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Development, Installation, Performance Testing and Commissioning of Temperature Control and Data Acquisition System (TCDAS) for 4.0metre Thermal Vacuum Chamber

Ramachandra[a*], Ganesh Kumar[b], Kanaka Mohana Rao Yerra[c], S.Sathish Kumar[d], K.B. Kannan[e], G.V.Hegde[f], Govindan.P[g], S.N.Prakash[h], Dr.N.K.Misra[i]

[a, b, c, d, e, f, g, h, i] *ISRO Satellite Centre, Bangalore-17, India.*
rama@isac.gov.in[a],ganesh@isac.gov.in[b],kmrao@isac.gov.in[c],sathishs@isac.gov.in[d],kbkannan@isac.gov.in[e], gvhegde@isac.gov.in[f],govindan@isac.gov.in[g],sprakash@isac.gov.in[h],nkmisra@isac.gov.in[i]

Abstract:
***Objective**:Thermal Vacuum test is mandatory to validate space-worthiness and functional performance of Spacecrafts and its subsystems. This test runs continuously for days requiring monitoring of a large number of facility health parameters with fast update rate for its accurate, uninterrupted and reliable operation. Recent augmentation of existing auxiliary shroud in 4.0m thermal vacuum chamber calls for minimum 240 numbers of Control & acquisition channels. As the present control and data acquisition system in 4.0m thermal vacuum chamber supports only upto 160 channels, a new Temperature Control and Data Acquisition System (TCDAS) capable of supporting upto 240 channels has been designed, developed and realized.*
***Methods:** An averaging technique is employed in the PID control loop, for shroud and package temperature control within ±5◦C and for reduced LN_2 consumption during cold cycle. If the temperature on any thermocouple on the package exceeds 5% of the set temperature, then it is detected by the program and all corresponding heaters & solenoid valves will be automatically enabled/disabled.*
***Findings:** This TCDAS offers several advantages including user-friendly operation with minimal human intervention, high reliability with hot redundancy, trend graphs, fault annunciation alarms, status indication, real time data plotting & offline data retrieval facility. The system is also designed for fully automatic as well as manual mode of temperature control operation.*
***Application/Improvements:** In conjunction with new TCDAS incorporation in 4.0m thermovac chamber, all the existing solenoid valves were replaced by Cryogenic Electro Pneumatic transducer Valves (EPT) to facilitate accurate control of test article temperature & better temperature uniformity. This in turn, reduced the LN_2 consumption significantly. A novel control technique has been incorporated under the new system which allows only optimum quantities of LN_2 and GN_2 to simulate the low temperature with better uniformity (within ±10°C).*
***Keywords:** CRIO - compact Reconfigurable Input and Output; TCDAS - Temperature Control and Data Acquisition System; LN2- Liquid Nitrogen; GN_2 Gaseous Nitrogen; Thermal vacuum tests.*

I. Introduction

ISRO(Indian Space Research Organisation) Satellite Centre (ISAC) has 4.0m dia vertical thermal vacuum chamber which is used for thermal vacuum performance testing of satellites and also, for thermal vacuum cycling of its appendages like Reflector |antenna, yokes, Solar Panels, etc. Thermal Vacuum chamber comprises of four main subsystems. a) The thermal subsystem which consists of various, Thermal lines, Infra Red (IR) heaters, LN_2 pipe lines, flow control valves and temperature controllers etc to simulate the space temperature. b) The vacuum subsystem which consists of various mechanical pumps and pump controllers to simulate space vacuum environments. c) The instrumentation system which consists of vacuum gauges, temperature sensors, RGA, QCM, etc, used to measure and display Chamber parameters. d) The control and data acquisition system is used to acquire & process the data, and controls various elements. Hermetically sealed feed through ports are provided at appropriate locations on the chamber for routing all sensors wires, electrical signals, power lines and thermal lines.

Thermal vacuum cycling test & Thermal baking tests are conducted for spacecraft appendages like solar panels, antennas, and yokes etc, as a part of its qualification in the 4.0m diameter thermal vacuum chamber (shown in Fig 1) using cuboidal shaped auxiliary shroud (shown in Fig 2). The test article is loaded within the auxiliary shroud. The chamber pressure of less than 10^{-5} mbar and shroud temperature of between -180°C to

+150°C are maintained. The required temperature on the test article is attained by radiative mode of heat transfer from the auxiliary shroud.
The cuboidal shaped auxiliary shroud are formed using fabricated SS shroud panels of rectangular shape joined together to form a box Shape. An array of electrical IR heaters is placed all around the SS shroud panels.

Hot temperature simulations were done by placing electrical IR heaters all around the SS shroud and passing hot GN2 through the flow passages of shroud. Cold temperature is simulated by regulating the flow of LN_2 through flow passages of the shroud. The test article attains temperature by means of radiation from the shroud. In the new system, computer based temperature data acquisition and control system has been incorporated to achieve and control the required temperature/heat flux. Accurate monitoring and control of temperature distribution on test article and shroud panels depends on the following factors.
LN2 flow patterns inside the shroud for achieving the cold temperature.
GN2 & LN2 mass flow rate inside the shroud for achieving the Hot & Cold temperature respectively.
Heat flux distribution on the shroud panels for achieving hot temperature.
Loop control elements in the thermal line.

II. Background

2.1 Main shroud

Satellite thermal vacuum performance tests and thermal balance tests are carried out in 4.0m thermal vacuum chamber. Main shroud temperature for these tests will be maintained up to
-100°C to +60°C with chamber vacuum of better than 10^{-5} mbar.

2.2 Auxiliary Shroud

2.2.1 Existing Cooling Control

LN2 flow to the shroud is controlled using ON/OFF Temperature controller**.** All the shroud outlets are connected to a flash chamber and outlet of the flash chamber is vented to the atmosphere. A thermo well is made at appropriate level in the flash chamber to control the liquid level using RTD (Pt-100) temperature sensor.

2.2.2 Existing Heating control in auxillary shroud

Hot temperature on the shroud panel is simulated using Infra Red (IR) lamp heaters. The IR heaters are switched in time proportion mode. Thermocouples (TC) are used as feedback sensors. IR heater power is switched through solid state relays (5-32V DC), which are controlled by digital output lines of the control card. Each IR heater is monitored by a thermocouple. Standalone PC based control system is used to monitor and control the shroud and test article temperatures.
However, the old TCDAS had some limitations as mentioned below:

- Lack of full proof protection of power control.
  No provision to sense open sensor condition.
  Low update time (1 minute for 120 channels).
  Non availability of software and hardware system for further up gradation.
  Single user display system for monitoring test article temperature.

Therefore, it was decided to replace the old system with a new upgraded system.

III. Description of New TCDAS

The new TCDAS configuration as shown in Fig3 was envisaged by taking into consideration the following features:

Multiple user display, two at control room and other at remote place.
Decrease the test risks by suitably adopting protective features.
High update rate (1 sec for all 256 channels)
Provision for future expandability.
Better control of temperature in different zones of shroud panels.
Automation of test to reduce manual intervention during tests.
Three level isolation for AC power to IR Heaters.
Software for analysis of test data and graphical report generation for subsequent analysis & reviews.
Reducing temperature transition time between cold to hot and hot to cold during thermal cycling tests.
Reducing LN_2 consumption during the tests.

3.1 Over view of new control system.

3.1.1 NI cRIO

National Instruments cRIO based system consists of three 8 slot chassis bearing all the input and output modules [Thermocouple modules, RTD module, Analog Input /Output module and Digital Input/Output modules] for Control & Data Acquisition. These are highly rugged and real time controlled to enable data acquisition in a very deterministic manner without any loss of data. Since, it is modular it offers high flexibility and scope for trouble shooting [1].

3.1.2 Programmable Controller Module

IPC- Industrial PC is used here as programmable controller module (PCM) to perform control and data logging operations. Two IPCs are used to perform redundant operations. The Application software for control & data acquisition would be running on these IPCs.

3.1.3 Main Computer

It is connected to redundant architecture of IPCs and with GUI monitor to display all readings and test data. A color printer is connected to the main computer to get print outs of test reports in a specified format. 3 monitors are used for GUI and display of test parameters.

3.2 Network Configuration

The first 3 applications are communicating with each other via TCP/IP protocol. Operation commands are being transmitted via TCP/IP between Host to PCM: PCM to RT and vice versa. Data is being transferred from RT to PCM: PCM to Host via CCC. For CPU redundancy there is a Heartbeat data being transmitted from PCM to RT and redundancy tags between Host and RT via CCC. The RT application is communicating to expansion I/O hardware chassis via Ethernet. Communication is one of the key features in this application and it is implemented as a local network. Network configuration of the overall system is shown in Fig 4[1]

3.3 I/O Hardware Configurations

In this section the cRIO system configuration is explained in detail. The cRIO-9068 system is running with NI Lab VIEW RT 2014 version OS. Other expansion chassis i.e. 9148-1 and 9148-2 are also installed with necessary drivers. The 4.0m TVAC Real-Time Application Software is integrated to cRIO-9068 which controls the modules of expansion chassis.

3.4 Host (Main PC) configuration

In this system there are 2 Host Application software's, namely 1) Aux Shroud Application and 2) Main Shroud Application for temperature control and DAQ of 4.0m TVAC Chamber. At a given time, any one of them is in use. Also an offline application is installed in the Main PC for test result and report generation.

In this section all 3 host application software and their configuration procedures are explained in detail.

3.5 Channel Configuration

The thermal vacuum chamber data acquisition and control system is developed, tested and commissioned to monitor a total of 256 channels with real-time data from 208 thermocouples, 16 RTDs, 8 EPTs, 8 valves, 6 vacuum gauges and 2 contamination(QCM) channels.

IV. Auxiliary shroud configuration, software and its control system

The details of auxilliary shroud channel configuration is shown in table-1.

4.1 Unique / Novel Application control system

During heating of the test article/package, temperature on the shroud is monitored by thermocouple which, after comparison with set point temperature, generates a time proportional digital ON-OFF signal corresponding to error. The generated signal is sent to digital output modules of NI hardware, which drives the SSR's of IR heaters. The control system simultaneously controls 64 digital output lines based on time-proportional control mode. Most of the shroud area is divided into subgroups and each subgroup is assigned with a group of thermocouples. Each IR heater has 3 levels of isolation namely Opto coupler isolation, Relay isolation, and SSR Isolation. The block diagram of new IR heater control loop is shown in Fig 5.

Each IR heater is assigned with one or multiple feedback thermo couples. The difference between set value and process value is measured and an error proportional signal is generated to control the difference in temperature. During cold cycle, individual shroud average temperatures are calculated and depending on the error with respect to set values, corresponding solenoid valves and Electro pneumatic valves are opened accordingly to control the flow of Liquid Nitrogen. The block diagram of control scheme for cold cycle control loop is shown in Fig 6.

In the cuboids shroud three input/output lines are designed namely side A &Front shroud, side B &Rear shroud, Top & bottom shroud. Liquid nitrogen flow through these shrouds is regulated using individual Electro pneumatic valves which are controlled by 4-20mA current output from TCDAS. In parallel to these EPTs , GN2 solenoid valves are also used to circulate gaseous nitrogen into the shroud. A time proportional control action is incorporated to maintain the shroud temperature in a defined rate. For each scan error is calculated between the processes and set variable and EPTs are regulated for LN2 flow. Whenever process variable leads, GN2 will be circulated through shroud to make uniformity and nullify the error. These GN2 solenoid valves will operate within a particular band to maintain the shroud temperature. In this mode of control action LN2 consumptions has drastically reduced and system performance enhanced. Testing cost also reduced.

4.2 Calculated channels Configuration

A physical channel is directly connected to real data measurement, while a pseudo channel that has no direct connection with an actual transducer and whose values are calculated based on mathematical formulas and the value of collected data points. For example in the present application, thermocouple, voltage and current transducers are represented by physical monitor, while IR heating power, minimum/ maximum and average transducers are represented by a pseudo monitor. The following are the important features of pseudo channels [2]

4.2.2 Maximum/Minimum value

The maximum value finds the largest value of a continuous group of channels or specified channels and displays that value at specified pseudo location. The channel number of the largest value on a subsequent pseudo channel can be also displayed. The minimum value except the smallest value is displayed [2].

4.2.3 Averaging

It consists of two functions group channel average and average value of specified period. In group channel averaging it finds the average of a contiguous group of channel from Cn to Cn+x. the time average is the average of specific channel over time. The average begins at a given point in time and continues through some other point in time. Over range data is excluded from the average [2].

4.3 System interlocks safety of payload/package and electrical isolation

4.3.1 Software safety

The new TCDAS is extremely useful to control different components of thermal vacuum system by software programming using interlock logic. The developed system also provides safety monitoring of the test test article. The interlock for the control logic output is provided based on software safety, OTP safety, vacuum safety and emergency safety which can lead to test article damage. The system also displays different alarm conditions and provides visual as well as audible notifications to the operator. If the temperature on any thermocouple on the package exceeds 5% of the set temperature, then it is detected by the program and all heaters are automatically shut off.

4.3.2 OTP (Over temperature protection)

One RTD sensor on each shroud acts as OTP and whenever it reads a temperature higher than the set limit, a visual/audible alarm beeps and all DIOs are deactivated in order to protect the system.

4.3.3 Vacuum fail Safety

In case, if chamber vacuum is below $5.0x10^{-4}$ mbar before starting the test, control cannot be started. During the test, if the vacuum level falls below $5.0x10^{-4}$ mbar, then alarm will be detected and automatically test will get paused by putting off all the IR heaters. Heaters will come online again when ever chamber vacuum is regained to $5.0x10^{-4}$ mbar, but test should be resumed by user manually.

4.3.4 Emergency shut off

In case of emergency, a push button switch provided in the front panel can be depressed to isolate all the controls.

4.4 Electrical isolation

There are three levels of isolation provided for high voltage entering into the digital cards. A very high isolation is also maintained between the stages. Short circuit protected SSRs are provided to eliminate the possibility of continuous heating of IR heaters due to shorting. Each IR heater power is routed through MCBs, for limiting the current to its rated values. Block diagram for three level isolation and high voltage protection is shown in Fig 7.

V. Graphical user interface (GUI)

5.1 Thermal schematics

The below screen page (Fig 8) shows the auxiliary shroud thermal schematic diagram. In this mimic, the status of control elements are displayed along with real time data like process value and set value temperature on the shroud, valve opening percentage etc.

5.2 IR Heaters and Thermocouple location

Fig 9 represents an exploded view of the existing shroud with locations shown for IR lamp heaters, and actual shroud thermocouples. Additional inputs such as DIO on/off, heater on percentage, temperature data are also displayed.

5.3 Master display

The master display consists of the following four displays: (1) Profile Mode, (2) Numeric value mode, (3) package temperature deviation control, and (4) switch buttons like acquisition, logging, power, emergency, alarms, mode selection etc as shown in Fig 10.

5.4 Home page diagram

It consists of test article image with sensors, temperature display, chart, vacuum, set temp, rate, with all control and indicators like auto/man, power, start acq, stop, IPC status, data log, alarm, cRIO, status etc as shown in Fig 11.

VI. Main Shroud Application

6.1 Acquisition Channel Configuration

The system is configured for monitoring an additional 108 thermocouples for temperature monitoring during space craft level thermal vacuum performance tests. It provides the shroud average, minimum, maximum, alarm limits, and Thermal line parameters as shown in Fig12. The details of Main shroud channel configuration is shown in Table-2.

6.2 Vacuum schematic

This represents vacuum lines of the system showing different pumps, valves, vacuum gauges and its process values as indicated in the diagram as shown in Fig 13.

6.3 Utilities

The mimic shows pressure and level of LN_2 in the Dewar, air pressure, cooling water pressure and flow rate, electrical voltage and current as shown in Fig 14.

VII. System Performance

The system has been installed and commissioned successfully to conduct thermal vacuum cycling tests and thermal baking tests on flight model test articles like solar panels, yoke and antenna in 4.0m TVAC Chamber. The system was continuously used round- the- clock throughout the test duration for all performance tests with each test lasting for about a week. The system performance during flight test article tests has been extremely satisfactory with high degree of reliability. The system was also tested with main shroud application software data acquisition system. For temperature cycling test in auto mode, time taken for transition from cold to hot and hot to cold has significantly reduced and package temperature uniformity during dwell time is also very well maintained. Since there is provision of rate control of temperature, it is now quite easy to set and control both the temperature limits as well as ramp rates by the operator as per the test requirements. Auto profile software has also been developed wherein by setting upper and lower temperature limits, rate of transition and dwell time, the system can automatically perform required number of cycles for a given test. Test parameters can be stored at a predefined interval and can be used for subsequent analysis.

VIII. Experimental Results

The typical test article thermal vacuum performance test results are shown for 10 thermal cycles in figures 15, 16 &17. The graph shows typical time of each cycle, dwell time, transition duration, along with averaging of channels.

IX. Conclusion

The system has been qualified to conduct Thermal vacuum performance and cycling tests in 4.0m thermal vacuum chamber. The protective features of the system have reduced the test risks to great extent. The system is user-friendly and flexible enough to allow reconfiguration. It provides total clarity of vital subsystems like, vacuum systems, thermal subsystems, instrumentation and power controls system. The new feature of Auto temperature control has reduced thermal transition time during tests. The developed control system resulted in reduced LN2 consumption for performing same temperature profile and also, test results indicate better uniformity of temperature on the test article.

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[2]. Ray A K, kumar D, Rajendran P N, shastri U D, Atchamamba A, Kumar D. Data acquisition and power control system for thermal test on spacecraft at 4m Thermal vacuum chamber, Proceedings of the 31st International Conference on Environmental Systems : Orlando, Florida, USA,,pp.1-11.

Fig 1: 4.0m Main Shroud schematic

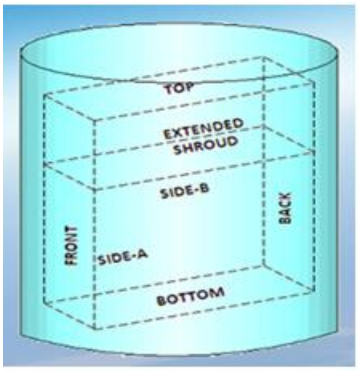

Fig 2: 4.0m Auxiliary Shroud schematic

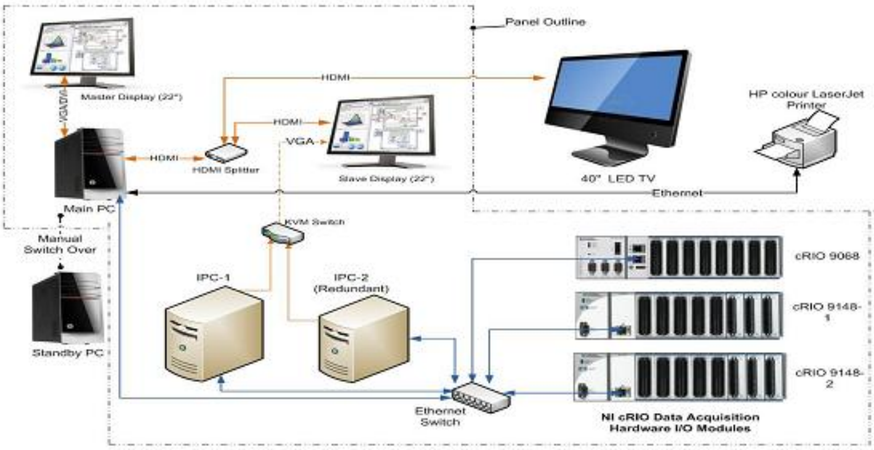

Fig 3: System over view and Functional Block Diagram of Data acquisition and control system

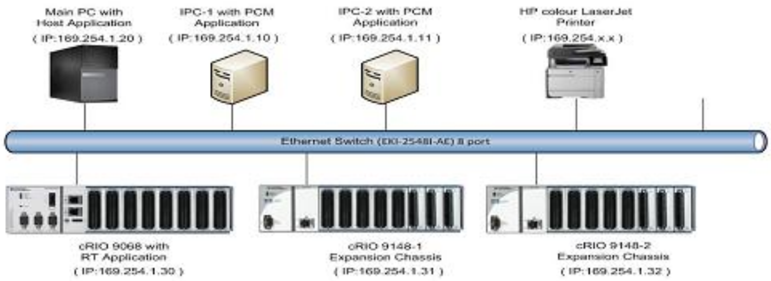

Fig 4: Network Configuration

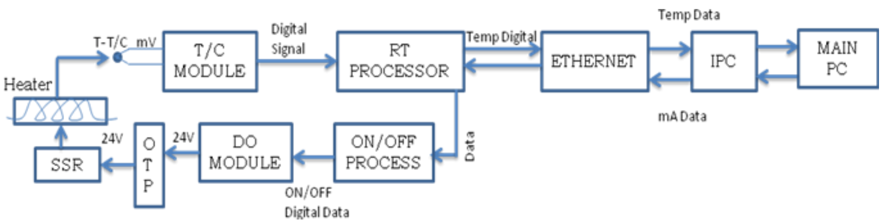

Fig 5: Block diagram of control scheme for Hot Cycle Control Loop

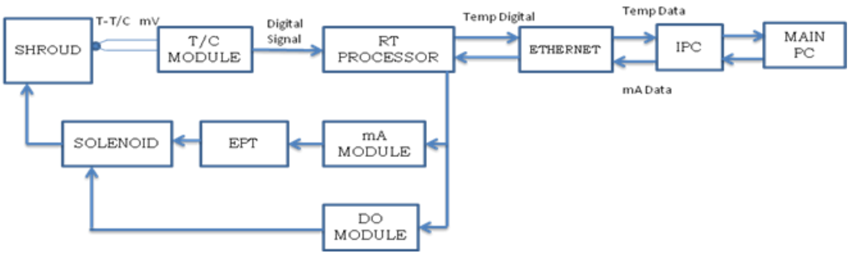

Fig 6: Block diagram of control scheme for cold Cycle Control Loop

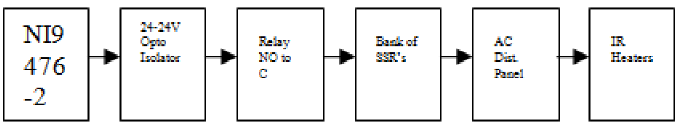

Fig 7: Block diagram shows three level isolation and high voltage protection

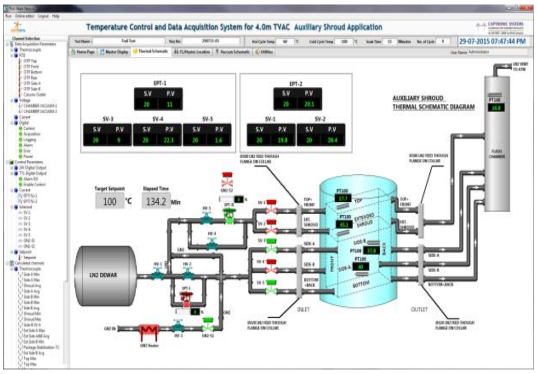

Fig 8: Thermal schematics diagram

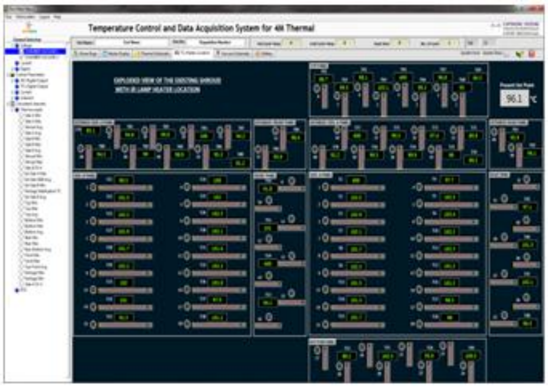

Fig 9: IR Heaters and Thermocouple locations

Fig 10: Master display

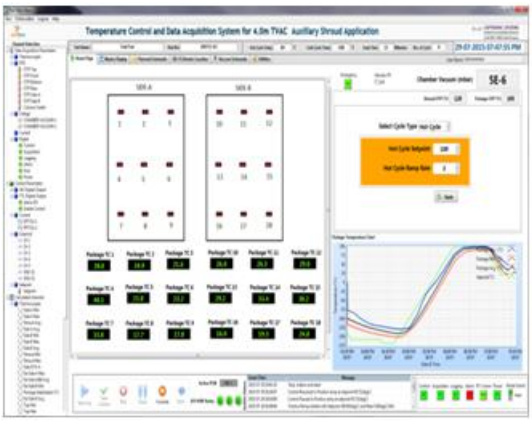

Fig 11: Home page diagram

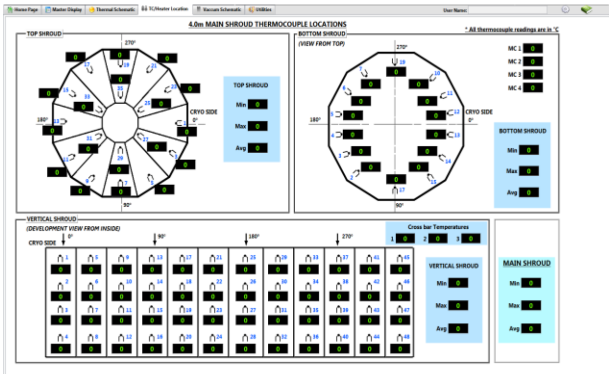

Fig 12: Schematic of main shroud thermocouples location

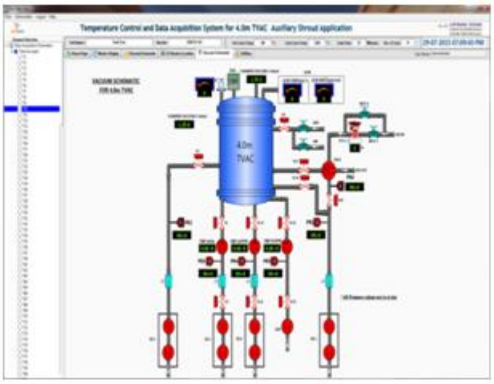

Fig 13: Vacuum schematic

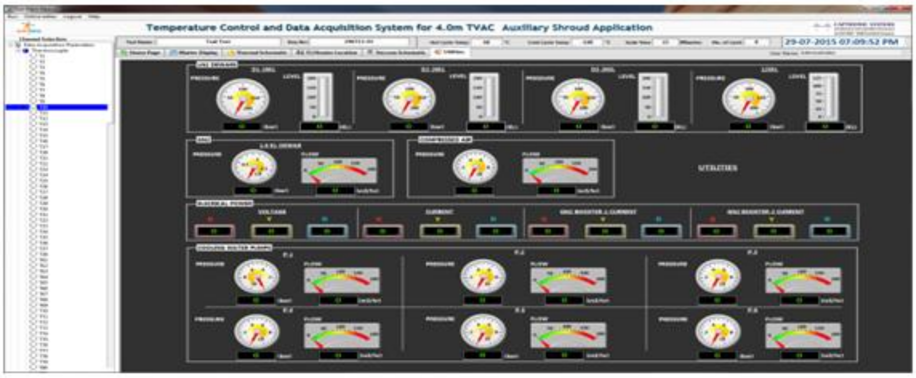

Fig 14: Utilities

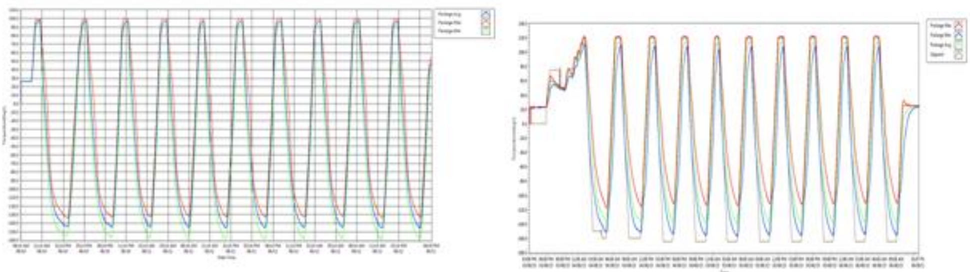

Fig 15 &16: Test results of solar panels Thermal vacuum cycling

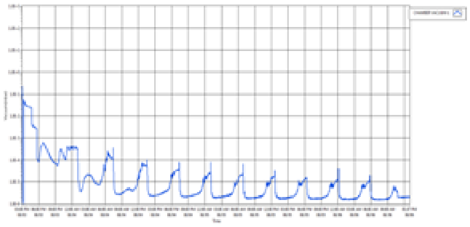

Fig17: Test results of vacuum profile during Thermal cycling Tests.

Table-1: Auxiliary shroud channel configuration

Sl No	Channels Configuration	No. Of Channels	Configuration
1.	T/C Channel	108 Nos.	Monitor and control the temperature
2.	RTD Channel	04 Nos.	Monitor the over temperature
3.	Voltage Channel (commonly shared)	04 Nos.	Acquire data from QCM and vacuum meters
4.	Current output (4-20mA) Channel	04 Nos.	Control EPT values
5.	DI(Digital input) Channel (commonly shared)	16 Nos.	Status indication

Table 2: Main shroud channel configuration

Sl. N0.	Channels Configuration	Nos. of channels	Configuration
1	T/C Channel T/C Ch b) Calculated/C ch	100	Monitor and control the temperature
2	RTD Channel T/C Ch b) Calculated/C ch	12	Monitor the Over temperature protection
3	Voltage Channel	8	Read vacuum and level parameters
4	Current output (4-20ma) Channel	8	Control EPTs
5	Control digital output channels	8	Control Solenoid valves
6	24V DO Channel	64	To control IR heaters
7	Current input (4-20mA) channels	4	Provision for feature pressure reading
8	TTL Do Channel	4	Status, shutdown, control operation