

Design Manufacture and Environmental Tests of Battery Pack for Spacecraft Freights

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Abstract: The satellite battery pack is one of the important and vital parts that are required conducting special design with multiple capabilities. Some parameters like the minimum weight, lack of outgassing of parts, avoiding from short-circuit in batteries inside battery pack, the possibility for making series connection in batteries, and prevention from destroying battery pack structure caused by vibrations due to displacement of missile upon launching of a satellite are included in some requirements for design and manufacture of satellite battery pack where in the present essay we will study on design and manufacture of battery pack structure by considering the above-mentioned requirements in mind. In order to determine the authenticity of design and manufacture of battery pack in real conditions for launching and vacuum conditions, several environmental test of thoroughness such as Thermal Vacuum Testing and Vibration Tests have been carried out on the manufactured structure so the results of batteries performance will be purposed within these tests. The results obtained from environmental test conducted on satellite battery pack structure suggest the fully successful and innovative achievement in design and manufacture of battery pack structure.

Keywords: Computer aid design (CAD), Design and manufacture, Satellite battery pack, Thermal vacuum testing, Vibration test.

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1 INTRODUCTION

The battery, which is used in all stages of mission including launching, climbing, and stationing on the given orbit, will be exposed to the severe mechanical shocks such as vibration and other mechanical stresses. Mechanical design for this pack should be rendered in such a way that the pack retain its solidarity throughout all steps and no problem might encounter within its performance. Mechanical design should be implemented by considering type of shuttle, satellite design, location of battery and the predicted vibrations in battery. Today, rechargeable chemical batteries may play noticeable role in supply electrical power within various industrial and military uses. Safety at high level, long use life and appropriate voltage profile are some of advantages of these energy resources. The existing chemical batteries are found in several sizes with different capacities in marketplace and they are used widely as energy storages in photovoltaic systems at satellites. To conduct research in this respect, batteries should be studied first under the given conditions. For this purpose, it requires considering some factors including discharge current, battery operation time, the needed voltage, maximum and minimum tolerable voltage, charging techniques (fixed current or current), and batteries operation temperature. We may identify the given battery for certain use after considering all of aforesaid conditions. Rechargeable batteries along with charger and discharger are tasked with energy storage and supply the needed power of loading at orbit- night and also at peak load during orbit- day.

2 SATELLITE BATTERY

Today rechargeable chemical batteries play a remarkable role in supply electrical energy for different industrial and military applications. Safety at high level, long use life and appropriate voltage profile are some of advantages for these energy resources. The existing chemical batteries are found in different sizes with various capacities in marketplace and they are widely used as energy storages in photovoltaic systems for satellites. To conduct study on this subject, initially the conditions of batteries should be taken into consideration. For this purpose, it needs to examine discharge current, battery operation time, the needed voltage, minimum and maximum tolerable voltage, charging techniques (fixed current or voltage) and batteries operation temperature. We could characterize the battery in certain application after considering the aforesaid conditions. Interior wiring systems should be arranged so that the voltage loss to be minimized in design of battery pack.

In addition to above points, subject of isolation should be noticed as well. The connections should be installed in such a way that voltages to be completely separated from each other at different levels and the interval between them to be observed (Fig. 1). If there is a little distance between different levels of voltage then the needed isolators should

be used to separate them. Kapton tape (film) may be utilized for isolation of battery cells from each other. The needed connectors for the total pack with the external circuits should be considered in mind. The connection should be installed in such a way that it would not be subjected to corrosion and rising the resistance among connectors. In fact, all of used cases for this purpose should be complied with the environmental conditions of performance in batteries [3].

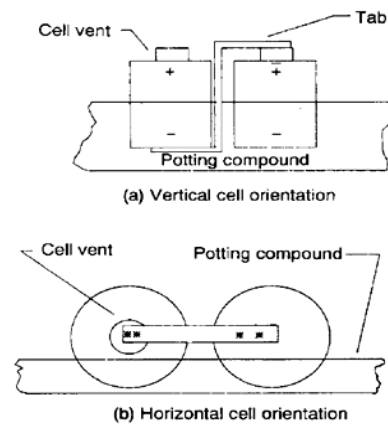


Fig. 1 A sample of connection in battery cells

3 DESIGN REQUIREMENT

With respect to the importance of battery pack in satellite, design of battery pack structure should be rendered in such a way to meet all the existing requirements. If we like to refer to some cases in respective of these requirements, we may express them as follows.

1. The minimum weight in design of battery pack structure
2. Lack of outgassing in parts of battery pack structure
3. Ability for thermal exchange between batteries that are related to arrangement of batteries
4. Resistance against the exerted vibration and shocks upon launching from missile
5. Higher thermal resistance and lack of inflammation
6. Operational ability at temperature (20-70°C)

4 PACK MECHANICAL DESIGN

Design of battery pack includes juxtaposition of electrochemical cells in series and in parallel in order to obtain the given voltage and capacity. This battery comprises of some cells in- series or in parallel, a case, connectors, sensors, interior wirings, thermal components, electronic shields and circuits. First of all, an appropriate shape should be taken for the pack. Battery cells should be put together in such a way that the need to interior connections to be minimized. To fix the battery cells, some materials may be used like epoxy, foam, bitumen or other

substances. This point should be considered in application of such materials that ventilation system of these cells (gas discharge chamber, if the pressure rises) not to be blocked. Moreover, an appropriate case may be utilized for mechanical stabilizing of battery. In all above stages, some points should be considered such as chemical compliance between the used materials, their flammability, and lack of blocking vent system. It requires noting that the used materials may be utilized within mission environment and they are not subjected to corrosion or evaporation in vacuum or any other possible problems.

The needed spacing should be allocated for expansion of battery and also they should be designed in such a manner that they be fixed at their place when the given cell has the least volume in charge at the low level. Furthermore, it necessitates that connecting wires not to be drawn. Another noticeable point is the possible leakage in electrolyte during operation. Design should be rendered in such a manner that no problem occurs in this regard. For instance, it should be avoided from insertion of administration board on inappropriate location. Alternately, given that battery is deemed as one of sources for Electro-Magnetic Interference (EMI), so mechanical pack structure should be installed in such a way that to prevent from exiting these waves [2].

5 PACKS DESIGNED FOR SATELLITE

With respect to necessity to benefitting from an appropriate design for battery pack, several designs were suggested for installation of battery cells in this structure. At first design, a metallic box was taken with ten batteries that were put together in five rows with four cells. Any row is placed between two metallic belts and these belts are fastened by a bolt. Two series of belt are considered per row. Batteries are connected via welded tabs to both ends of batteries. Since belts have sharp edges and they may scratch batteries cases and their connector, adhesive was used for primary sample. This problem reflects the necessity for isolation of battery pack structures.

The main problem in this design was not to be able to manufacture this part with the needed accuracy. On the other hand, very high pressure was exerted to batteries after fastening the belts so the batteries were damaged. Also thermal sensors included two sensors for telemetry and one sensor for charging and they were attached to batteries by adhesive. Since the given design might not meet the battery requirements, another design was offered for battery pack. Batteries are installed circularly together in the suggested design. Two isolated plates, which were made of poly-tetrafluoro-ethylene (PTFE), are placed at the top and bottom of batteries. PTFE is the trade name for well-known Teflon and it is dark substance that is resistant thermally up to temperature 260°C and possesses a very small friction coefficient and it is totally resistant against chemical corrosive factors. There are some holes on these plates for installation of battery. Batteries are connected together by tabs. There is a groove to pass tabs among a pair of holes.

Finally, a metallic cylinder encompasses pack. With respect to isolation of body in this design, the problem of short-circuiting will be alleviated between batteries. Alternatively, two plates form through fastening by bolt and consequently the strength of pack is met without exertion of pressure on battery cells.

Battery connector is also located within cells thereby saves the space. On the other hand, tabs are not exposed to body of battery by creation of grooves within passage of tabs. Thermal sensors, which include a temperature sensor for telemetry and another sensor for charger, are placed at a suitable location. Telemetric temperature sensor is placed through the grooves between two batteries. Alternately, given that the connector wires to sensor are placed at its ends therefore pressure of these wires and body of batteries may retain sensor at the given place. Through soldering to negative tab of total pack, charger sensor is fixed on its location.

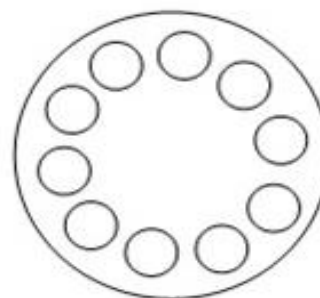


Fig. 2 A schematic of battery rack in a circular pack

6 DESIGN OF COMPONENTS OF SATELLITE BATTERY PACK

The final design for battery pack structure is shown in Fig. 3-a. Part no 1 from Fig. 3-a is cylindrical case made of aluminum in which the rack parts and battery system is placed there. To set electrical connection between group of batteries with charger and other fed components, the upper section of cylindrical case is allocated to installation of two connectors. Part no 2 is made of PTFE that was rather designed for holding batteries by creation of some grooves, which might provide electrical connections between batteries. The upper rack part (part no 2) is placed inside cylindrical case in sliding form and since battery pack is suspended within main structure of satellite, part no 2 should be installed in such a way that it can damped vibration effects upon launching it by missile and to convey the minimum vibration to batteries. Part no 3 shows satellite batteries about of which some issues were explained in details at above. Part no 4 is the lower rack of batteries system that has been selected from PTFE in terms of thermal conduction and electrical isolation properties. Vibration Non- Destructive Test (NDT) for satellite battery pack to review its performance upon launching it by shuttle was done.

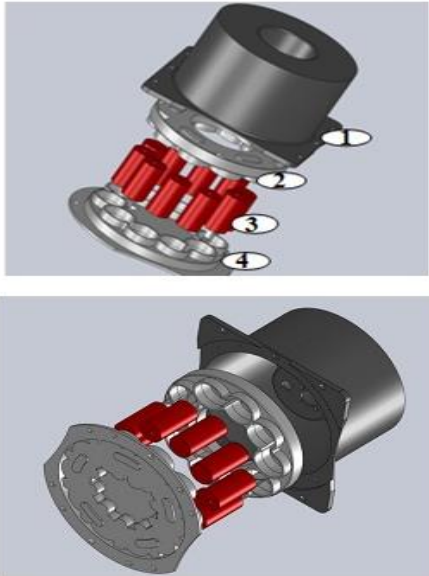


Fig. 3 (a) Explosive view of elements in battery pack

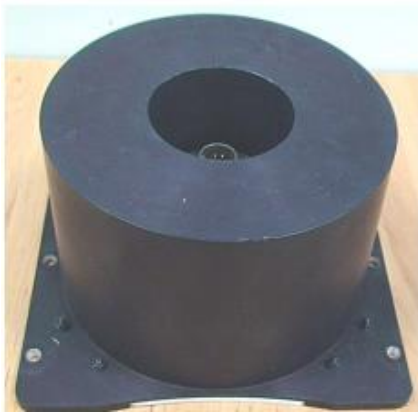


Fig. 3 (b) View of the assembled structure of battery pack

Due to its noticeable weight, a battery pack may be always damaged against vibration and shocks caused by launching while it leads to short-circuiting risk, therefore in order to confirm the correct design of vibration mode and to guarantee successful performance of battery in a satellite during a mission, especially upon launching by a shuttle, battery should be examined by land-borne vibration tests. Conducting vibration tests successfully may increase safety level in success of spacecraft mission. We will examine performance test of battery pack under some conditions like acceleration and upon launching moment by a shuttle. Design of vibration and shock test is based on spatial standards like ECSS-E-10-03A and ECSS-Q-70-02A [5]. In this test, rather than establishing some standards at the level of spatial standards, we might present performance of spatial part of a battery pack at the higher accuracy rate. The results of vibration test are deemed as an effective empirical parameter on providing appropriate vibration modes in design of satellite structure.

7 SINUSOIDAL TEST

In Sine test, satellite is exposed to a sinusoidal stimulation which sweeps throughout a frequency band and or it is fixed on a certain frequency band. Sweeping rate for a sinusoidal motion may be linear so that here it is expressed as Hz per second and or it may be logarithmic, which is usually characterized as octave per minute. 1 unit change in octave denotes doubling of frequency and or bisection of frequency as the fluctuations increase. Amplitude of sine sweeps is generally a function of frequency and it is characterized by unites of acceleration, velocity, displacement and or a combination of these components. Sinusoidal testing is useful for determination of the effects of response conditions as well as simulation of the environments that include frequency segments with narrow bandwidth. In general, compared with random test, this test is at the second place in terms of importance while it needs to a frequency spectrum with bandwidth for stimulation. Sine test is intended to insure that the parts are able to tolerate against low frequency stimulations exerted by shuttle on the given structure. In sine testing, parts are exposed to sinusoidal stimulation that sweeps throughout a frequency band 5-100Hz. Sweeping rate may be linear for a sine motion where it is expressed as Hz per second and it might be logarithmic that is identified as octave per second as usual. According to ECSS standard, sweeping rate is 2 octave. This test is done at all three axes of part and during 2 minutes for each of axes. Fig. 6 indicates vibration test results that were received by a tri-directional sensor.

8 TESTING DESCRIPTION

Prior to test startup, initially functional test is carried out on the part. To find natural frequency within the range of 5-2000Hz, vibration test is done based on Table 1 after functional test. According to ECSS standard, sine testing is done for the parts lighter than 50kg with frequency 100Hz according to Table 2.

Table 1 Trend of determination of natural frequencies

Frequency	Level	Sweep Rate
(5-2000) Hz	0.5g	2 octave per minute

Table 2 Sine testing frequencies according to ECSS standard in testing of satellite parts

Frequency	Level	Remarks
(5-2000) Hz	11 mm (0-peak)	No notching
(21-60) Hz	20g (0-peak)	
(60-100) Hz	6g (0-peak)	

Finally functional test should be done after any sine testing on the given work piece.

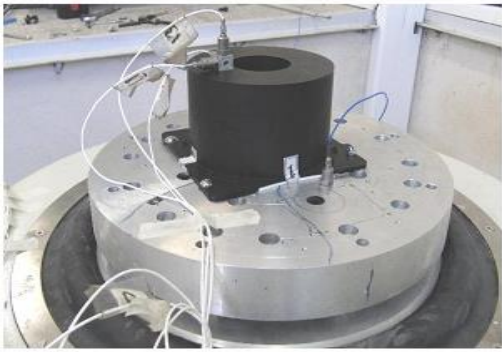


Fig. 4 Manual vibration device during test of satellite battery pack



Fig. 5 Tri- directional vibration sensor random test on a satellite battery pack

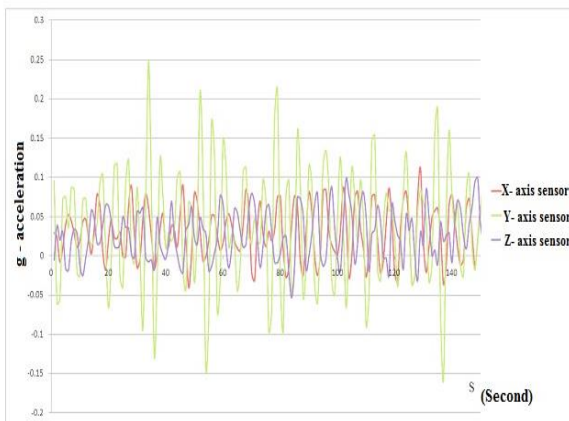


Fig. 6 Results of sine vibration test in satellite battery

9 SHOCK TEST

To simulate the effects of phenomena with high amplitude within short time such as strokes, explosion of ignition device (an effect that causes satellite to be detached from shuttle with explosion and combustion), and transient test is applied to create shockwaves via sounds etc. Separation stage, which is done by ignition devices, is deemed as a general form and typically as the foremost effect of the

shock. Waveforms that are used for transient test generally are divided into three groups: classic waveform, combined shock- spectrum, and transient fields.

Classic waveforms include semi- sinusoidal waveforms, sawtooth waves, square waves, and triangle waves. Amplitude and time of this waveform are controlled to find the given response. Shock spectrum wave is purposed to express certain spectrum. This spectrum is derived from non- algebraic sum within short times such as damped sine curves that are related to different frequencies. Dampening, amplitudes, start point and primary dampening point are adjusted in these compositions to obtain spectrum response for the given shock spectrum. Formation of this transient wave requires operator’s skill at high level. Waveform of shock spectrum generally presents more realistic simulation from transient events in real environment rather than rendering them with classic strokes.

Transient fields are temporary effects which are recorded during satellite operation in its natural environment and they are used as input or source of waveform. This method may be seemed as the optimal approximation for transient test but it is suffering from some shortfalls. There are no field data in general and operational transient effect typically has disorder at high level. No single transient effect may denote throughout field environment statistically. To derive reasonable information for this test, it needs many sensors for measurement and several statistical mean valuations are done to obtain a variance curve to denote this test. Whenever a shock spectrum is determined, it could be used as test criterion. Usually, diagrams of shock spectrum are characterized as Gs (gravitational acceleration) based on frequency on a graph.

Shock test should be carried out at all three axes of the work piece separately. This test is done within certain period of time and frequency limit 0-400Hz. The stimulation is exerted as a half of sinusoidal pulse within time limit 0.5ms with maximum 200g in shock test. Shock test should be conducted based on ECSS in diagram of Fig. 7.

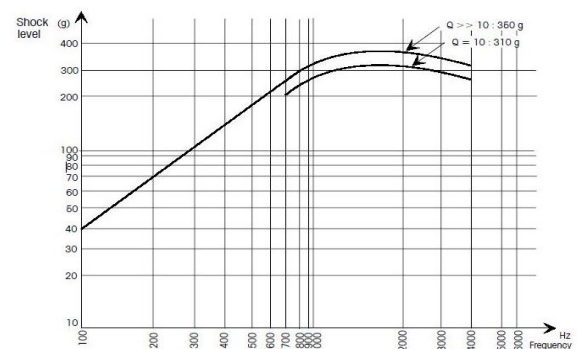


Fig. 7 Shock spectrum based on ECSS standard to conduct

10 VIBRATION RANDOM TEST

Vibration random test is carried out in satellite to stimulate in all frequencies with bandwidth 1 that are ranged typically

from 20 to 2000Hz and considered in this limit. Energy is controlled in any frequency at certain level. In general, random vibrations present the best simulation in real environment and they are considered as main tests.

No one could stimulate all frequencies in a single bandwidth in practice since there are not many natural frequencies in that band. For this reason, conducting random test on bandwidth of a line (filter bandwidth) depends on ability of controlling vibration and operator’s skill in this system. Amplitude levels are naturally expressed by unit G^2/Hz (where G is the acceleration that is given to the fluctuating object). Hz values are placed within the limit of filter bandwidth. Random test is done to achieve the tolerability in work piece against random stimulations exerted by shuttle. Random test is carried out in all three axes of part within the limit 5-2000Hz.

11 DESCRIPTION OF VIBRATIONS RANDOM TESTS

Functional test is done on work piece before starting any test on it. At the next step, random test is rendered to find natural frequency within range of 5- 2000Hz based on Table 3. According to ECSS, random test is done for two minutes and functional test after random test. Fig. 8 shows the test results for vibration random tests by means of tri-directional sensor during the recorded test.

Table 3 The Random test level

Frequency	Level	Sweep Rate
(5-2000) Hz	0.5g	2 octave per minute

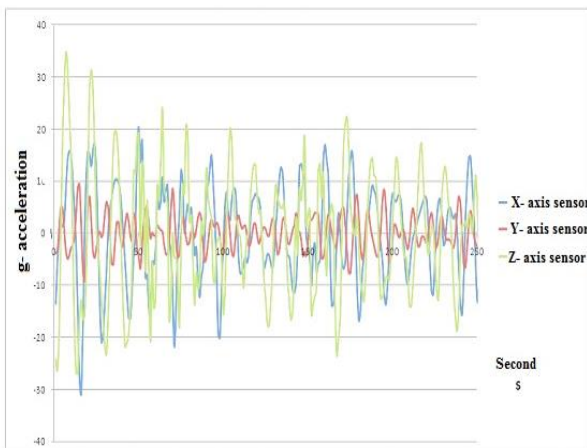


Fig. 8 Results from vibration random test in satellite battery

12 TEST RESULTS

Results of test are divided into two functional results before and after vibration test. Since BT main function included two states of charging and discharging, these two functions in the board are examined. Functional test of battery charging is done before transfer of a battery to vibration test

and charging curve is given in Fig. 9. The given results show that battery may indicate its natural behavior before vibration test.

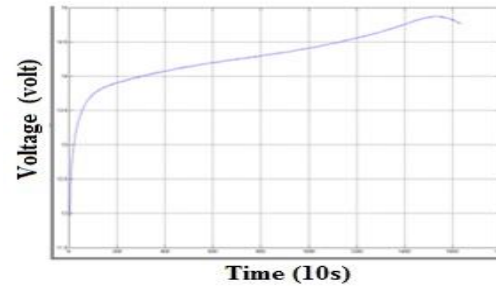


Fig. 9 Charging curve in a sample flight battery before doing vibration test

After doing vibration test and exertion of mechanical stress on group of boxes and batteries, functional test has been carried out on batteries one again so charging curve is given in Fig. 10.

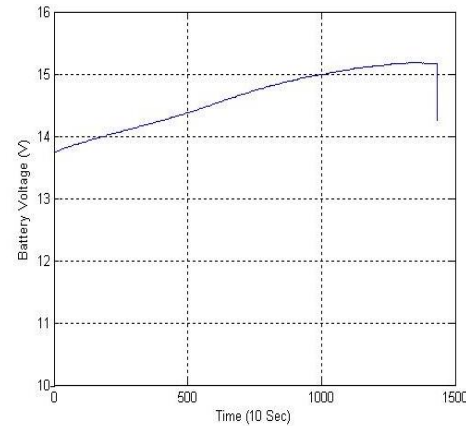


Fig. 10 Charging curve for a typical flight battery pack after vibration test

The functional test results after vibration test approve proper performance of a battery after vibration test. In other words, the given battery passed successfully the vibration test. With respect to the results of functional tests before and after vibration test, it is identified that satellite battery may tolerate mechanical stresses and its performance is also appropriate after exertion of vibration test conditions. It seems that a little deflection occurred in charging curve but this variance may be due to lack of identical conditions in batteries and thus primary voltage of batteries. It is because of this fact that chemical batteries have non- linear behavior and such a behavior depends on initial point.

13 NON- DESTRUCTIVE TEST ON THERMAL VACUUM CYCLE IN SATELLITE BATTERY PACK

Test mechanism and thermal vacuum cycle test- the tested sample is a satellite battery. Battery structure is made of aluminum with anodized surface and performance of the

battery is evaluated with existing standards before starting the test; at the next step, a vacuum chamber is used for conducting vacuum test and thermal cycle test simultaneously where trend of cycle is similar in both of these tests; however, with respect to less number of cycle in vacuum test in comparison with thermal cycle, number of the given cycle should be controlled to verify these two tests. Work piece is placed inside vacuum chamber with controlled environment in terms of temperature.

Table 4 Permitted temperature limit of a battery for vacuum test

	Property	Quantity	Unit	Test Standard (Reference)
1	Vacuum pressure	$1 * 10^{-3}$ ($7.7 * 10^{-5}$)	Pa (Torr)	ECSS-E-10-03A & MIL1540B
2	Number of cycle	4	Time	ECSS-E-10-03A & MIL1540B
3	tE- time	2	Hour(s)	ECSS-E-10-03A & MIL1540B
4	Temperature variance rate	1 degree per minute	°C/min	ECSS-E-10-03A & MIL1540B
5	Temperature stability criterion	Fluctuation less than 1 degree per hour	°C/hr	ECSS-E-10-03A & MIL1540B
6	Minimum temperature of part throughout circuit	°C+1	°C	Thermal Analyses
7	Maximum temperature of part throughout circuit	°C+14	°C	Thermal Analyses
8	Maximum test temperature at shutdown	°C +39	°C	ECSS-E-10-03A & MIL1540B
9	Minimum test temperature at shutdown	°C+ 24	°C	ECSS-E-10-03A & MIL1540B
10	General temperature-high performance	°C + 29	°C	ECSS-E-10-03A & MIL1540B
11	General temperature-low performance	°C - 14	°C	ECSS-E-10-03A & MIL1540B

Temperature should be controlled, measured and selected so that experimental results are identical to the minimum and maximum temperature which is appropriate based on Quality Control with a secure margin for that purpose. Diagrams of thermal and vacuum cycles are given in Fig. 11-a & b. As it seen in this figure, numbers of cycles as well as the permitted points were identified in functional test. At next step, the covered page was subjected to vacuum test with 10^{-5} Pa pressure based on special thermal cycle for 36 hours. Table 4 presents the exerted conditions in thermal cycle in a battery. As it is shown in Table 4, with respect to Spatial standards diagram of thermal vacuum cycle was

extracted and the results of thermal cycle in 10^{-5} Pa pressure were shown in Diagram of Fig. 11-b after exposure to test standard conditions.

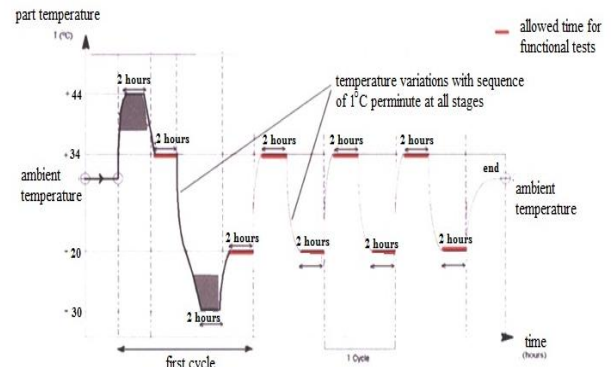


Fig. 11 (a) Trend of thermal cycle test for spatial testing

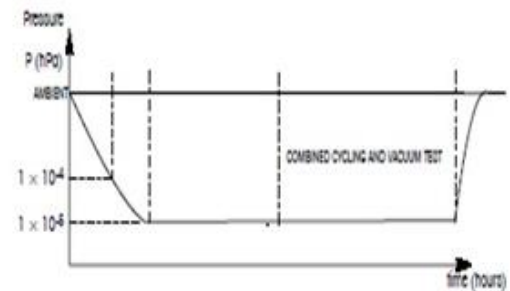


Fig. 11 (b) Trend of vacuum test for spatial testing

Thermal vacuum chamber includes number of thermal sensors, which have been arranged at appropriate place with respect to importance of their situation. An hour elapsed until the level of vacuum chamber reached to the given pressure. According to standard of reference sensor based on which we adjust trend of temperature in thermal vacuum cycle, it should be placed on the panel and the closest point to the given part as possible. Heating trend for the given part is to turn on xenon bulbs so that this is done automatically by purposing an appropriate software program for this task.

Often it requires that both ends of tested work piece to be undergone different temperatures in vacuum chamber then these settings will be done by notation of codes again. As it is given in Table 4, we use nitrogen gas to create temperature below zero. By controlling output discharge and the needed calculation of below zero (cryogenic) temperature for us, nitrogen may provide us the necessary temperature as it needs.

As it is presented here, panel (table) temperature is thermal control reference so that the derived results from panel control inside thermal vacuum chamber are given in Fig. 12. One of the other sensors that are placed on work

piece and it shows different temperature from the table with respect to height of work piece than in this panel might be seen in results of Fig. 13. With respect to thermal cycle test standard, vacuum conditions should be exerted with pressure level 10^{-5} Pa that is given in pressure-to-time graph in Fig. 14.

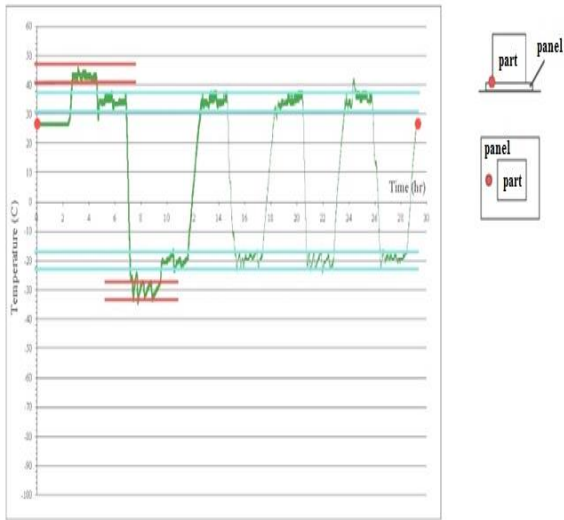


Fig. 12 Diagram of ambient temperature test

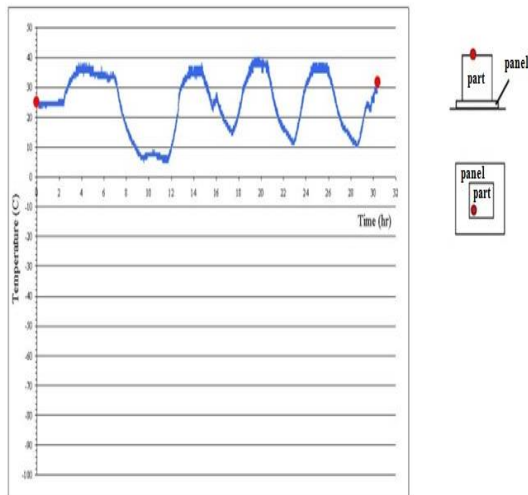


Fig. 13 Diagram of sample temperature

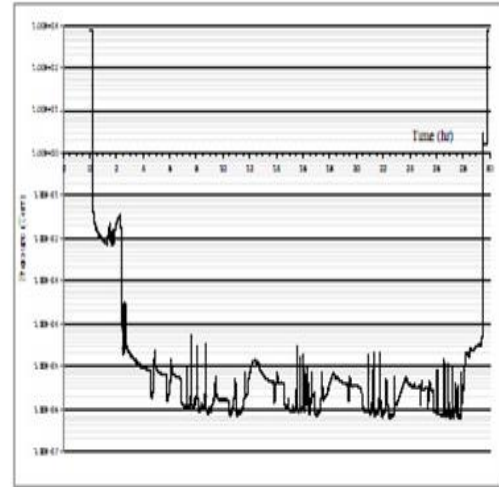


Fig. 14 Diagram of ambient pressure test

14 CONCLUSION

Since satellite battery pack acts entirely as energy feeder for the satellite, it is very crucially important. Design of a battery pack was done by considering all of the requirements and it was made at highest level of accuracy and several vibration and thermal vacuum tests were carried out in order to determine the authenticity of design and manufacture of this structure in satellite. As it was observed in test results, this structure can meet all requirements for maintenance of batteries with vacuum pressure of 10^{-5} torr under conditions of launching vibrations and through the space.

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