_3, 5 capacities are measured: $C_{residual\_1}(\tau_2;T_3)$; $C_{residual\_2}(\tau_2;T_3)$; $C_{residual\_3}(\tau_2;T_3)$; $C_{residual\_4}(\tau_2;T_3)$; $C_{residual\_5}(\tau_2;T_3)$.
- For the 4th group stored at T_4, 5 capacities are measured: $C_{residual\_1}(\tau_2;T_4)$; $C_{residual\_2}(\tau_2;T_4)$; $C_{residual\_3}(\tau_2;T_4)$); $C_{residual\_4}(\tau_2;T_4)$; $C_{residual\_5}(\tau_2;T_4)$.

Then the plots "capacity versus time" and "accelerated ageing factor versus temperature" are updated and the duration of the test (t_{Ea_test}) is recalculated.

At time $\tau_3 = t_{Ea\_test}$ the last set of 5 batteries is extracted from each climatic chamber and their remaining capacity is measured.

- For the 1st group stored at T_1, 5 capacities are measured: $C_{residual\_1}(\tau_3;T_1)$; $C_{residual\_2}(\tau_3;T_1)$; $C_{residual\_3}(\tau_3;T_1)$; $C_{residual\_4}(\tau_3;T_1)$; $C_{residual\_5}(\tau_3;T_1)$.
- For the 2nd group stored at T_2, 5 capacities are measured: $C_{residual\_1}(\tau_3;T_2)$; $C_{residual\_2}(\tau_3;T_2)$; $C_{residual\_3}(\tau_3;T_2)$; $C_{residual\_4}(\tau_3;T_2)$; $C_{residual\_5}(\tau_3;T_2)$.
- For the 3rd group stored at T_3, 5 capacities are measured: $C_{residual\_1}(\tau_3;T_3)$; $C_{residual\_2}(\tau_3;T_3)$; $C_{residual\_3}(\tau_3;T_3)$; $C_{residual\_4}(\tau_3;T_3)$; $C_{residual\_5}(\tau_3;T_3)$.
- For the 4th group stored at T_4, 5 capacities are measured: $C_{residual\_1}(\tau_3;T_4)$; $C_{residual\_2}(\tau_3;T_4)$; $C_{residual\_3}(\tau_3;T_4)$; $C_{residual\_4}(\tau_3;T_4)$; $C_{residual\_5}(\tau_3;T_4)$.

The plots "capacity versus time" (Figure 10) and "accelerated factor versus temperature" (Figure 11) are updated.

Figure 10: Capacity Versus Time at τ_3

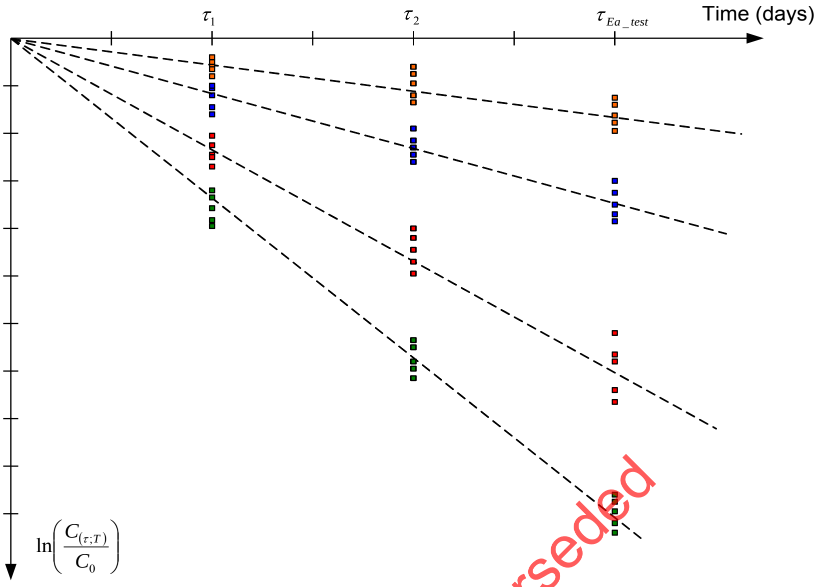
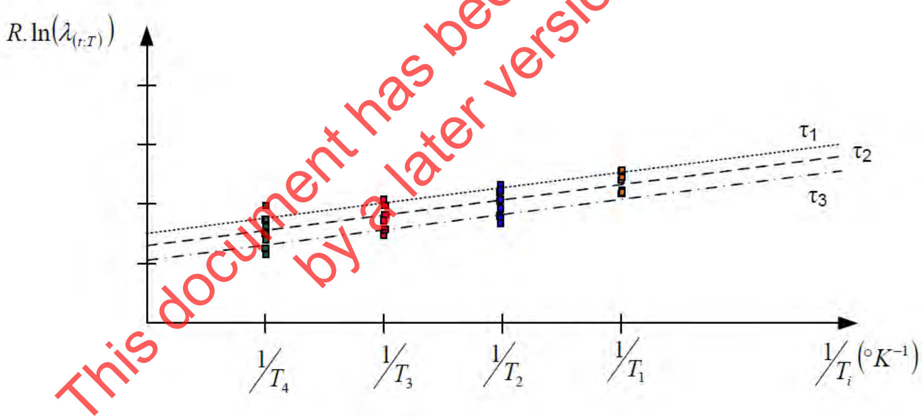


Figure 11: Accelerated Ageing Factor Versus temperature at τ_3



The final value of the applicable activation energy (Ea) for the selected technology is the third slope of the best straight fit line shown in Figure 11[10].

[10] At τ_3, 60 values should be reported in Figure 10, hence 60 slopes corresponding to 60 points in Figure 11 (i.e. 15 at $1/T_4$, 15 at $1/T_3$, 15 at $1/T_2$ and 15 at $1/T_1$). The activation energy is calculated using value from the individual storage period. Figure 11 presents three slopes for each storage period.

ATTACHMENT A

Supplementary Characteristics for Beacons equipped with LIRBs

Characteristic	Specification
Battery chemistry	
Battery cell model name, size and number of cells	
Battery cell manufacturer	
Battery pack manufacturer and part number	
Initial capacity of new battery after first charge	______mAh
Required capacity to meet the operating life time at minimum temperature	______mAh
Battery replacement life time	______Months______Years
Charge indication	☐ Visual / ☐Audio ☐ In Normal Mode / ☐Not in Normal mode ☐ Charge Ongoing ☐ Charge Complete Type :
Time Between Recommended Charges at ambient temperature (TBRC)	______Months
$T_{wake-up}$ (wake-up period to check battery)	______Days
$R_{discharge}$ (resistor for discharge process)	______Ω
Reversible losses between TBRC: $C_{maximum\_reversible\_losses\_during\_TBRC}$	______%
Voltage drop after TBRC: $V_{partial\_discharge\_mean}$	______V
Irreversible losses during TBRC: $C_{maximum\_irreversible\_losses\_during\_TBRC}$	______%
Activation Energy Ea	__J.mol^{-1}
Test temperature (if applicable) for measurement of irreversible capacity loss during storage	__°C -
Worst Case Life Time (WCLT)	______Months - ____Years

Characteristic	**Specification**
Irreversible losses in two-year storage: $C_{irreversible\_loss\_in\_storage}$	______%
Test temperature (if applicable) for measurement of irreversible capacity loss in standby mode	___°C
Irreversible losses in standby mode over replacement life time: $C_{irreversible\_loss\_in\_standby\_mode}$	______%
Measured operating life time in Worst Case Life Time configuration	______Hours
Battery Charger	
$I_{charge\_initial}$	______mA
I_{charge_final}	______mA
$V_{charge\_initial}$	______V
V_{charge_final}	______V
Charge time : t_{end_charge}	______Mn
Charge capacity	______mAh
Oscillator type (e.g. OCXO, MCXO, TCXO) …	

[…]

Characteristic	**Specification**	
Self-Test Mode Characteristics:	Self-Test Mode	Optional GNSS Self-Test Mode
[…]		
- Maximum number of GNSS Self-Tests (beacons with internal navigation devices only)	N/A	
- Self-test automatically activated after each charge process (for beacon using rechargeable batteries)		

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