

Operational experience with Nickel Hydrogen and Lithium–Ion batteries

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In this work we discuss about the two widely used energy storage systems in space applications namely, Lithium–Ion (Li–Ion) and Nickel Hydrogen (NiH₂) batteries. A few of the satellite missions operated by the German Space Operations Centre (GSOC) is used in this work for case study.

The NiH₂ batteries have been a part of energy storage applications for over two decades and have a very good track record for their reliability and performance. These batteries are still one of the much preferred energy storage system for satellites. The TET–1 (called as "Technologie Erprobungs Träger" in German) was launched in 2012 is among the newer generation of satellites which is powered by NiH₂ batteries. Even after having experienced some problems shortly before launch, the batteries are performing excellently. We have discussed some of those issues and their solutions.

The use of Li–Ion chemistry in satellites is quite new but over the last decade has proved its reliability in several deep-space as well as low earth orbit missions operated by various space agencies worldwide. The operational experiences of the satellites TerraSAR–X (TSX, launched 2008) and TanDEM–X (TDX, launched 2010) are discussed to demonstrate the capabilities of the Li–Ion batteries. Although, the NiH₂ chemistry is still widely used, our operational experience shows that the Li–Ion technology might power the majority of future spacecrafts.

I. Introduction

ENERGY storage is currently the most widely discussed topic among the satellite manufacturers and space mission designers. The ever increasing demand for new areas of application drive the development of new instruments which can perform complex operations. Such instruments end up being power hungry and demand a better power source. Early days of space race fuelled the need for a robust energy storage and delivery system. The nickel–cadmium batteries pioneered the generation of high energy batteries in space application and was soon replaced by the nickel–hydrogen chemistry. Even today the NiH₂ batteries are widely regarded for their reliability and robustness. These are environment friendlier, more robust and resilient to operational damages such as over charging and deep discharging. The NiH₂ batteries retained some of the drawbacks like the "memory effect", bulky construction of the NiCd era. The other drawback of this battery chemistry lies in its construction, it is bulky and occupies considerable amount of space. In spite of its drawbacks it is still used in several missions.

Over the years, the rising launch costs and increased complexity of satellites have created the need for a more compact battery that can provide high power and at the same time occupy very less volume of space. The shrinking of computers and instruments has put a significant influence on battery manufacturers to try and find new chemistries which occupy less space, weigh less and at the same time deliver more power. The Li–Ion batteries are very efficient and compact in terms of volume and posses high power to weight ratio. The specific energy of lithium-ion batteries is between 85 - 130 W–h/kg. They do not suffer from any memory effect and have a modular design. The construction of a Li–Ion cell is also very flexible. This allows the satellite system designers to be able to accommodate more instruments on board and thereby increase the usability of a satellite. The high specific energy of Li–Ion batteries allow more powerful instruments to be flown. The cells are sensitive to over charging as well as to over discharging. Hence, any excess heat generated during charging can easily damage the cell.

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II. Nickel–Hydrogen Operations

There were several missions flown at GSOC powered by NiH_2 batteries and this section discusses in detail about the operational experiences from the recent TET-1 satellite. Regarded as one of the robust battery chemistry it has powered several German satellite missions such as CHAMP and BIRD. The GRACE satellites that are powered by NiH_2 batteries are in operation for over 14 years generating valuable science data even today. The long term analysis of the telemetry data from GRACE has led to the understanding of a new failure mechanism⁷ in the CPV design of NiH_2 battery chemistry that was previously either unknown or was not investigated in detail. The TET-1 operations have given a good insight into several reconditioning mechanisms which could be employed to recover some of the lost capacity. The batteries in TET-1 encountered some problems prior to launch and the satellite itself had to deal with temperature issues during its early orbit phase. The problem encountered and the methods adopted to recover some of the battery cells have been discussed in the subsection B in detail.

A. TET-1 Satellite

TET-1 spacecraft was launched into a sun synchronous orbit with an LTAN of 11:27 UTC. It is built based on the BIRD bus. Similar to BIRD, the TET has two solar panels on the $\pm X$ -side that are deployed using pyros after separation. The third panel is mounted directly on the body of the satellite such that when the side panels are deployed, all three panels are in the same plane facing the sun. In total; the panel has 17 strings plus one payload solar panel string. The spacecraft is flown with its solar panels pointing towards the sun internally known as Sun-Pointing Fix Mode (SPFM).

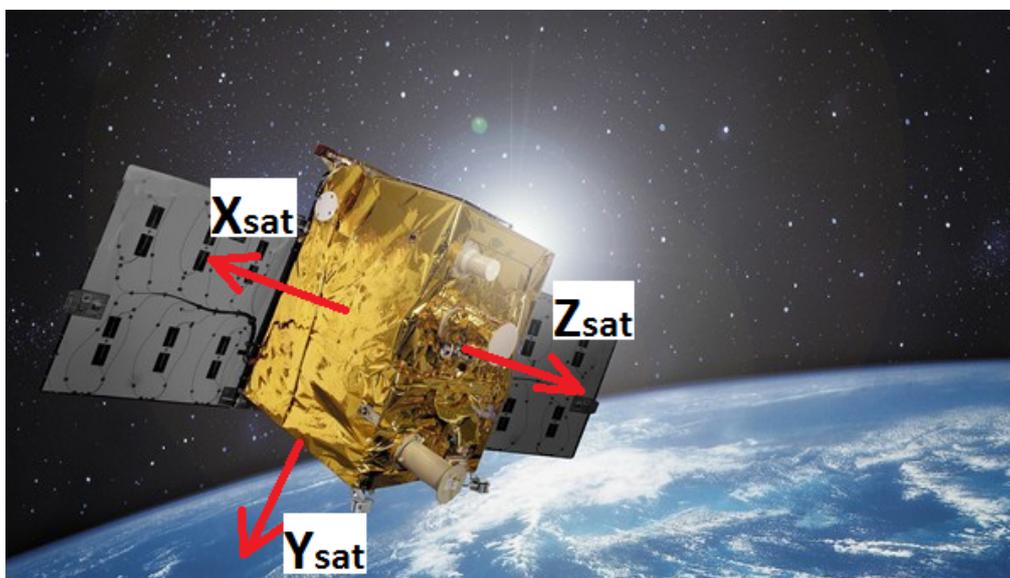


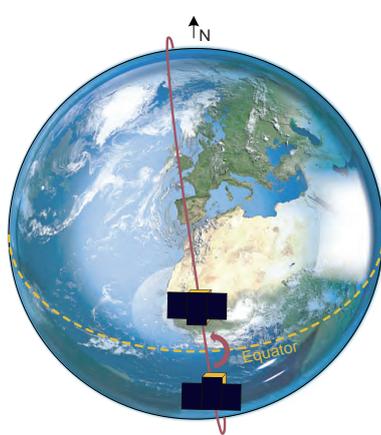
Figure 1: TET-1 Satellite with solar panels deployed

A 12 Ah (name-plate capacity) NiH_2 battery with eight CPVs of type RNHC-12-3 made by Eagle-Picher industries augment the solar panels. The batteries are used during eclipses and during payload operations. The charge of the battery is monitored and regulated by a charge controller. All the solar panel strings including the payload string are controlled by the charge regulator. As a standard setting the middle panel with its 5 strings is never shunted. The charge of the batteries are measured via strain gauge. The charge regulator controls the amount of energy flowing into batteries by regulating the strings in the solar panels. They can be individually shunted or unshunted based on the energy requirement. Further, the temperature of the CPV measured is taken into account to calculate the calibrated charge. When the temperature of the battery is higher the energy input is reduced to avoid overcharging and to prevent a thermal runaway. The solar panels are shunted if the calibrated charge value reaches the pre-set End-of-Charge (EoC) value and the shunts are opened as soon as the charge level recedes below a certain value. The "Unshunt" level is defined by the hysteresis parameter, currently set to 98% of the calibrated charge. Temperature measurement forms an integral part of NiH_2 operations. The shunt trigger points can be individually set via ground commands. A power safe-mode of the satellite is triggered by the on-board FDIR mechanism as soon as either the voltage or the charge of the batteries drop below 18.5 V or 6 Ah respectively.

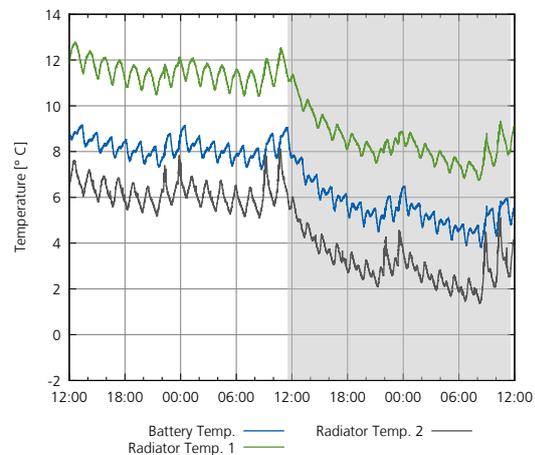
B. TET-1 Operational Issues and Solutions

The battery operations in the TET-1 satellite began facing problems before launch. Some of the cells had undergone reversal shortly prior to launch and created an imbalance within the battery packs. This resulted in increased battery temperature and as a consequence the overall temperature within the satellite increased. Further, the battery voltage was found to be slightly above the limit for payload operations. The battery temperature was always above the expected 15°C ¹¹. During ground based thermal tests the radiator area was found to be larger than necessary and was covered with MLI to reduce the effective radiation surface but during these tests, the additional heat generated via payload operations was not considered. This slightly reduced effective radiator area was found out to be the reason behind the not so efficient temperature radiation from the spacecraft. Therefore, the team worked on possible recovery procedures to prevent any further damage.

To begin with the battery temperature was reduced by charging them to a slightly lower than the nameplate capacity. This method was not used for long as it might reduce the useful capacity of the battery in the long run due to the memory effect. It could lead to the non-availability of adequate power for payload operations. Hence, a different approach was developed. This involved rotating the satellite by 30° along its Y-axis (pitch). This meant that the angle between the sun vector and solar panels is not 0° . This restricted the amount of energy generated in the panel. Along with this the payload operations were suspended for one day of every week to allow the satellite to cool down. Subsequently, the Earth-pointing mode was also sparingly used in order to keep the thermal loads within acceptable limits. The not so efficient radiator was among the driving factors that resulted in unstable battery as well as bus temperatures. Hence an attempt was made to improve its efficiency. In nominal attitude of the satellite the radiator partially sees the Earth. The albedo decreases the effectiveness of the radiator. Thus, the Sun-Pointing Rotate Mode (SPRM)^{4,5} was conceived as a solution. The orientation in this mode is similar to that of the SPFM but the spacecraft is rotated 180° about the z-axis at every equator crossing (figure 2a). The observed temperature reduction was about 4°C (figure 2b). On the downside, the SPRM restricted the view of the star cameras which in this mode were partially pointing at the Earth. Due to an IMU failure, it was decided not to use this mode unless otherwise required due to extreme thermal load situations.



(a) TET-1 SPRM Mode



(b) Temperature within TET-1 during SPRM Mode

Figure 2: TET-1 SPRM mode representation and temperatures measured when flying in this mode

In spite of all the above efforts the battery temperatures did not fall under the expected 15°C . Therefore the satellite support team decided to recondition the battery in an attempt to eliminate any imbalance within the pack. The efforts were inspired by the results of the Hubble Space Telescope (HST) battery reconditioning¹. Following the testing on the engineering model of TET satellite which displayed positive results for the reconditioning, it was decided to implement the same in the actual satellite. The EoC level was chosen as the variable and was increased by 0.2 Ah every week until the maximum capacity of 14.4 Ah was reached. Alongside the hysteresis parameter that drives the shunts was also increased from 95 to 98 percent of the EoC. The idea was to slightly overcharge the weaker cells of the battery pack so as to bring them to the same level as the healthy ones. The discharging of the batteries was done via various payload operations. This method of ratchet charging as called by the HST team, allowed the battery to reach a certain level of EoC before the payload operations begin discharging the battery

again. This discharge triggers the shunt parameter which in turn "unshunts" or opens the shunts of the solar panel strings for recharging the battery again. This second cycle of recharging runs until the batteries reach the pre-set final EoC level (figure 3).

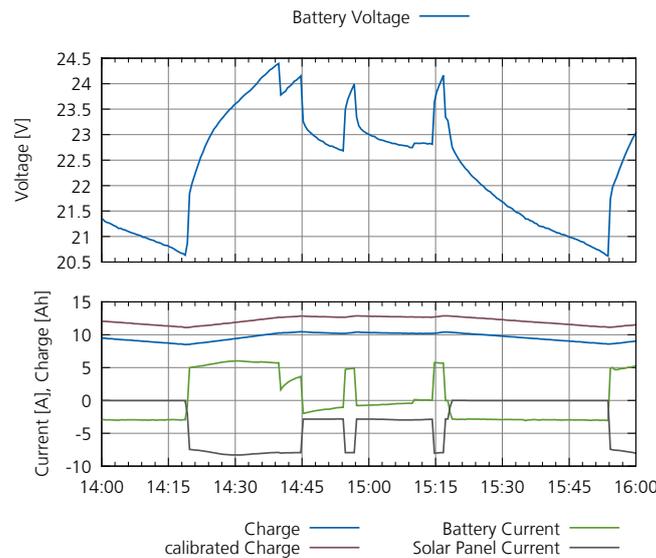


Figure 3: Example of Ratchet charging scheme employed in TET-1

As seen in figure 4, the temperature began to stabilize after a slight increase during the initial week. This gave an indication about the effectiveness of the reconditioning method and a possible recovery of the cells. The solar panel string regulation became more flexible after a software update in the first half of 2013. It is now possible to shunt or "unshunt" individual strings in the solar panels and this allowed us to fly the satellite at 0° to the sun instead of the earlier 30° pitch offset. A new shunt mask is also a part of the new software which "unshunts" all the strings during a charge cycle and shunts them on both the side panels. This allows the batteries to be trickle charged as they near their full capacity using only the energy generated by the middle panel. It ensures that the batteries are subjected to minimum damage. The charging and the discharging process of the battery management is constantly updated to keep up with the effects due to ageing. Further, a new low-high-low charge profile was considered for charging the batteries. This low-high-low method was derived from Hartley² and was tested in the form of simulations.

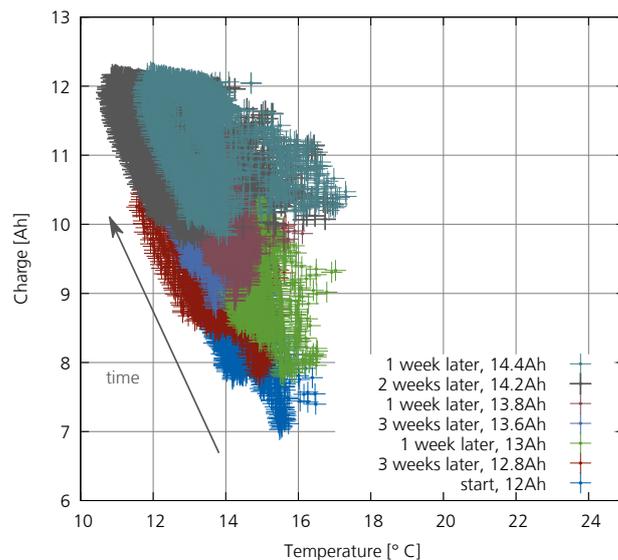


Figure 4: Results of reconditioning efforts shown via battery temperature

Although there is no noticeable positive effect, it is understood that the optimization based on this method is expected to significantly prolong the life of the batteries in the long run. It is currently not

possible to draw any conclusions on the precise condition of the batteries due to the lack of enough data but as the mission progresses it will be possible to determine the precise health state and to test this new charge scheme.

III. Li-Ion Operations

A. The TSX and TDX Twins

The lithium-ion batteries are gaining a wider acknowledgement in the field of space applications mainly based on their success in the commercial markets. The twin satellites TerraSAR-X and TanDEM-X launched in 2007 and 2010 respectively are among the first German LEO missions to be powered by Li-Ion batteries. TerraSAR-X satellite was launched into a sun synchronous orbit⁸ at an inclination of 97.4 degrees with a design life of 5 years. The TanDEM-X satellite was launched in 2010, into an orbit⁹ similar to that of TSX. Both the satellites are equipped with similar batteries and with the same nameplate capacity. The battery pack consists of cells of type Sony US 18650 HC with a cell capacity of 1.5 Ah and maximum cell voltage of 4.2 V. A robust battery management system, namely Power Control and Distribution Unit (PCDU) regulates the power supply to and from the battery. The batteries are automatically charged as soon as the voltage drops below 50.4 V. The charge controller executes the charging until the cut-off value is reached and taper charging is used thereafter.

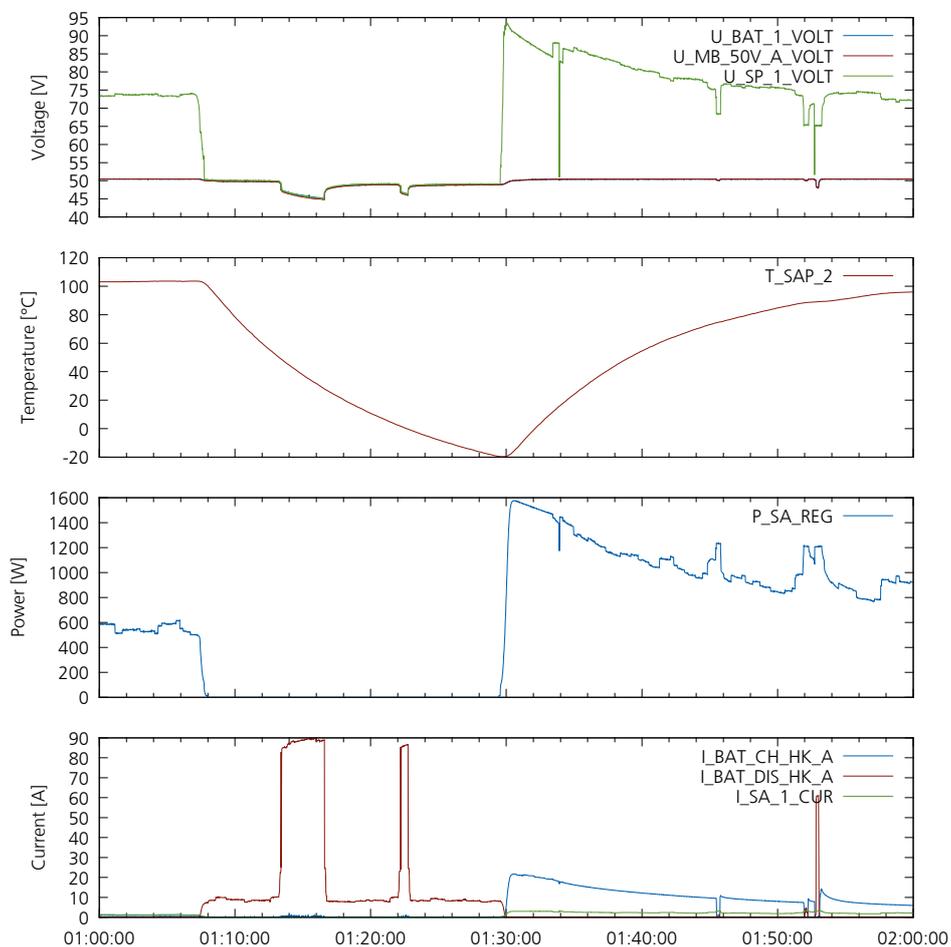


Figure 5: A typical discharge-charge cycle of TSX and TDX batteries

During sun phase the payloads and the satellite bus are entirely powered by the solar panels and the energy from the battery is used only when there is any payload operation that demands higher power than what the solar panel can generate (figure 5). Apart from payload operations the batteries are used during orbit eclipses. The sun synchronous orbit of the TSX and TDX satellites is such that the spacecrafts undergo short periods of eclipse during a particular time (April - August) in every year. The TSX mission was designed to fly for five years and it has crossed its design life without showing any sign of weakness. The capacity degradation of the TSX batteries is much lower than what was predicted

during the design phase. Presently, the capacity degradation of the TSX batteries is at about 20%. Over its lifetime, the batteries were subjected to varying depths of discharges mainly due to different payload operational modes. The maximum Depth-of-Discharge (DoD) so far is roughly 13% with an average of 4%. The mean temperature of the battery stacks is around 19°C. The batteries are expected to last for another 4 to 5 years before a real power restriction may be applicable. Since the time of its launch the TDX batteries similar to TSX have not shown any sign of weakness. The capacity degradation rates are similar to that of what TSX showed after 4 years of operations. It is therefore expected that similar to TSX, the TDX will also out live its design life. The corresponding DoD values of TDX are very similar to that of the TSX. Since one satellite more or less repeats the datatake of the other satellite, their operational power requirements are almost the same apart from a few extra payloads in TDX.

B. Battery Maintenance

As a part of satellite maintenance, every year a special datatake is carried out and the energy drain during it is used to analyse the capacity degradation of the batteries. This special datatake discharges the battery to a deeper than the usual level. The capacity fade is determined using an empirical formula¹⁰ (equation 2). The degradation is calculated relatively by comparing the change in internal resistance in the current year with that of the one from the launch year. The change in internal resistance is a direct indicator of the capacity lost because the rise in internal resistance reduces the energy available within battery. Using Ohms law, the resistance is calculated from the voltage and the current and this is used in the empirical formula to arrive at the capacity fade for the current year. The internal resistance changes when the batteries are either charged or discharged. Therefore it is necessary to calculate the difference between the voltage values at the beginning and at the end of a discharge process. The difference in currents is obtained by using the same principle. Applying Ohms law and using the voltage (difference) and current (difference) the change in internal resistance is determined. This is then used to determine the capacity fade.

$$Resistance = \frac{V}{I} * 1000 [mOhm] \quad (1)$$

$$Capacity\ fade = \left(R_{increase} * \left(\frac{15}{50} \right) \right) * 100 [\%] \quad (2)$$

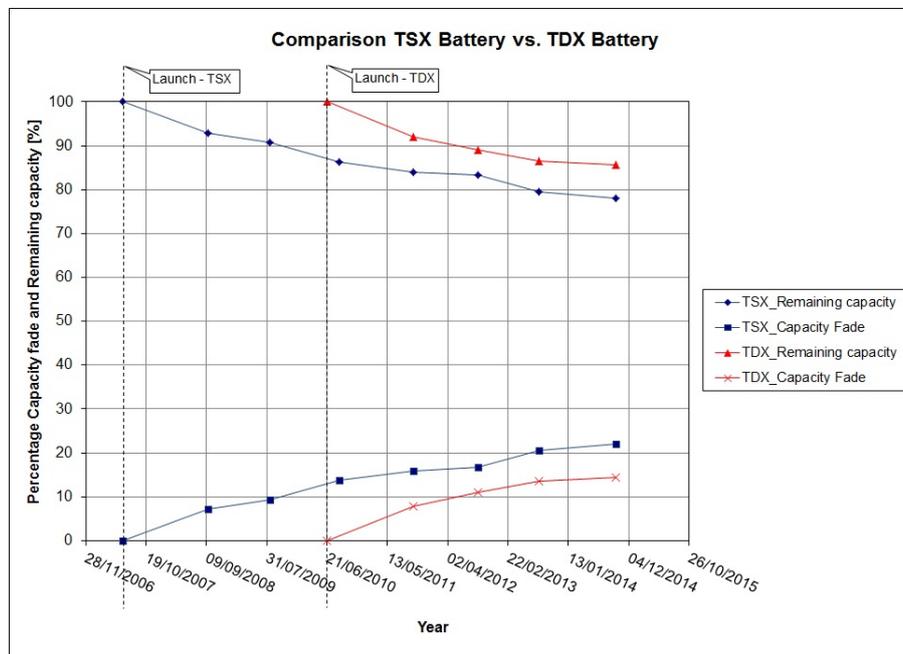


Figure 6: Capacity fade calculation results for TSX and TDX

It can be seen from the capacity fade plot (figure 6) that the degradation of batteries is following a linear path and that the two satellites are showing a similar trend. The values shown by TDX after four years of operations are more or less similar to that of the values that were seen in TSX. It is expected that the batteries in both the satellites will continue to function without any issues for another 3–4 years or until the on-board fuel is empty.

IV. Lessons Learned

A. Nickel–Hydrogen Operations

The NiH₂ is a very robust and well proven energy storage system. The major advantages and limitations are well known within the space community. Analysis of TET–1 mission has given valuable information about the importance of cell balancing and the effects of deep discharging. Further, the effect of temperature upon the batteries is now better understood. The different reconditioning methods attempted has given a learning which will be useful during EoL operations. Thus, a sum-up of the learnings about the NiH₂ is:

1. The best operating temperature for NiH₂ batteries lies in the range of 15°C
2. The CPV type NiH₂ batteries have an additional mode of failure namely electrolyte bridging, apart from the ones already known.
3. The other lesson learnt is the need for a slight overcharge to compensate for the loss due to ageing. It is necessary to correctly determine the limit upto which the batteries can be overcharged and this value varies from satellite to satellite.
4. A temperature controlled charge regulation is necessary to maintain the battery health.
5. As the batteries near their EoL, constant monitoring and accordingly resetting the charge parameters such as hysteresis and maximum charge level etc., will help prolonging their life.
6. The low-high-low charging method in theory helps in prolonging the battery life by adopting a slow start while charging i.e., using a low current at the beginning and slowly increasing it to maximum and towards the end, the charge current is again slowly reduced to a minimum. This method of charging the batteries has to be tested in future.

B. Lithium–Ion Operations

The operational experience from TSX and TDX gives a very positive impression about the Li–Ion batteries. These batteries have been powering TSX for over 7 years and the TDX for 4 years without any trouble. All along, the battery temperatures have remained between 17 and 20°C and the capacity degradation due to ageing has been linear. The increase in internal resistance has been in line with what was predicted by the battery manufacturer. So far there has not been a single incident related to the performance of the batteries. The Li–Ion batteries have been very reliable and have supported the operations whenever necessary. This kind of reliability shows that if these batteries are operated within their limits they can outlive their design life and could become the preferred high power, low weight secondary energy source for space applications.

V. Conclusion

The two different energy storage systems originating from different eras are proving their mettle in their own ways. The NiH₂ inspite of being an old technology is still performing well on-board the TET–1 and several other satellites. On the other hand, the Li–Ion technology is quickly maturing and aiming to be a suitable replacement for the NiH₂ batteries. It would be interesting to know and understand the behaviour of the Li–Ion chemistry as the batteries near their end of life. There have been several successful long term tests conducted by manufacturers and a large amount of valuable information has been gained out of them but a real test of its reliability will be in the real world operations. We know from our applications that the Li–Ion technology is very reliable and is robust and when operated under proper conditions it could be a replacement for the NiH₂ technology.

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