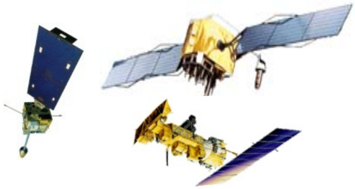


Problems with the Interim Li Ion Rechargeable Batteries Type Approval Procedure

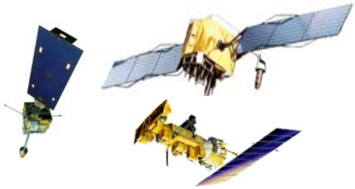
Presentation to RTCM SC-110 and the BMW

Jim Christo/SAR Ground Systems Manager

Search and Rescue Mission Office

NASA/Goddard Space Flight Center

May 20, 2010



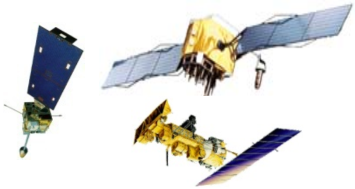
Agenda

- C/S History
- Executive Summary
- JC recommendations
- Backup Charts
- Experts consulted
- Comparison of Battery Use
- Arrhenius Equation
- Temperature Issues
- State of Charge Indication
- Safety Factor
- Suggested Testing
- LIRB Approaches
- Final thoughts

Comparison with paper JC-24/5/xx

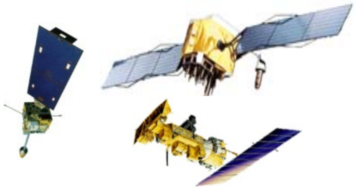
- This presentation is a condensation of the contents in corresponding JC-24 paper from the USA
- All information in this presentation also appear in that paper

C/S History with Li Ion Batteries



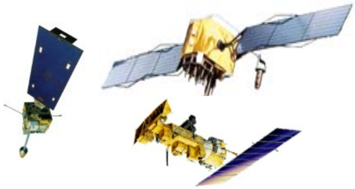
- At JC-22, France submitted papers JC-22/5/9 Rev 1 and JC-22/5/9 Rev 1 Add 1
  - Presented results of capacity tests on some Li Ion batteries at various temperatures and test times to substantiate use of Arrhenius equation to determine a lifetime test at elevated temperatures as an alternative to full life time testing
- At JC-23, France in paper JC-23/5/7 Rev 1 proposed a change to the beacon type approval process to allow rechargeable batteries
  - Numerous splinter meetings in TWG
  - Objections from the USA citing operational concerns
  - OWG never considered the issue: all work was done in the TWG
  - Compromise at the TWG: an Interim type approval procedure was agreed to and forwarded to council
- At CS -43, council approved the interim procedure and levied action items:
  - Participants consider operational issues
  - Investigate impact of long term exposure to high temperatures
- Here we are-this presentation and corresponding paper are designed to answer the two actions

Arrhenius Equation Problems



- The reason for trying to use the Arrhenius equation was to find an elevated temperature where accelerated life testing is equivalent in order to avoid the full life testing protocol.
- The Arrhenius equation, which relates the rate of capacity fade to temperature, is not applicable to batteries because it assumes all other factors are held constant and temperature is the only variable.
- Unfortunately, Li Ion batteries experience different capacity fade mechanisms and internal impedance growth mechanisms that occur at higher temperatures.
- A study from the Jet Propulsion Laboratory shows that for each cell tested, there is one activation energy value for the anode, and another value for the cathode which resulted in eight different activation energies almost over a 2:1 range for four prototype Li Ion cells
- According to the JPL experts, accelerated life testing cannot be assumed to hold – one might get unexpected results due to the different capacity fade mechanisms and internal impedance growth mechanism that occur at higher temperatures. It is better to do full lifetime cycle testing and then analyze the data to determine whether any empirical relationship can be made which will allow accelerated lifetime testing of the same battery chemistry is possible.

Temperature Problems

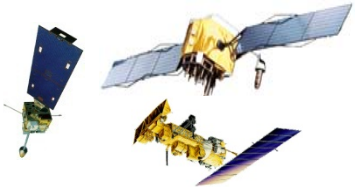


- **The Li Ion battery experiences higher fades at higher temperatures and the effect is non-linear with temperature.**
- **This results in the fact that there is a complex relationship of recharge interval to aging and temperature effects. A chart presented in the JC paper shows that a battery can need a charge at intervals that range from 10-300 days based upon the time of year, location of the battery and the age of the battery.**
- **The interim LIRB's treatment as a single recharge interval is not supported by the temperature data presented in the JC paper.**
- **A second mechanism of temperature related capacity loss occurs with temperature cycling, especially at high temperatures.**
  - **Capacity fades at the minimum operating temperature are affected most when the battery is subject to high temperature cycles.**
  - **Data is presented in the JC paper that shows some batteries can lose all capacity at the -40^{o}C discharge temperature when it is exposed to 175 temperature cycles – which is less than a half a year in some desert climates.**
- **How this temperature effect will affect SAR is unknown- it needs to be studied**.

State of Charge (SOC) Problems

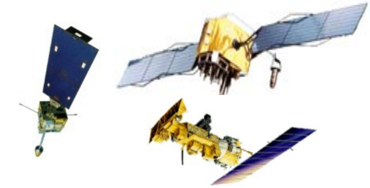
- **Problem is trying to measure battery capacity**
- **Some Li Ion discharge voltage curves vs.. time in the storage mode have a slope sufficient to allow voltage measurements to determine capacity but some other chemistries have voltage slopes that are flat with time and consequently measuring voltage will not work.**
- **In that case, integrating current over time is needed**
- **A fuel gauge may need to be considered for those battery chemistries where the slope of the voltage vs. time curve is flat.**
- **This is discussed more in the backup slides.**

Self tests to measure SOC



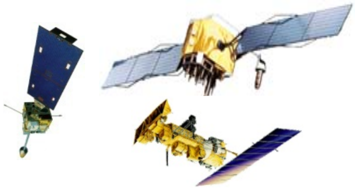
- The allowable self test to check state of charge (SOC) of the battery can have large operational impacts.
- If thousands of beacons owners do self tests just to check the state of the charge, it means that there will be thousands of additional self tests bursts over what is experienced today impinging on the system.
- These extra bursts may have an impact on LUT capacity and/or channel capacity.
- Before this method is allowed, there should be a study to model this effect and to determine the system impact from the projected number of beacons doing self tests just to check the battery state of charge.

Battery Safety Factor Problem



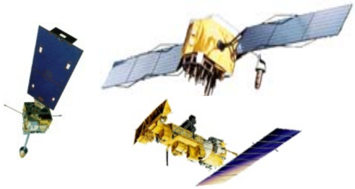
- The existing 1.65 battery safety factor for rechargeable batteries was assumed to be valid, but in reality, is not supported by any studies presented to C/S.
- The existing safety factor is designed to allow for:
  - average current drain resulting from constant operation of the circuits powered by the beacon prior to beacon activation over the rated life of the battery pack and
  - the number of projected self tests,
  - but it does not include temperature as a factor.
  - Does not include self tests to check state of charge
- In order to determine a realistic value for the safety factor, there should be an analysis of the performance of many Li Ion batteries in the SAR environment

Customer experience



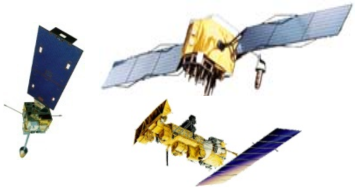
- Consumer Experience with Li Ion Batteries
  - Batteries used in cell phones and computers typically have short storage intervals, frequent recharge experiences and a limited temperature operational range.
  - Distress beacons, on the other hand, have long storage times, infrequent recharging, pulsed high current draws for the bursts and can experience temperature extremes from -40^{o}C to over +80^{o}C.
  - The experience people have with Li Ion batteries in consumer devices like cell phones and laptop computers is not very applicable to the environment in which SAR distress beacons operate.
- Military applications of Li Ion rechargeable batteries mirror the consumer applications except they too have to function in environments with large temperature extremes.
- The experience of the US Military is also significantly different even though they share operation in temperature extremes and thus is not that applicable to SAR
- SAR’s use of Li Ion batteries is so different from everyone else’s

Specmanship



- SAR does not make use of the strengths of Li Ion rechargeable batteries which is short storage times and frequent re-chargings.
- Vendors make batteries that are designed for short storage intervals and frequent recharging because that is what their applications require.
- Each application has a different spec for the battery performance and battery vendors design and test the batteries for the specific application.
- There is no spec currently available that applies to SAR, so no vendor makes batteries specifically designed to effectively work in environments where there are long storage times and infrequent recharging
- Due to the lack of experience with an application like SAR, SAR is basically left with developing its own experience.
- In order for these batteries to effectively work well with SAR, a SAR specific spec needs to be developed, some candidate batteries needs to be selected and a body of test experience is needed.

Proposed Testing Programme



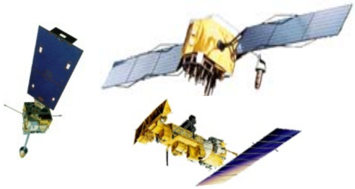
- This will require a large testing program - testing of a number of candidate chemistries for full lifetimes at various discharge temperatures and various temperature cycles. Without such data, C/S is only guessing how they will operate in a SAR application.
- The annexes lay out a number of points that a testing program should address. This testing program will be long and expensive but the experts saw no other way to proceed.
- Finally, the US research into batteries yielded the conclusion that batteries are so complicated that the subject is best left for the experts. The US Military and NASA each have groups of people and laboratories dedicated to the study of batteries. Cospas-Sarsat should tap into that or equivalent expertise in order to develop the best battery product for future beacons.

Recommendations

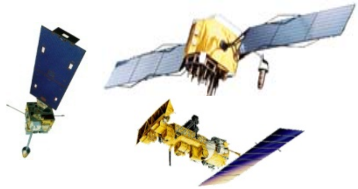
- USA recommendations to the JC is based upon the concern that distress beacons (EPIRBs, ELTs and PLBs) type approved under the LIRB will result in much higher incidents of failure and lives lost:
- Recommendations to the JC
  - Suspend operation of the LIRB until questions have been addressed and resolved
  - Ask interested participants to further study the issues raised in the JC paper

BACKUP CHARTS

Experts consulted



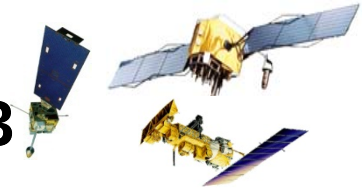
- The listed organizations use Li Ion rechargeable batteries for their application
- US Navy: Naval Surface Warfare Center (NSWC) Carderock: batteries for Navy use, ships torpedoes, man-packs, aircraft
- US Army: batteries for Army use, vehicles, man-packs
- NASA/Goddard Space Flight Center (GSFC): batteries for low earth orbit satellite use
- NASA Jet Propulsion Laboratory (JPL): batteries for deep space mission use
- NASA Johnson Space Center (JSC): batteries for shuttle space suit use, space station use
- National Renewable Energy Laboratory (NREL): deep cycling batteries for energy storage from solar power/wind power systems
- USA interagency groups
  - Lithium Battery Technical/Safety Group
  - Power Sources Technical Working Group (PSTWG)



Comparison of Various Applications 1/3

	Cell Phone use	Notebook computer use	SAR Distress beacon use
Battery in Storage Mode time period	1 -2 days	Short, most times connected to charger	Long-months
Recharge frequency	Every few days	High, most times connected to charger	Very low
Number of Recharge cycles over battery lifetime	High (8 in 2 weeks translates to 416 over two years	High (8 in 2 weeks – 416 in 2 year lifetime)	Very low
High temperature exposure	Not subject	Not subject- typically room temperature, sometimes used outdoors	Can be subjected to extreme temperatures depending on location of beacon
Effect of discharged battery	Can't use cell phone until recharge battery	Can't compute until connect to charger/electrical power	Beacon will not work when needed, may not be able to recharge when needed, probable loss of life

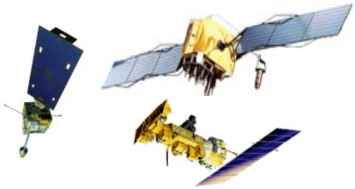
Comparison of various applications 2/3



Item	Navy	Army	NASA	SAR
Mission Use	Training only; not for real missions	Soldier and vehicle use	Spacesuits, shuttle, space station, spacecraft	PLB, EPIRB, ELT
Battery Storage interval times	short	short	short	long
Recharge frequency	high	high	high	Very low
High Temperature exposure	Test to MIL STD - 810	Test to MIL STD 810	Use temp control to limit high temps	Land beacons in desert areas see high temps
Low Temperature exposure	Test to MIL STD - 810	Test to MIL STD 810	Use heaters to limit low temps	Beacon in arctic regions see low temps
Effect of failure	Mission failure	Mission failure	Loss of life /mission failure	Loss of life

Comparison of various applications 3/3

- Experts: Search and Rescue use is unique because of long storage times, infrequent recharges, periodic high current draws and high temperature and temperature cycling exposure in combination
- Every application develops own spec for battery performance so SAR should develop specs for its application
- Vendors build and test batteries according to the intended specific use
- Testing results and specs from cell phones, laptop computers, Army, Navy, and NASA use is of limited use for SAR
- SAR has a need for high current in bursts which is unique.
- We need to develop our own database of test results for the SAR application



Arrhenius Equation

- Equation is from paper JC-22/5/9 Rev 1
- 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:

$$k = A*exp(-Ea/(R*T))$$

Where: k : rate of capacity fade

A : pre exponential factor

Ea : activation energy (in kCal • mol^{-1})

R: gas constant (in kCal • mol^{-1} • K^{-1})

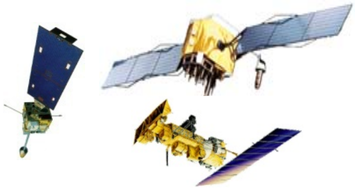
T: temperature (in Kelvin)

For the Li-Ion reaction, Ea is 15 kCal • mol^{-1}, the gas constant R is 1.987 kCal • mol^{-1} • K^{-1}.

Conclusion: The Arrhenius law indicates that an accelerated equivalent aging of the battery capacity can be achieved by placing the battery at a higher temperature than the assumed ambient temperature of 25°C. Note that only one activation energy Ea is specified by the French paper.

This is the number that appears in the LIRB interim type approval standard

JPL research on the Arrhenius Equation



- **JPL tested 4 prototype batteries with common anode and cathode materials but with different electrolytes**

- **Several of the following charts is based upon an investigation the NASA's Jet Propulsion Laboratory (JPL) did and it was presented to the 79th meeting of the Lithium Battery Technical/Safety Group in February 2009.**

- **The cells used in the study are as follows:**
- **Y40 is a MCMB anode and $LiNiCoO_2$ cathode in high EC electrolyte solution**
- **Y35 is a MCMB anode and $LiNiCoO_2$ cathode in low EC electrolyte solution**
- **Y43 is a MCMB anode and $LiNiCoO_2$ cathode in solution without VC.**
- **Y44 is a MCMB anode and $LiNiCoO_2$ cathode containing VC**

- **MCMB is Graphite for lithium ion battery anode materials,**
- **EC is exchange currents (The rate of the electrode reaction can be expressed as an equivalent current density and the "exchange current density" of a reaction is the current density flowing "equally" in both directions in equilibrium. A large exchange current density indicates a fast reaction (see also non-polarizable electrode), while a small exchange current density indicates a slow reaction (see also polarizable electrode)**

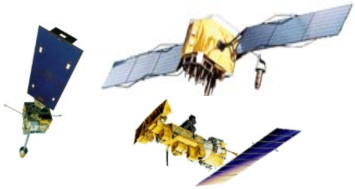
- **VC is Vinylene Carbonate**

Arrhenius factors of prototype Li Ion battery

Cell	Electrode	Arrhenius Slope	Activation energy (kcal/mol)
Y35 (low Exchange Current)	Anode	3.18	14.39
	Cathode	2.51	11.38
T40 (high Exchange current)	Anode	2.90	13.16
	Cathode	2.38	10.79
Y43 (No Vinylene Carbonate)	Anode	2.38	10.77
	Cathode	1.80	8.18
Y44 (Vinylene Carbonate)	Anode	2.69	12.21
	Cathode	1.85	8.40

Arrhenius equation Conclusion

- Activation energy for cathode and anode is different and is battery chemistry dependent
- Not possible to specify a single Arrhenius value for Ea in the LIRB interim type approval standard
- Need to determine Ea from measurements with specific battery chosen by the beacon manufacturer

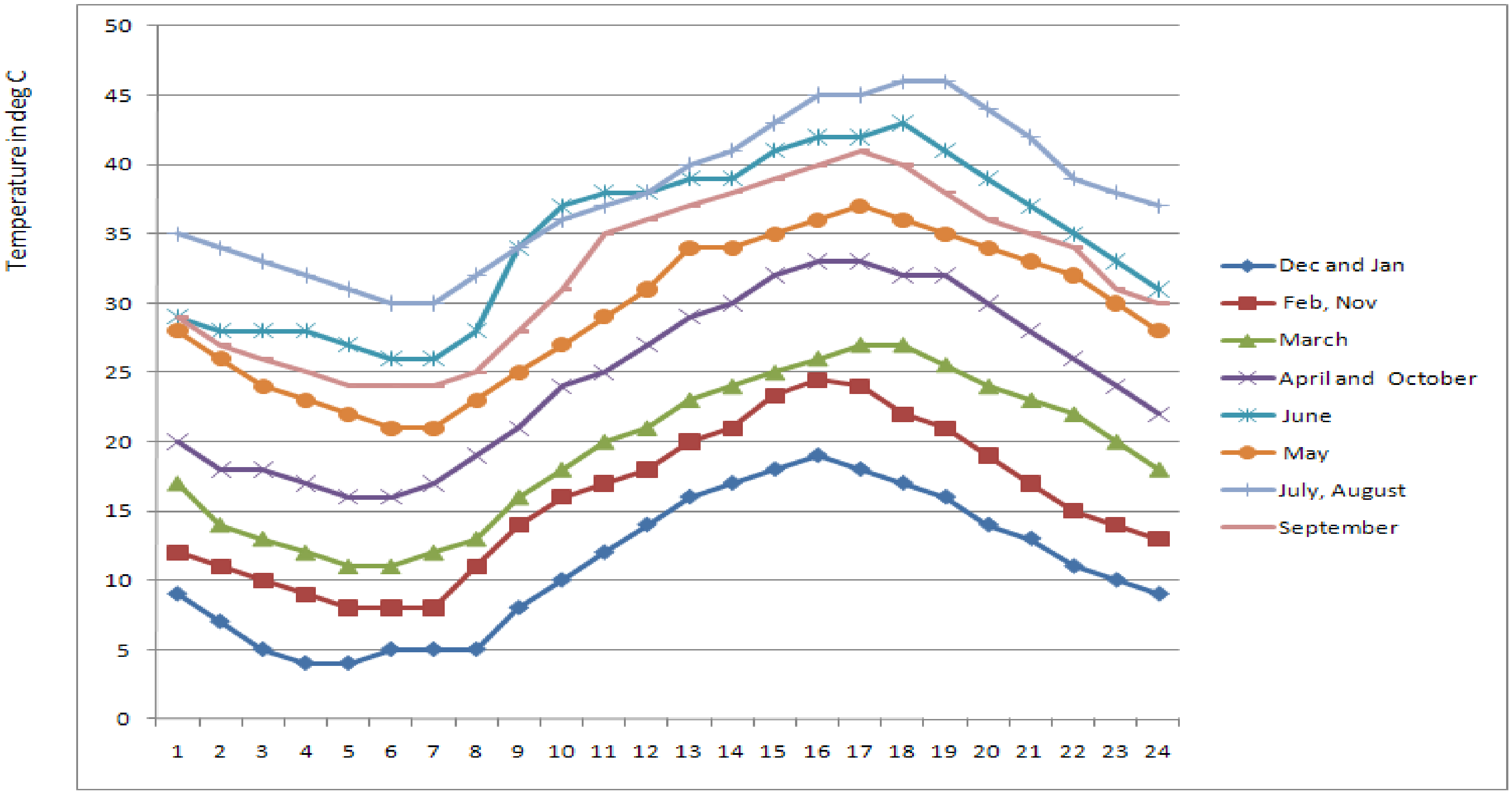


High Temperature Effects

- Used RTCM compilation of the 100 year average temperatures on an hourly basis over a full year for Death Valley California USA
- Location was selected as an example of the extreme temperatures that can be experienced by a land based distress beacon
- Battery capacity requirements and losses based upon French JC-22 papers
- The Arrhenius equation (parameters based on the French JC-22 paper) to calculate the storage losses at various temperatures
- Note that Arrhenius equation is not accurate so the following graphs should be interpreted to show what can happen to recharge intervals vs. temperature. The numbers found by testing for the specific battery chemistry will be different but the take away point will remain the same
- Note that no cloud cover was used so the real life temperature experienced will be not quite as high
- Battery recharge interval calculations based on a recharge a the first of the selected month
- Following Death Valley charts assume there is no other high temperature effects on battery capacity: so the recharge chart is overly simplistic

Death Valley Temperatures 1/2

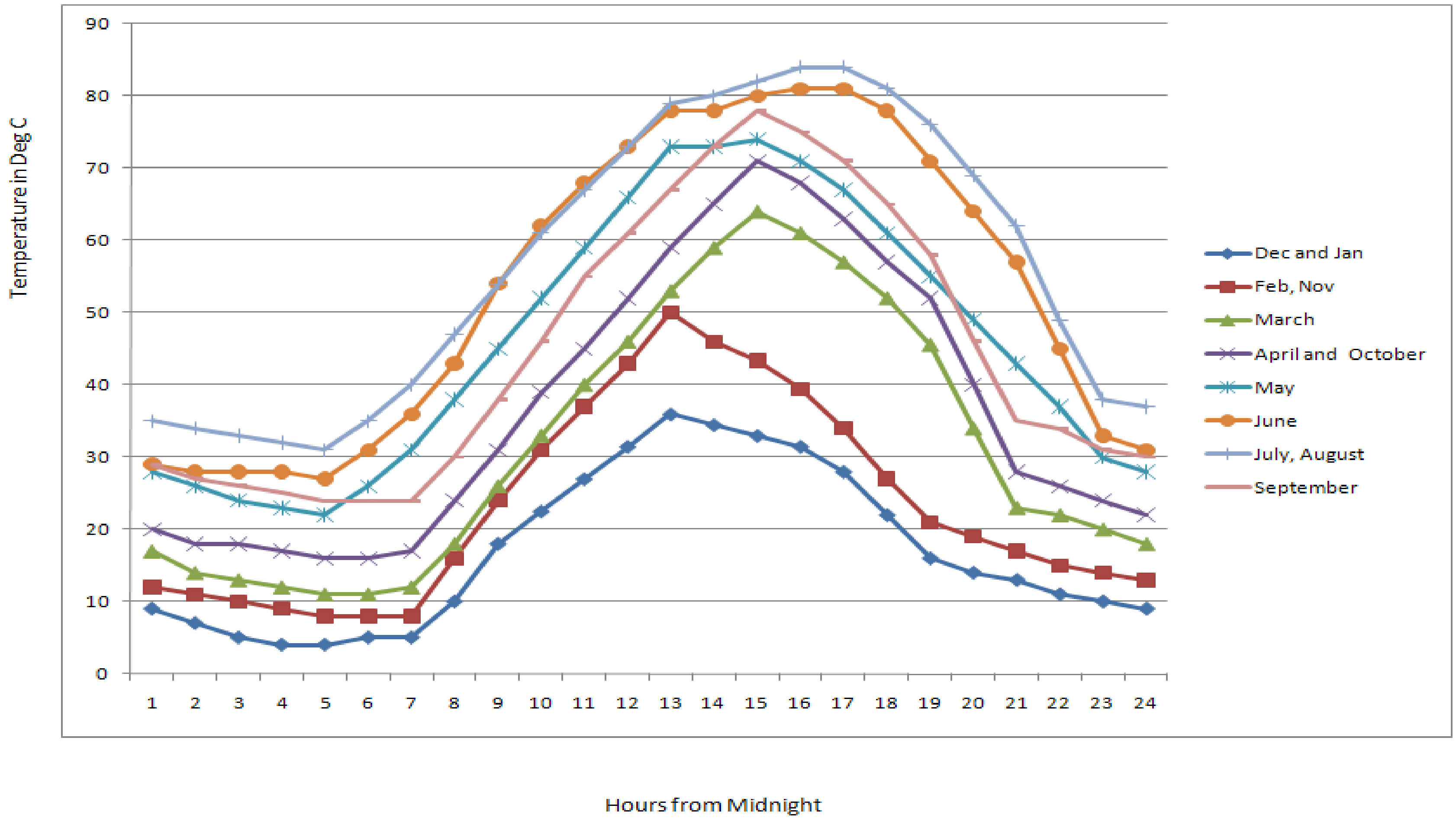
Air Temperature at Death Valley USA



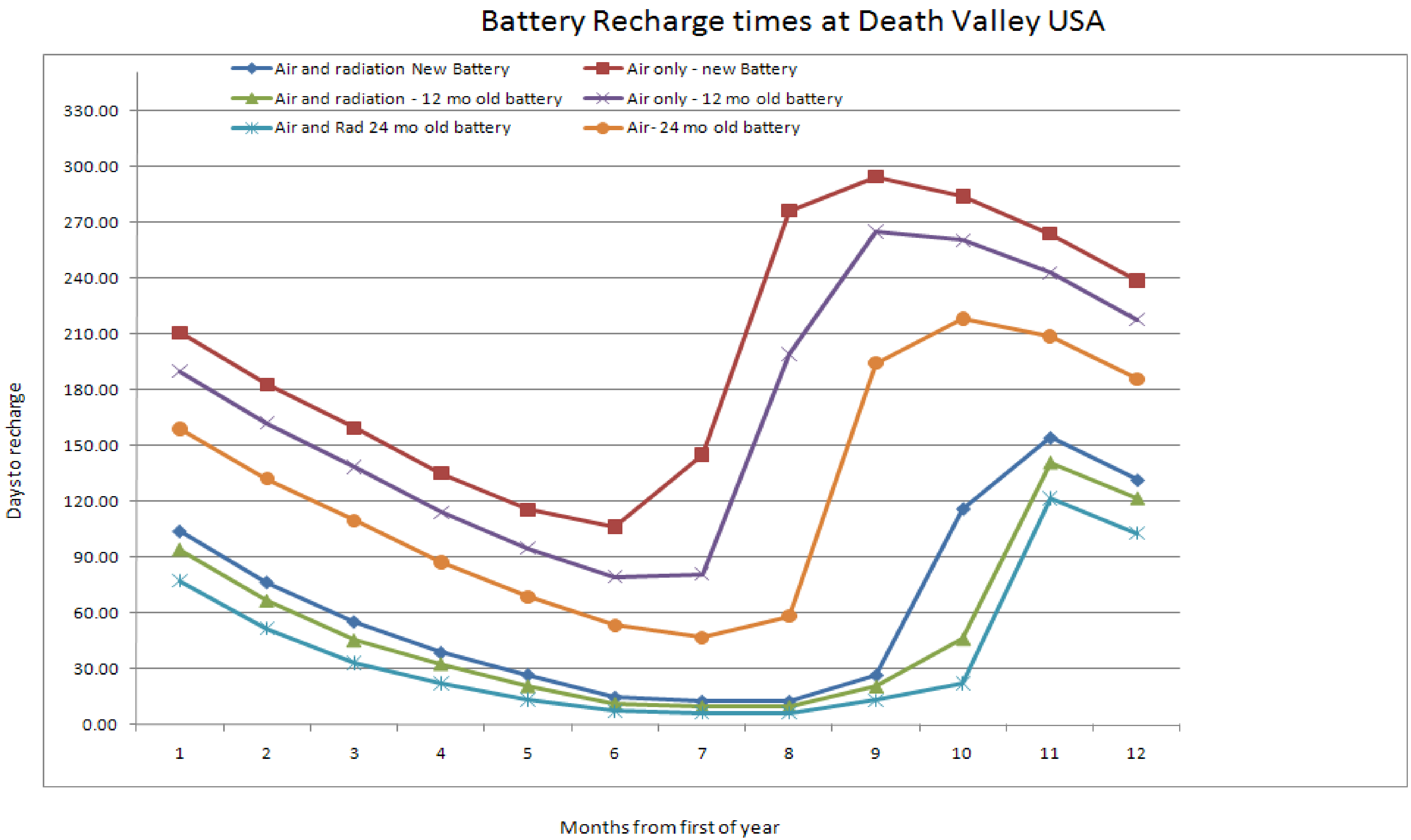
Hours from Midnight

Death Valley Temperatures 2/2

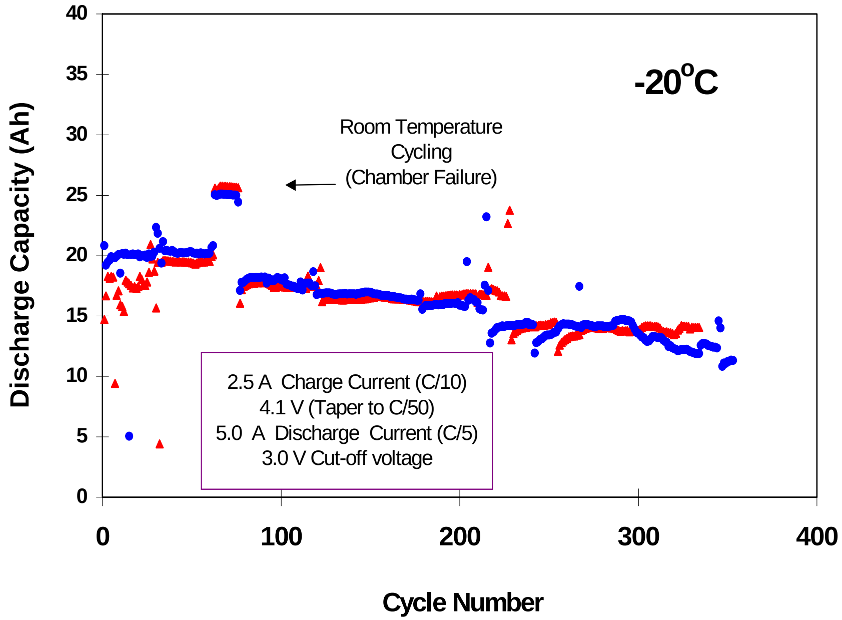
Death valley Temperatures due to air and Radiation in a closed vehicle

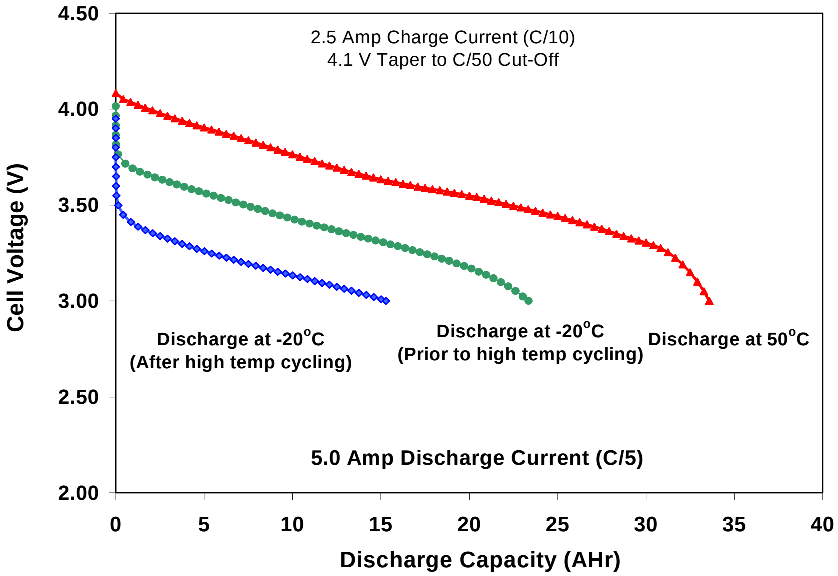


Recharging Intervals at Death Valley



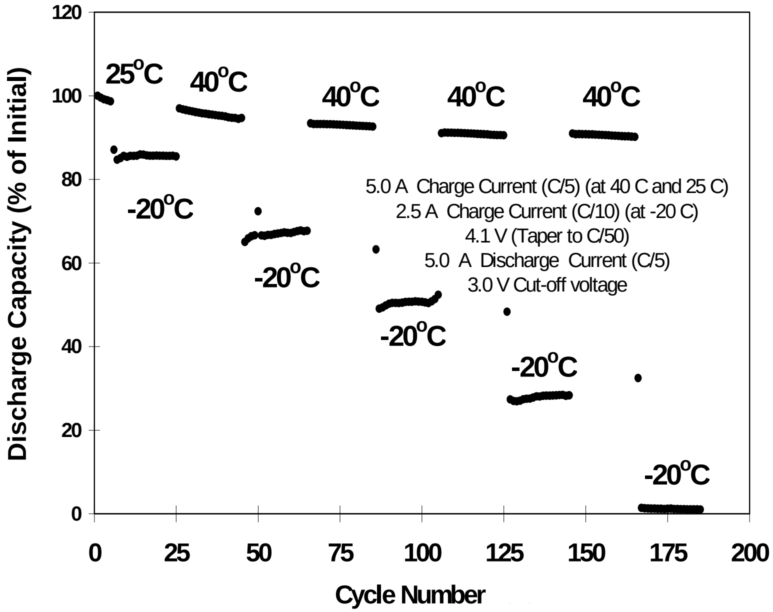
JPL: Effect upon high temperature cycling on capacity 1/2

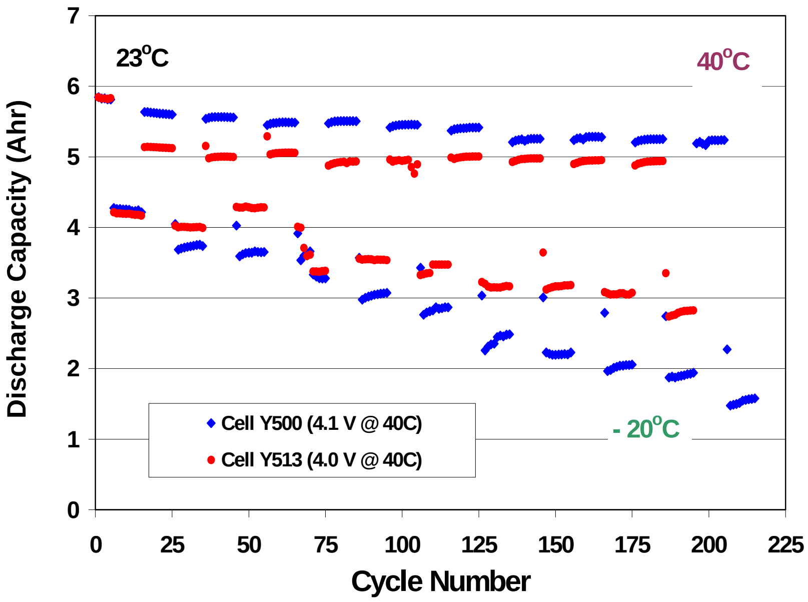




- During at 100% DOD cycling test at –20ºC, significant capacity loss was observed after the cells were subjected to cycling at higher temperatures (25-30ºC)
- Significantly poorer low temperature performance was observed after moderate cycling (~ 16 cycles) at 50ºC.

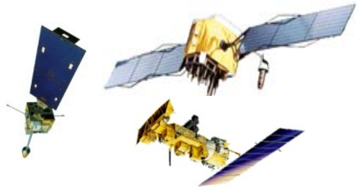
JPL: Effect upon temperature cycling on capacity 2/2



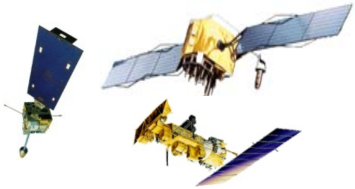


- ➢ It was ascertained that the *charge voltage at high temperature* can influence trend.
- ➢ It was also determined that cell chemistry (especially electrolyte type) can have a dramatic influence upon performance.
- ➢ An increase in cell impedance and a decrease in low temperature performance capability was observed upon cycling between two temperature extremes.

JPL: Effect of high temperatures on Li Ion cells- conclusions



- SOA Lithium-ion cell technology generally displays a wide temperature range of operation depending on cell chemistry (-20 to +50^{o}C).
- However, it is known that high temperature storage and exposure can be detrimental to cell health and lead to performance loss.
- Prototype cell testing at JPL (and elsewhere) has resulted in a number of observations related to high temperature exposure.
  - Increased capacity fade rates with cycling.
  - Irreversible capacity loss associated with high temperature storage.
  - Increased cell self-discharge rates.
  - Diminished low temperature performance capabilities.
  - Increased cell impedance.
  - Increased gas generation and pressure build-up within cell.
  - High voltage operation and/or storage resulting in increased cell degradation and performance loss.



Conclusions from JPL studies

- The Arrhenius parameters are battery chemistry dependent: they will have to be determined by testing from the specific battery chemistry selected by the beacon manufacturer. Even then, the equation may not be of any value. The problem with the Arrhenius equation is that other factors like cell impedance cannot be held constant.
- High temperature cycling's effect on the capacity of a specific battery chemistry at various discharge temperatures needs to be tested to be understood
- According to the study's principal author, JPL's Dr Marshall Smart, "One should avoid the strategy of attempting to accelerate life testing of Li-ion by performing the testing at higher temperatures because the tests can give you unexpected results, due to the fact that different capacity fades and impedance growth mechanisms occur at higher temperatures. Unfortunately, real time performance testing is still the most valid route to take".
- The LIRB's references to testing at elevated temperatures needs to be removed and lifetime testing should occur over the full lifetime of the specific battery chemistry selected

State of Charge: self test

- JC-23/5/7 indicated that the user will have to be informed that the battery has to be charged
- Suggests a self test could be performed and the LIRB allows it
- Since a self test generates a burst there will be impacts on the operational system of thousands of beacons doing regular or irregular self tests just to check state of charge of the battery
  - LUT capacity issues
  - Beacon frequencies may have to be opened or closed on a different schedule
  - Paper offered no analysis of these effects
  - Many self tests use up energy and will result in lower capacity available to the user necessitating a shorter recharge interval. This additional load upon the battery will need to be taken into account when specifying the initial battery capacity.
- Note C/S has moved to limit number of self tests with location to maintain battery capacity
- What to do about self tests to determine battery capacity?

State of charge: fuel gauge

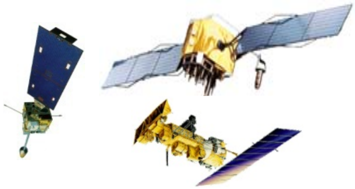
- Some battery chemistries display a flat voltage curve until capacity is reaches so measuring voltage may not work in all cases
- Alternative is to use a “fuel gauge” to mere voltage measurement- keeps track of current into and out of battery and indicates state of charge by integrating current over time
- Requirements
  - Operation over full temp range
  - Automatic reduction in capacity with age and temperature history
  - Doesn’t require user calibration
  - Remaining capacity: how much transmit time is left
- One possibility is to use something equivalent to the Texas Instruments (TI) BQ 27000 although it is not yet clear if it satisfies all of the above criteria. These questions forwarded to TI technical support but no response yet.
- Issue is whether industry products will be of use to SAR

State of charge: the charger

- **Requirements**
  - Stopping charging when battery is at full capacity to prevent overcharging
  - Indicating to the user when charger cannot charge the battery
  - Charger fault
  - Battery fault

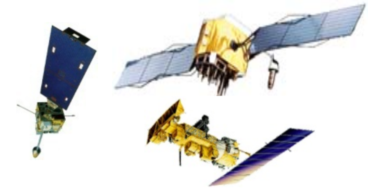
Battery Safety Factor

- JC-23/5/7 proposes to use the existing safety factor of 1.65 for rechargeable batteries.
- The original factor appears in C/S T001 Annex A.2.3 item iv. to address the following:
- 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.
  - Item (ii) is the average current drain resulting from constant operation of the circuits powered by the beacon prior to beacon activation over the rated life of the battery pack and
  - item (iii) refers to 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). Not clear if the original battery safety factor applies to re-chargeable batteries as well or how irreversible capacity loss affects the number
- Not clear if the original battery safety factor applies to re-chargeable batteries as well or how irreversible capacity loss affects the number
- Not clear, considering the temperature issues previous raised, if 1.65 is the best number to use
- Efforts to get original studies concerning how the safety factor was established to date unsuccessful
- Recommend testing and further analysis to establish the proper safety factor



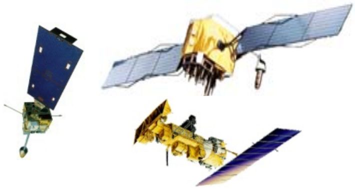
Suggested Testing

- Since SAR has a unique application and existing tests may not be that applicable , SAR needs to do testing
- Run tests of various Lithium Ion battery chemistries at various constant and cycling temperatures to develop a data base on the performance of Li Ion batteries in SAR applications.
- Any combination of cathode, anode and electrolyte chemistry that is likely to be chosen by a beacon manufacturer to be used in a beacon is a candidate for this study. The typical pulsed load of a beacon should be used in determining capacity.
  - Both constant and cycling temperatures for the long term storage parameter should be used.
  - Different beacon activation temperatures from -40^{o}C to +55^{o}C should be used.
  - Measurements of the internal resistance of the battery should be undertaken for later analysis.
- Full life testing at each temperature should be used, so this set of tests many take 2 - 3 years to accomplish.
- The test capacity should be over a temperature cycling range and storage times and final discharge at -40^{o}C, -20^{o}C , 0^{o}C and +20^{o}C and +40^{o} C.
- Get real battery experts involved!



Suggested Analysis

- Study the database of testing results to determine what battery lifetimes are achievable with the existing battery technology and whether accelerated testing is possible
- Study the requirements of a charger, including what fidelity of self tests and/or diagnostic tests should be made requirements
- Study what requirements are needed to indicate the battery condition. Should the SOC indicator be a “fuel gauge” as indicated in this paper or as part of a self test as proposed in the 2009 French paper. The study should include operational impacts on the system from the projected population of beacons doing self tests to ascertain the battery state of charge condition.
- Study whether operation above +55^{o}C and storage above +70^{o}C should be required for beacons that operate in hot desert climates. Perhaps a new type or category of beacon is needed for the hot temperature regions.
- Analyze the data base to ascertain what re-charge requirements and how best to pass that information onto the user, whether it be by a placard attached to the beacon, some automatic calculation of the beacon of its re-charge time or some other means.



Final Thoughts

- Use of Li Ion batteries for Search and Rescue applications is a complicated subject; The efforts to date have not treated the subject in a comprehensive way and the SAR community has no understanding of the use of Li Ion batteries in distress beacons
  - How to determine recharge interval ?
  - What are the High temperature and temperature cycling effects on SAR use, especially at low temperature use
  - Can the Arrhenius equation be made applicable to reduce lifetime testing batteries? Or do we have to use full life time testing?
  - What is the Operational impact of increased number of self tests to determine state of battery charge?
  - Is the current 1.65 safety factor is applicable to rechargeable batteries?
  - What about a Battery fuel gauge and charger requirements?
- We need to do our own testing to generate data specific to SAR applications
- Experts couldn’t understand why SAR wanted to use rechargeable batteries in our application.
  - Universal recommendation was to stick with primary batteries.
  - Our use does not maximize the best features of Li Ion batteries
- Testing program will be expensive in terms of time and money
- The LIRB type approval procedure should be suspended