

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**MULTIFUNCTIONAL SOLAR PANEL DESIGN
FOR NANO AND MICRO SATELLITE**



M.Sc. THESIS

Süleyman SOYER

Department of Defence Technologies

Defence Technologies Programme

AUGUST 2022

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**Süleyman SOYER
(514191075)**

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Thesis Advisor: Prof. Dr. Alim Rüstem Aslan

AUGUST 2022

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

**NANO VE MİKRO UYDULAR İÇİN
ÇOK FONKSİYONLU GÜNEŞ PANELİ TASARIMI**

YÜKSEK LİSANS TEZİ

**Süleyman SOYER
(514191075)**

Savunma Teknolojileri Anabilim Dalı

Savunma Teknolojileri Programı

Tez Danışmanı: Prof. Dr. Alim Rüstem ASLAN

AĞUSTOS 2022

Süleyman SOYER, a M.Sc. student of İTÜ Graduate School student ID 514191075 successfully defended the thesis/dissertation entitled “MULTIFUNCTIONAL SOLAR PANEL DESIGN FOR NANO AND MICRO SATELLITE”, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor : **Prof. Dr. Alim Rüstem ASLAN**
Istanbul Technical University

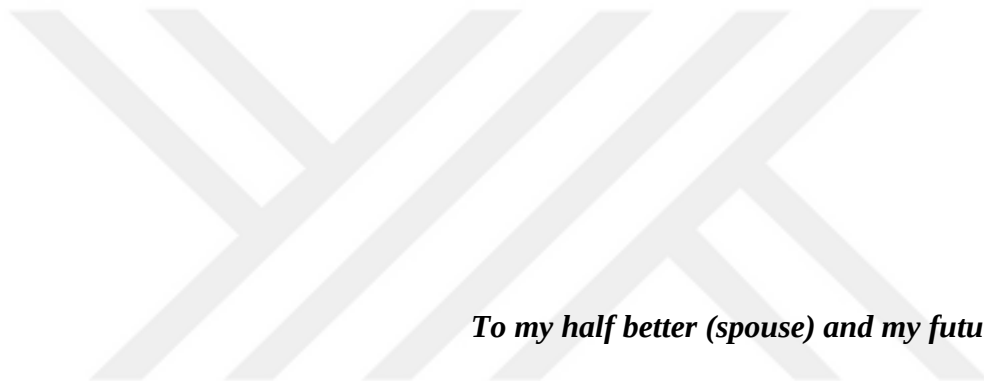
Jury Members : **Prof. Dr. Alim Rüstem ASLAN**
Istanbul Technical University

Prof. Dr. Emrah KALEMCI
Sabancı University

Asst. Prof. Cuma YARIM
Istanbul Technical University

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To my half better (spouse) and my future children,



FOREWORD

In this study, it was tried to develop a solar panel which is used to nano and pico satellites. I started this work by bringing together the experience when I gain of working on ITU Space Systems Design and Testing Laboratory.

This study contains the outputs of the design, production, testing and evaluation studies carried out within the scope of this project. In this project, which started with a literature review, experience was gained by conducting solder integration trials with old solar cells after material supply. Some tryings, design improvings, testings were done successfully with this project.

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August 2022

Süleyman SOYER
(Astronautical Engineer)



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ABBREVIATIONS

ADCS	: Attitude Determination and Control Systems
ATOX	: Atomic Oxygen
Cal-Poly	: California Polytechnic State University
C&DHS	: Command & Data Handling Subsystem
CS	: Communication Subsystem
CubeSat	: Cube Satellites
CVCM	: Collected Volatile Condensable Material
EASA	: European Union Aviation Safety
ECSS	: European Cooperation for Space Standardization
EL	: Electro-Luminescence Test
EMC	: Electromagnetic Compatibility
EPS	: Electrical Power Subsystem
ESD	: Electrostatic Discharge
EXA	: Ecuadorian Civilian Space Agency
GEVS	: General Environmental Verification Standard
GUMUSH	: Gumush Aerospace & Defense Company
ITU	: Istanbul Technical University
ITU SSDTL	: ITU, Space Systems Design and Test Laboratory
İTÜ USTTL	: ITU, Uzay Sistemleri Tasarım ve Test Laboratuvarı
LEO	: Low-Earth-Orbiting
MILGES	: The National Solar Power Plant Development Project
MIL-STD	: Military Standards
NASA	: National Aeronautics and Space Administration
ODTU GUNAM	: ODTU, Center for Solar Energy Research and Applications
PCB	: Printed Circuit Board
PMP	: Parts, Materials and Processes
POD	: Picosatellite Orbital Deployer
P-POD	: Poly Picosatellite Orbital Deployer
PVA	: Photo Voltaic Assembly
RML	: Recovered Mass Loss

RTG	: Radioisotope Thermoelectric Generator
R&D	: Research & Development
SMC	: Space and Missile Systems Center Standard
SS	: Structural Subsystem
SSB	: Savunma Sanayii Başkanlığı - Defense Industry Agency
SSDL	: Stanford University, Space Systems Development Laboratory
SSP	: Smart Solar Panel
TCS	: Thermal Control Subsystem
TIM	: Turkish Exporters Assembly
TP	: Technical Paper
TUBITAK	: Scientific and Technological Research Council of Türkiye
TUBITAK MAM	: TUBITAK, Marmara Research Center
TURKSAT	: Türksat Uydu Haberleşme Kablo TV ve İşletme A.Ş.
TVAC	: Thermal Vacuum Chamber
U	: Unit
QB50	: An international project network of 50 CubeSats for multi-point

SYMBOLS

A	: Area of Solar cells on Panels
cm	: Centimeter
kg	: Kilogram
lt	: Liter
m²	: Square Meters
mA	: Mili Ampere
μm	: Micro Meter
N	: Newton
nm	: Nano Meter
η_n	: Nominal Efficiency of Used Solar Cells [%]
P	: Power
S	: Sunlight Power Density [W/m ²]
U	: Unit
V	: Volt
W	: Watt
°C	: Celsius Degree
φ	: Angle of sunlight irradiance measured from the panel base plane [°]



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MULTIFUNCTIONAL SOLAR PANEL DESIGN FOR NANO AND MICRO SATELLITES

SUMMARY

Solar panels are one of the most important subsystems in satellite projects. Considering that solar energy is generally the only energy source after satellites are sent into space, the importance of solar panels can be better understood. The production cost of such a critical subsystem and dependence on foreign sources stand out as factors that slow down the development of satellite technologies. For this reason, a project started in Istanbul Technical University, Space Systems Design and Test laboratory in order to gain this subsystem capability and to make this subsystem space-qualified.

This thesis contains some of the outputs of the design, production, testing and evaluation studies carried out within the scope of this project. A comprehensive literature review was conducted before starting the project. With the literature review, a detailed preliminary information was obtained about the design specifications and requirements that should be used in the solar panel development process, academic studies like examples, and the companies that produce the solar panel by converting it into a final product. The information obtained here has enabled the study to be carried out with a more effective and accurate method.

First of all, the methods required to develop a multifunctional solar panel and which are intended to be tested within the scope of the project were determined. There are two different method selection processes in this study. The first of these is the method selection process for creating a coupon by mounting solar cells with each other. It is envisaged to try two different methods for this coupon creation process. The first of these is the classical soldering method. It was observed that partial damage occurred in the cells near the soldering area due to the heat of the soldering iron. Although the soldering made by different trials and increasing the hand sensitivity has been made more beautiful, it has not been possible to get rid of this effect completely.

The second method related to the coupon creation process is the cold-welding method. In order to apply this method, the facilities of the Mechanical Design Laboratory at the TUBITAK MAM Research Center were utilized. Since this method is not done with heat, it does not cause any damage to the cells. As a result of the tests, we can easily say that the correct and effective method for the coupon creation process is the cold-welding method.

The second method selection process is related to the mounting of the prepared coupons to the solar panel. Three different application methods have been proposed for this process. The first of these is to be mounted with epoxy-based adhesive, the second is to be mounted with silver-based epoxy material, and the third method is to mount the coupon to the panel with double-sided tape. Due to the intensity of the project schedule, only the first of these three methods, epoxy-based adhesive, could be mounted.

Standard developers such as ECSS, NASA and MIL-STD were used in the design, production and testing processes of test coupons and solar panels. In this way, it is aimed to reach a conclusion by carrying out the process successfully.

Within the scope of the thesis, first of all, a pre-control called “visual inspections” was made on the solar panels under a 15X microscope. After this control, the Electro-Luminescence (EL) test, which was performed by energizing the cells, was started. With this control and cells that passed the test, the coupon creation process was started. Afterwards, the coupon, which passed an EL control again, became ready for mounting on the panel. Within the scope of this thesis, the demo solar panel and the panel produced from TUBITAK MAM were used. The demo panel and the produced panel are subjected to a tensile test, also known as the Suction test, to test their strength. In the tests carried out on the machine specially developed for the tensile test, a holding strength of 25N was initially applied to the panels. While the demo panel came out of the test intact, the bottom cell of the produced panel was broken. These tensile tests were carried out in the Mechanical Design Laboratory at TUBITAK MAM.

After the tensile test, the panels were brought to ITU SSDTL Laboratory to be tested in space environmental conditions. The panels were subjected to a TVAC test (three cycles between -30 °C and 70°C and 10^{-3} and 10^{-5} Pa) lasting approximately fourteen hours. The panels, which were not damaged after the test, were subjected to an eye control and EL test again. These controls showed that the panels did not suffer any deterioration or damage in the TVAC test. After the TVAC test, the panels were taken to TUBITAK MAM for tensile testing again. In the tests performed here, 80N adhesion strength was applied to the demo panel and it was observed that the cells remained intact at this strength without leaving the panel. The upper cell of the produced panel, which was intact, was also put into the tensile test again. The panel with 100N adhesion strength has passed the test successfully. It can be easily said that the panel and the demo panel produced in this state have a robustness above the design specifications.

Within the scope of the project, a unique printed circuit board that can be used on a 1U satellite with a magnetorquer was designed and produced. With this card, it is aimed to provide a positive effect to the ADCS system thanks to the magnetorquers on the panels.

It can be said that the academic results of the panels produced after this study are satisfactory. In our country, which wants to get a share from the developing space technologies, it is of great importance to support the conversion of prototype products developed in this and similar studies into final products.

NANO VE MİKRO UYDULAR İÇİN ÇOK FONKSİYONLU GÜNEŞ PANELİ TASARIMI

ÖZET

Güneş panelleri bir uydu projesinin en kritik alt bileşenlerinden biridir. Uyduların genellikle uzaya gönderildikten sonraki tek enerji kaynağının güneş enerjisi olduğu düşünüldüğünde güneş panellerinin önemi daha da iyi anlaşılabilir. Bu kadar kritik öneme sahip bir alt bileşenin üretim maliyeti ve üretiminde dışa bağımlılık ise uydu teknolojilerinin gelişimini yavaşlatan unsurlardan biri olarak göze çarpmaktadır. Bu sebepten bu alt sistem kabiliyetini kazanmak ve bu alt sistemi uzay kalifiye (space-qualified) yapabilmek amacıyla İTÜ USTTL Laboratuvarında “Nano ve Mikro Uydular için Çok Fonksiyonlu Güneş Paneli Geliştirilmesi” adıyla bir proje yürütülmektedir.

Bu tez bu proje kapsamında yapılan tasarım, üretim, test ve değerlendirme çalışmalarının çıktılarının bir kısmını içermektedir. Projeye başlamadan önce kapsamlı bir literatür taraması yapılmıştır. Literatür taraması ile güneş paneli geliştirme sürecinde kullanılması gereken standartlar ve gereksinimler, örnek benzeri akademik çalışmalar ve uzay kullanımına yönelik güneş panelini son ürüne dönüştürerek üreten firmalar ile ilgili detaylı bir ön bilgi sahibi olunmuştur. Burada elde edilen bilgiler çalışmanın daha etkili ve doğru bir yöntemle yapılmasını sağlamıştır.

Literatür taramasının ardından hazırlanan proje dokümanı ile Türkiye İhracatçılar Meclisi’ne destek başvurusunda bulunulmuştur. Bu başvurunun kabulü ile birlikte projenin malzeme tedarik ve temin süreçlerine geçilmiştir. Proje takvimine bağlı olarak yürütülen proje süreci etkili ve etkin bir şekilde devam etmektedir. Malzemelerin temini ile birlikte proje takviminde aktif bir şekilde çalışmalara başlanmıştır.

Öncelikle çok fonksiyonlu bir güneş paneli geliştirmek için gerekli olan ve proje kapsamında denenmesi amaçlanan yöntemler belirlenmiştir. Bu çalışmada iki tane farklı yöntem seçim süreci bulunmaktadır. Bunlardan ilki güneş hücrelerinin birbiri ile monte edilerek bir kupon oluşturulması ile ilgili yöntem seçim sürecidir. Bu kupon oluşturma süreci için iki farklı yöntem denenmesi öngörülmüştür. Bunlardan ilki klasik lehimle yöntemi olarak bildiğimiz ve birçok elektronikle uğraşan kişinin sahip bildiği bir yöntemdir. Başlangıçta bu yöntemin pozitif etkileri konusunda çekinceler vardı ve beklendiği gibi bu yöntemin kupon oluşturma süreci için çok da başarılı olmadığı söylenebilir. Bu yöntem denenirken eldeki eski projelerden kalan ve uzay kullanım olanağı kalmayan güneş hücreleri deneme amaçlı kullanılmıştır. Bu hücreler ile lehim entegrasyon denemeleri yapılarak ikili test kuponları hazırlanmak istenmiştir. Havyanın ısısından kaynaklı lehim yapılan bölgenin yakınlarındaki hücrelerde kısmi hasarlar olduğu gözlemlenmiştir. Farklı denemeler ve el hassasiyetinin artırılmasıyla yapılan lehimler daha güzel hale getirilse de bu etkiden tamamen kurtulma sağlanamamıştır. Kupon oluşturma süreci ile ilgili ikinci yöntem ise cold-welding yani soğuk kaynak yöntemidir. Bu yöntem çok yaygın değildir ve uygulamak için ilave bir altyapı gerekmektedir. Biz de bu yöntemi uygulamak için TÜBİTAK

MAM Araştırma Merkezi'nde bulunan Mekanik Tasarım Laboratuvarının imkanlarından faydalandık. Başlangıçta uygulaması ve karşılanması gereken altyapı gereklilikleri zor gibi gözükse de süreç içerisinde yönteme aşına olunarak tecrübe kazanılmıştır. Bu yöntem ısı ile yapılmadığından hücrelere herhangi bir zarar vermemektedir. Yapılan testler sonucunda kupon oluşturma süreci için doğru ve etkili olan yöntemin cold-welding yöntemi olduğunu rahatlıkla söyleyebiliriz.

İkinci yöntem seçme süreci hazırlanan kuponların güneş paneline montajı ile alakalıdır. Bu süreç için üç tane farklı uygulama yöntemi önerilmiştir. Bunlardan ilki epoksi bazlı yapıştırıcı ile monte, ikincisi gümüş bazlı epoksi malzeme ile monte, üçüncü yöntem ise çift taraflı bant ile kuponun panele monte edilmesidir. Proje takvimindeki yoğunluktan dolayı bu üç yöntemden sadece ilki olan epoksi bazlı yapıştırıcı ile monte işlemi uygulanabilmiştir. İkinci ve üçüncü yöntemler ise devam eden süreçte uygulanarak akademik bir yayın halinde sonuçların açıklanması planlanmaktadır. Epoksi bazlı yapıştırıcı olarak Huntsman firmasının ürettiği Areldite-2014-2 marka ürün kullanılmıştır.

Test kuponları ve güneş panelleri tasarım, üretim ve test süreçlerinde ECSS, NASA ve MIL-STD gibi standart üreticilerinin standartlarından yararlanılmıştır. Bu sayede sürecin başarılı bir şekilde yürütülerek sonuca varmak hedeflenmiştir.

Tez kapsamında öncelikle güneş panellerine 15X bir mikroskop altında “visual inspections” denilen bir ön kontrol yapılmıştır. Bu kontrol ile hücrelerde herhangi bir hata veya kusurun varlığını gözle tespit etmek amaçlanmaktadır. Bu kontrolün ardından hücrelere enerji verilerek yapılan Elektro-Luminans (ışık akısı) testine geçilmiştir. Bu testin amacı hücrelere enerji verilerek görsel kontrolde belli olmayan hata ve kusurların montaj işlemlerinden önce tespit edilmesi ve boş yere üretim sürecine geçilmemesini sağlamaktır. Bu kontrol ve testten geçen hücreler ile kupon oluşturma süreci başlatıldı. Sonrasında tekrar bir EL kontrolünden geçen kupon panele montaja hazır hale geldi. Bu tez çalışması kapsamında TUBITAK MAM'dan temin edilen demo güneş paneli ve üretilen panel kullanılmıştır. Demo panel ve üretilen panel sağlamlıklarının testi için Suction test olarak da bilinen bir çekme testine sokulmaktadır. Çekme testi için özel geliştirilen makinede yapılan testlerde başlangıçta panellere 25N'luk tutunma mukavemeti uygulanmıştır. Demo panel sağlam bir şekilde testten çıkarken, üretilen panelin alt hücresi kırılmıştır. Bu üretilen panelde üretim süreçlerinde tecrübenin ve standartlara uymanın farkını anlamak adına montaj sırasında bir farklılık yapılmıştır. Üstteki hücre tamamen uygun bir şekilde panele yerleştirilirken, alttaki hücrede bu hassasiyet gözetilmemiştir. Sonucunda da 25N'luk bir çekme ile hücre kırılarak panelden ayrılmıştır. Bu çekme testleri TUBITAK MAM'da bulunan Mekanik Tasarım Laboratuvarında yapılmıştır.

Çekme testi sonrası paneller uzay çevre koşullarında test edilmek için İTÜ USTTL Laboratuvarına getirilmiştir. TVAC testi için hazırlanan paneller -30°C ve +70 °C aralığında üç çevrim olacak şekilde yaklaşık on dört saat süren bir uzay çevre koşul testine tabi tutulmuştur. Bu test esnasında panellere yerleştirilen sıcaklık sensörleri ile veri alınmıştır. Test sonrasında herhangi bir hasara uğramadığı görülen paneller tekrar bir göz kontrolüne ve EL testine tabi tutulmuştur. Bu kontroller panellerin TVAC testinde herhangi bir bozulma ya da hasara uğramadığını göstermiştir. TVAC testinden sonra paneller tekrar çekme testi yapılmak üzere TUBITAK MAM'a götürülmüştür. Burada yapılan testlerde demo panele 80N'luk tutunma mukavemeti uygulanmış ve hücrelerin bu mukavemette panelden ayrılmadan sağlam bir şekilde kaldıkları gözlemlenmiştir. Üretilen panelin sağlam olan üst hücresi de yeniden çekme testine

sokulmuştur. 100N tutunma mukavemeti uygulanan panel testten başarılı bir şekilde çıkmıştır. Bu haliyle üretilen panelin ve demo panelin standartların üstünde bir sağlamlığa sahip olduğu rahatlıkla söylenebilir.

Proje kapsamında ayrıca üzerinde manyetorker bulunan 1U boyutlarındaki bir uyduda kullanılabilecek özgün bir baskı devre kartı tasarlanmış ve üretilmiştir. Temin edilen güneş hücrelerinin bağlantı şemaları ve devre korumaları incelenerek bu proje özelinde baskı devre kartı tasarlanması konusunda altyapı oluşturulması sağlanmıştır. Bu kart ile panellerde yer alan manyetorkerlar sayesinde ADCS sistemine artı bir etki sağlanması amaçlanmıştır.

Bu çalışma sırasında üretilen panellerden elde edilen ilk sonuçların in akademik açıdan hedeflenen seviyede olduğu söylenebilir. Ancak bu ve benzeri çalışmalarda geliştirilen prototip ürünlerin son ürüne dönüştürülmesine verilecek destekler çok önemlidir. Gelişen uzay teknolojilerinden pay almak isteyen ülkemizde konusunda destek verilmesi büyük önem arz etmektedir. Prof. Jordi Puig-Suari ve Prof. Bob Twiggs'in ortak çalışmasıyla başlatılan Küp uydu projesi günümüzde beklenenden daha büyük katkılar sağlamıştır. Tahminimce bu iki kıymetli bilim insanının hayallerinin çok ötesine geçen bu fikir zaman içerisinde gelişerek muazzam bir sisteme dönüşmüştür. Tez kapsamında yapılan bu çalışmanın da küp uyduların bu muazzam sisteminden beslenmiş olup ve bu alana katkı sunmak hedeflenmiştir.



1. INTRODUCTION

With this thesis, I aimed to introduce what is done/achieved in the thesis and relevant background/state of art on this topic. In this section, an overview of satellite technologies is made and it is aimed to present informations about the idea of the CubeSat technology, its current effectiveness, and the studies carried out in our country. In addition, there are partial sections on the design specifications used in the development process of CubeSats, their subsystems, and how the test processes that need to be applied are performed. The solar panels used in CubeSats are also mentioned.

1.1 Satellites

Satellite technology stands out as an indispensable technological element in today's world. Thousands of artificial satellites have been produced and sent into space since Sputnik-1, which looks like a basketball in diameter with mass 83 kg, the first artificial satellite seen in Figure 1.1 sent into space by the Soviet Union on October 4, 1957.

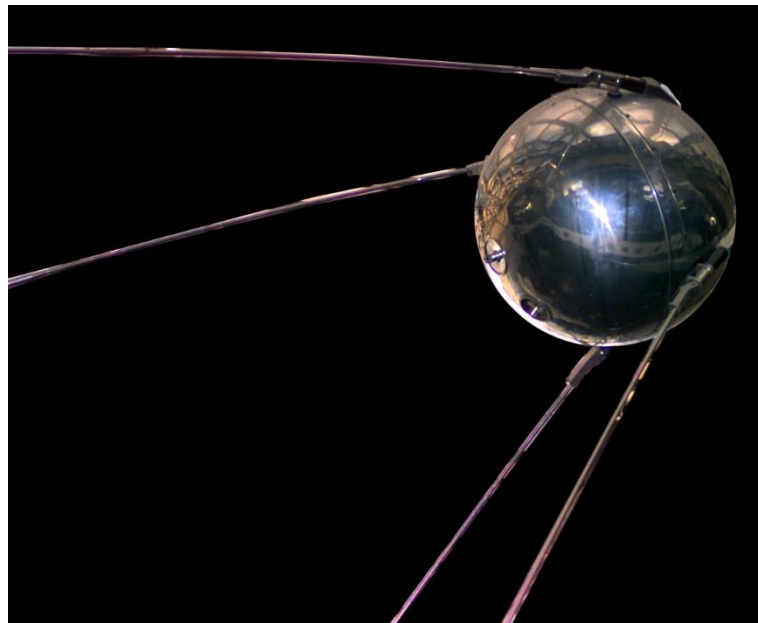


Figure 1.1 : The first artificial satellite, Sputnik-1.

Space/satellite technology has nowadays become eligible to develop by startup companies and academia (such as universities and even lower education groups) when although formerly only accessible for giants in the developed countries. Even though, this technology has been developed and used for military issues, it has countless numbers of benefits and convenience for civils. This benefits have been created a desire for expansion for this technology and resulted as a quick shift from military use to civilian use. Additionally, It can be said that, developing CubeSats and cansats as a part of training qualified manpower also supported this shift. These days, Satellites continue to be used extensively for military purposes, as well as for civilian uses such as communication, imaging, reconnaissance, remote sensing, weather forecasting. If we make a general classification according to production and usage purposes, we can say that satellites developed for many purposes.

These are listed as (Aslan, Sözbir, & Öz, 2021):

- Communication Satellites,
- Military (Reconnaissance) Satellites,
- Earth Observations Satellites,
- Space Observations Satellites,
- Biological Satellites,
- Space Stations,
- Scientific (Astronomical) Satellites,
- Global Navigation Satellites and
- Weather Forecasting Satellites.

To simply mention the applications of satellite technology that facilitate today, navigation applications that we use every day to go from one place to another and the broadcasts we watch on our televisions can be given as the simplest and daily examples. It goes without saying that these examples are too numerous to be counted within the scope of this thesis. The efforts to transform the products/outputs developed within the scope of space technologies called spin-off into products/outputs suitable for daily life have added many advantages to our lives for many years (Maini & Agrawal, 2011, s. xvii).

Satellites are also classified according to their mass. If we look at it from this point of view, we can more easily understand the origin of the CubeSats and the reasons for

their spread, which are the subject of our thesis. In Table 1.1, you can see how satellites are classified according to their masses. Basically, we can divide the satellites into three classes according to their masses. Satellites of 1000 kg or more are in the Large Satellites class, 500 kg and above are in the Medium Satellites class, and satellites with a mass of less than 500 kg are in the Small Satellites class. Small satellites with a mass below 500 kg are divided into seven classes as seen in Table 1.1 (Mauro, Lawn, & Bevilacqua, 2018), (Kulu, Nanosats Database, 2022).

Table 1.1 : Satellite platform classification based on mass.

Quantity	Platform mass, kg
Large Satellites	≥ 1000
Medium Satellites	≥ 500 and < 1000
Small Satellites	< 500
➤ Mini Satellites	≥ 100 and < 500
➤ Micro Satellites	≥ 10 and < 100
➤ Nano Satellites	≥ 1 and < 10
➤ Pico Satellites	≥ 0.1 and < 1
➤ Femto Satellites	≥ 0.01 and < 0.1
➤ Atto Satellites	≥ 0.001 and < 0.01

On the other hand, NASA uses a slightly different classification for small satellites in its reports and studies. NASA has determined the 180 kg limit for the small satellites class in the document numbered NASA/TP—20210021263, prepared in October 2021. In Figure 1.2, you can see the satellite classifications and examples in the report (NASA Ames Research Center, Small Spacecraft Systems Virtual Institute, 2021).



Figure 1.2 : Overview of small spacecraft categories (Credit: NASA, SpaceX, Redwire Space, and Alba Orbital).

1.2 CubeSats – Cube Satellites

Although these classifications seem to be collective classifications, in fact, the developing technology and needs have determined the result of the rapid shift of today's satellite technologies trend towards smaller structures. There are many challenges in the development of space and satellite technologies. At the beginning of these are large materiality necessity and qualified human resources. From this point of view, scientists and engineers have given more importance to reducing the dimensions and weights of satellites with the developing technology. For that reason the scientists focussed to reducing of costs and reducing the time of development. The CubeSat idea emerged as a result of these searches.

With this quests, two academic scientists, who set out with the idea of transforming satellite technologies into a cost-effective university project and thus increasing the qualified manpower working in this field, came up with the idea of “CubeSat-Cube Satellite” and “Cansat-Can Sized Microsatellite”. Professor at California Polytechnic State University (Cal Poly) Jordi Puig-Suari and Prof. from Stanford University's Space Systems Development Laboratory (SSDL) Bob Twiggs started these projects in 1999 with a collaborative effort (Introduction: The history of the CubeSat by Bob Twiggs and Jordi Puig-Suari, 2020).

This new study, called CubeSat, went far beyond what was expected and turned into more professional structures developed not only by universities and students, but also independently and jointly by many companies and governments. Figure 1.3 (prepared in 2022) should be analyzed well to see how widespread CubeSats have become. While many countries are stepping into satellite technologies thanks to CubeSats, the development of developed countries in space regarding CubeSats seems to be enormous (KULU, 2022).

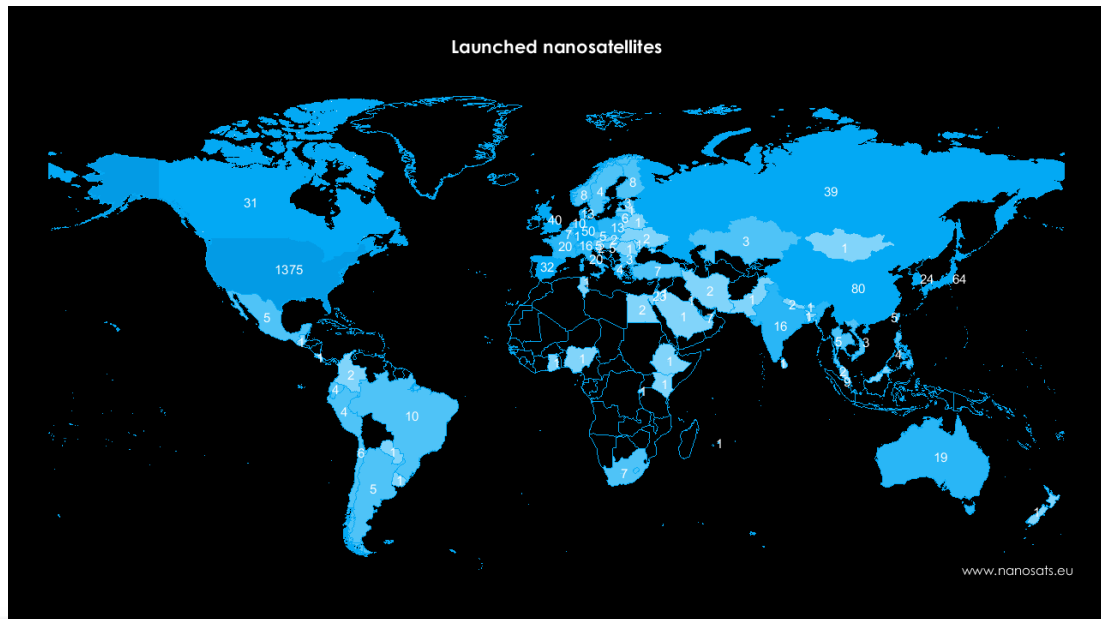


Figure 1.3 : Map of all nano satellites launched around the World.

Countries that want to develop technology in this field and have fewer financial means have made serious investments in this field. Dozens of companies in business in this field have been established in developed and developing countries in the field of space, and they continue to operate successfully. At the same time, owing to the research and development laboratories established in universities, qualified human resources can be found easily encountered even at the undergraduate level. The process accelerated even more as the launcher providers responded to the existing interest. In the twenty years since the first CubeSat was launched in June 2003, we quickly realized what we can do with CubeSats. We are still faced with a rapidly developing technology at a point that even those who came up with the first idea could not even imagine. Recently, we have seen that commercial space entrepreneur companies such as MICROSAT are trying to establish their own satellite constellations with projects such as Starlink. These projects and entrepreneurs shows us how effective small satellites, especially CubeSats, will be in satellite technologies in the near future. In Figure 1.4, the graph of the nano-satellites that have been sent since 1998 and the satellites that are planned/anticipated to be sent are given (Kulu, NanoSats Database, 2022).

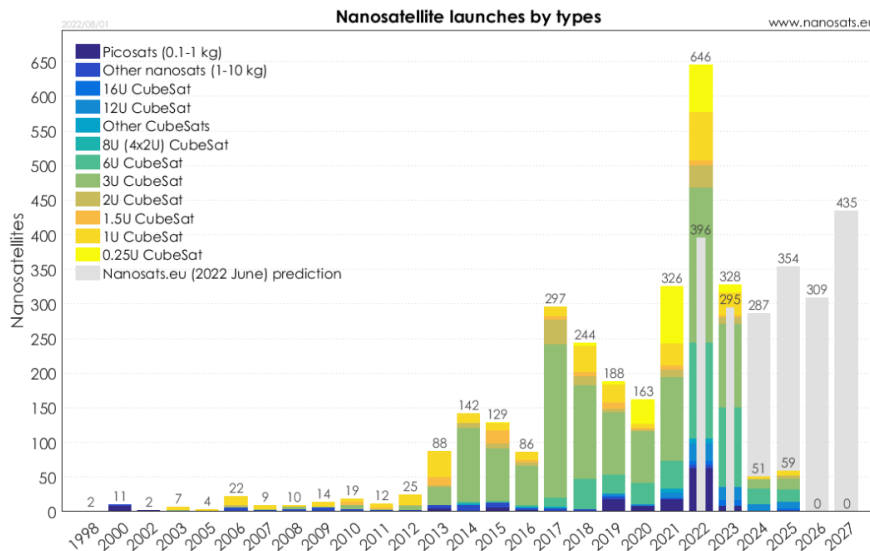


Figure 1.4 : Statistics of nanosatellites launched/predicted launch by type (source: <https://www.nanosats.eu/#figures>).

1.2.1 Dimensions of the cubeSats

CubeSats has design specifications that was determined from the very beginning and that are still being developed is a detailed education and developing project. CubeSats are a class of satellites whose unit is defined as "U" and adopts a standard size and form factor. Each unit i.e. "1U" defines as a 10x10x10 cm cube and weighs up to 2 kg. So, a 1U CubeSat is a 10cm cube dimensions with a mass of up to 2kg. CubeSats dimensions today range from 1U to 27U. In this respect, CubeSats are in the class of both nanosatellites and microsatellites in terms of their mass. It is foreseen that these dimensions may be updated higher in the future. In Figure 1.5, the dimensions of the CubeSats and their classifications can be seen more clearly (NASA Ames Research Center, Small Spacecraft Systems Virtual Institute, 2021).

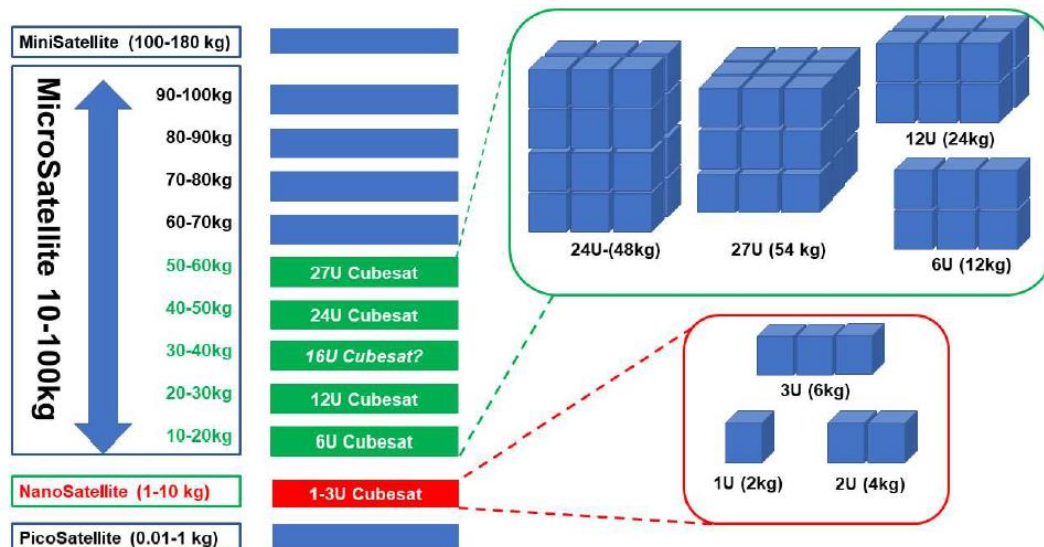


Figure 1.5 : Nanosatellite sizes compared to CubeSat containerized sizes (Credit: NASA).

1.2.2 Development processes of cubesat and design specifications used

As in all space projects, in CubeSat projects, it is very important to determine the requirements for the targeted mission. The biggest difference that distinguishes CubeSats from each other is the payload you put on them. For this reason, careful planning and scheduling of the main structure, subsystems, integration and test phases and payload development processes will increase the probability of the project being successful. In order to ensure this precision and success, the design specifications and procedures determined on the day the CubeSat idea was introduced are developed and continued rigorously. While developing the CubeSat project, the “CubeSat Design Specification” standard developed and constantly updated by Cal-Poly University is used. The design specification announced in February 2022, named as 14.1 update version is used in the execution of the whole process, in harmony with the launch providers, in the validation of the test criteria (California Polytechnic State University, 2022). In short, these design specifications guide you from start to finish as to what to do and how.

In addition, these design specifications greatly facilitate the adaptation of people who have just started working in this field to more advanced space projects and add a common culture of working in space projects. On the other hand, setting these design specifications is a necessity. Because CubeSats are sent to space with the same rockets as together other large satellites and no one wants the a CubeSat to damage a multi million-dollar satellite in launch. For this reason, a protective and launching aid unit

called a "deployer", other name is POD is used to prevent CubeSats from damaging other satellites during launch and to facilitate their placement in orbit.

With the first studies initiated at Cal-Poly University, a deployer called P-POD, which can carry and drop 3 1U cubed satellites, was developed. While determining the design specifications of this deployer mechanism, factors such as being compatible with launch vehicles, being economical and light, easy to manufacture, and not damaging the CubeSat and other satellites were taken into consideration. Most particularly, these design specifications were developed to place CubeSats in the correct orbit with minimal rotation, without the possibility of colliding with other CubeSats or large satellites and the launcher (Suari, Turner, & Ahlgren, 2011).

In Figure 1.6, you can see the deployer mechanism named P-POD developed by Cal-Poly University. The deployer, which has the capacity to launch 3 1U CubeSats, has been developed to be suitable for multiple launches by adding to each other

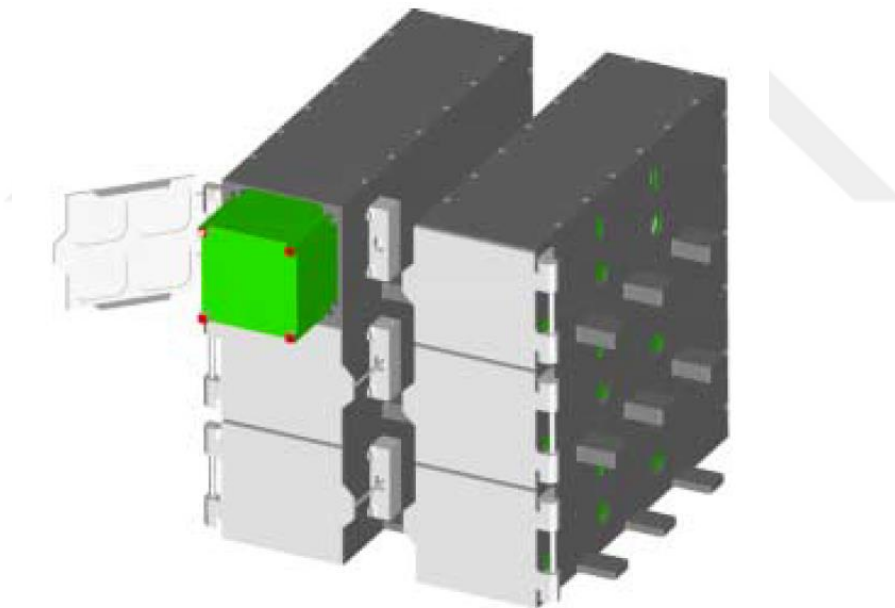


Figure 1.6 : P-PODs in a 3x3 configuration.

In addition to these design specifications, there are mandatory and recommended design specifications developed by NASA (NASA, 2021). Military standards, known externally as MIL-STD abbreviation, are also used from time to time. These design specifications are developed separately for each stage, and ultimately they are in harmony with each other. Owing to these design specifications, you will not encounter any obscurity or bad surprises at every stage of your project. With the use of these

design specifications, a common language is become widespread all over the world and people from different countries can work very easily on the same project.

These design specifications also tell you how to conduct every phase of the CubeSat project. Staying above or below the design specification is entirely related to your working principles and the competence of your work team. Additionally, a guide named CubeSat 101 has been prepared by Cal-Poly University to support NASA's CubeSat launch program. It stands out as a guide document explaining the basic concepts and processes for institutions, universities or groups that want to develop cube satellites for the first time (NASA CubeSat Launch Initiative, 2017).

1.2.3 Subsystems of cubesats

Before talking about the subsystems of satellites, it would be more accurate to make a distinction accepted by the general literature. Satellites are divided into two main parts. Platform and Payload. Payload is the load carried by the satellite, which determines which mission the satellite will aim for and for what purposes it has been developed. The platform, on the other hand, is a whole that takes this payload to space and includes the basic subsystems in order to perform its duty healthily.

CubeSats are similar in structure to larger-mass satellites in terms of basic subsystems. The propulsion systems stand out as the difference in the main subsystems. However, recently, it is known that propulsion systems have been studied specifically for CubeSats. It is foreseen that one hundred and thirty-four nano-satellites will be sent into space with propulsion systems in 2023 (KULU, 2022). In addition, an exemplary study in this field in our country is being carried out at ITU SSDTL and its outputs are expected to be announced soon.

In Figure 1.7, you can see the CubeSat's basic subsystems. If we want to briefly summarize these subsystems and their tasks;

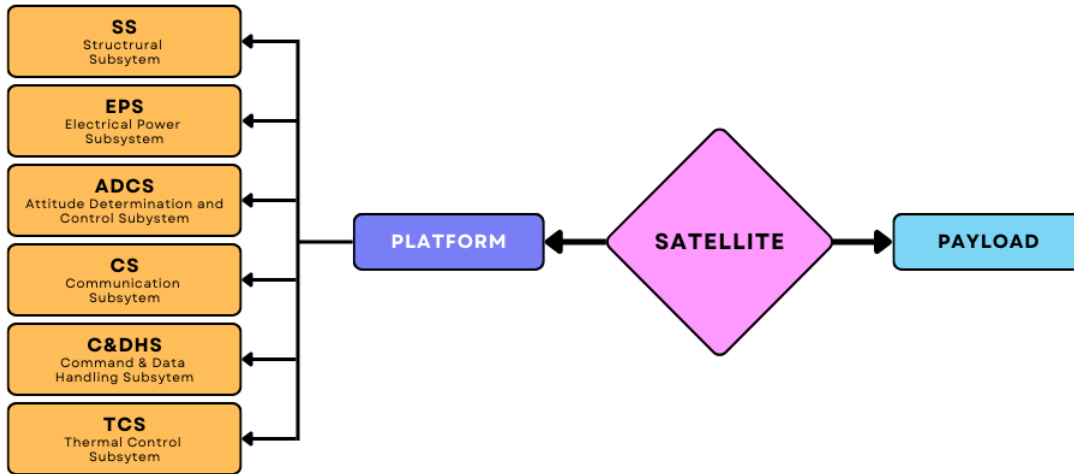


Figure 1.7 : Subsystems schematic of CubeSats.

1.2.3.1 Attitude determination and control systems (ADCS):

This subsystem is used to detect and control the status of the satellite, determine its direction, and keep the satellite in the desired direction. Embedded ADCS modules are commonly used for status detection, control, and direction stabilization in CubeSats. These modules usually contain sensors and control elements such as reaction wheels, sun sensors, rare sensors, coarse sun sensors, rate sensors, star tracker and magnetorquer rods.

1.2.3.2 Electrical power subsystem (EPS):

It would be very accurate for this subsystem to make the analogy for the satellite's life source. Because the Electrical power subsystem provides the necessary supply voltages from the battery for other subsystems and payload. EPS consists of three sub-elements. These are: Electrical Power Management Unit, Solar Arrays, and Battery Package.

Solar panel design, which is the main subject of our thesis, serves this sub-system. EPS is responsible for maximizing the power level by converting the solar energy obtained with solar cells into electrical energy with maximum efficiency. Since there is energy in the work, EPS is also responsible for the efficient use of all this energy and the battery in maximum time. Owing to the short circuit and over voltage protection, the avionics on the satellite are prevented from being affected by instantaneous power changes and their lifetime is improved.

1.2.3.3 Structural subsystem (SS):

The structural subsystem is a subsystem made of lightweight materials that provide interfaces with subsystems to keep the payload and other subsystems safe and to ensure the safe passage of all phases required by the mission. Ease of manufacturing and assembly provides great convenience in all production, testing, and integration stages of the satellite. The design of the structural system requires great dedication and has its own tests and design specifications. For this reason, many developers prefer ready-made products that have previously been space-qualified (NASA, 2021).

1.2.3.4 Communication subsystem (CS):

The Communication Subsystem is one of the critical subsystems for a satellite. Because, through CS, satellite data and telemetry information are transmitted to the Earth, and necessary interventions are made by receiving commands from the Earth. It allows the mutual exchange of information. You can think of it this way, if this subsystem did not exist, the satellite would be in a self-powered state, where we do not know its state after being sent into space. Satellites can communicate with ground stations on the ground as long as they are in the transition zones. This communication protocol must be studied before the satellite is sent, and the satellite communication time, also known as the transit time, should be known. Uploading and data download can be provided from other ground stations if necessary (NASA, 2022).

Through CS, a hobby culture known as amateur radio has also spread and people have gained a new competence by listening to data from satellites and processing them. While amateur radios are not allowed to communicate with military or larger satellites, CubeSats has no such permission requirement and even in this sense, support can be obtained from amateur radio operators. In this respect, we can count its contribution to the development of amateur radio as one of the advantages of CubeSats.

1.2.3.5 Command & data handling subsystem (C&DHS):

Command & Data Handling Subsystem is like that the brain of the satellite. In this subsystem, there is an onboard computer called OBC that controls the operation of the satellite. OBC has software that manages programs written to perform various tasks. CDHS performs two main functions. It first receives, validates, decodes, and distributes commands to other subsystems, collecting and processing data from them.

Its other main function is to format housekeeping and mission data of the satellite for downlink using an onboard computer. This subsystem usually includes additional systems such as spacecraft timekeeping, computer health monitoring (watchdog), and security interfaces. The CDHS subsystem used especially in CubeSats should be small, light, efficient, easy to integrate with other subsystems, and, if possible, space-qualified (Nguyen, Yuknis, Pursley, Haghani, & Albaijes, 2008).

1.2.3.6 Thermal control subsystem (TCS):

Thermal control is vital because satellites are heavily exposed to sunlight and radiation. While the sun-exposed surfaces of the satellite rise to very high temperatures, the non-sun-exposed surfaces are quite cold. If this temperature difference in the structure is not directed actively or passively, it will directly affect the life of the all materials. Also, if it is not taken into account, it will cause damage to the materials at the first moment. Generally, passive thermal control systems are used in CubeSats.

1.2.4 CubeSat testing requirements

As I have already indicated, one of the most important parts of the construction process of the CubeSats is validation which is the way you can guarantee the compatibility of the satellite you have designed. To achieve this, you must fulfill the tests (or test requirements) outlined in the design specifications. Because the satellite development process is not only related to the satellite itself but also needs to be compatible with the launcher. For this reason, the design specifications and requirements used are adopted, developed and announced internationally.

For example, to define test environments and requirements in cases where the launcher is not known the General Environmental Verification Standard (GEVS) GEVS, GSFC-STD-7000A (NASA, 2013) developed by NASA , and SMC-S-016 (Air Force Space Command, 2014) developed by Air Force Space Command should be used. In addition to these, if the launch provider requests any further specific tests, these are additionally carried out.

It is necessary to protect a balance between low cost and fast delivery, which are seen as the most important advantages of CubeSat, and test requirements that are

fundamental to reliability. For this reason, design specification developers seek not to lose the cost-effectiveness advantages of CubeSats without compromising reliability.

At a minimum level, random vibration, thermal vacuum bake out and shock tests are compulsory to be performed on CubeSat. Especially, the test program to be applied to the engineering model will show that the flight model is safe against tough space environmental conditions and mechanical load experiences during flight. Acceptance tests are made from over the real flight model and are performed at a lower level than the tests applied to the engineering model and by characterizing the test times.

The functionality of the systems is checked after each test to control that the test does not change the performance and functions of the satellite. A test unit called TVAC (Thermal Vacuum Chamber) as shown in Figure 1.8 is used to test the satellite in particular environmental conditions. By this means, functional tests can be performed on the satellite in company with a thermal cycle close to space conditions.

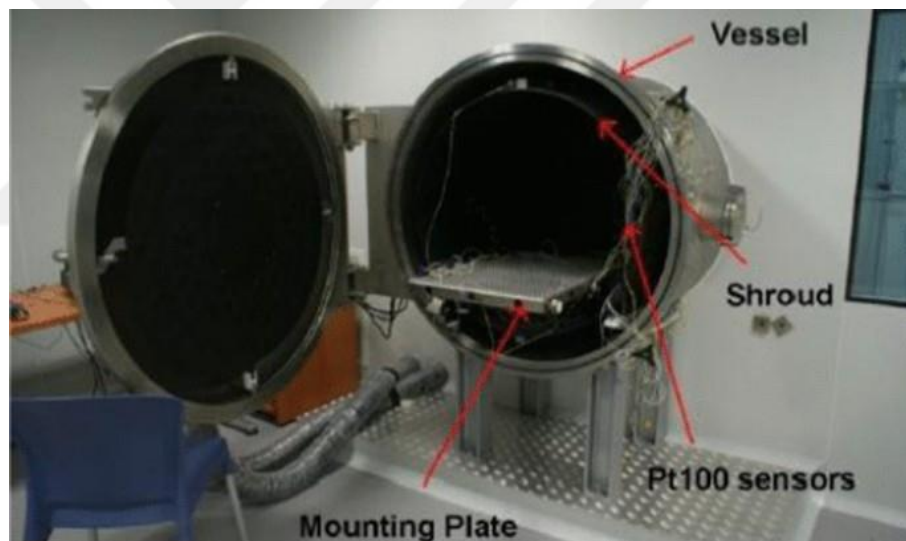


Figure 1.8 : Detail view of TVAC located in the ITU-SSDTL laboratory.

Although the tests we call Electromagnetic Compatibility (EMC) are not applied to every satellite, they are very crucial tests as they show that the satellite does not cause electromagnetic disturbances in the electromagnetic environment and works in accordance with its purpose. The standard of ECSS-E-ST-20-07C is usually used when EMC test will be performed. Finally, in addition, the thing is that, to be said about the tests, each satellite must pass certain obligatory tests, and meet approval criteria but the tests to be performed according to the tasks and payload defined on it must change and be customized. For this reason, each satellite has and must have an independent test plan.

1.2.5 Solar panels used in cubesats

So far, Solar panels are the only energy source for CubeSats. It is also the most important or the only energy source for many classical satellites. Because the energy is obtained by transforming from a continuously existing source, this is a very useful method for satellites. Since an active ADCS system is not used for the panels to obtain the most efficiency from the continuous sun in CubeSats, the electrical energy obtained is limited. For this reason, it is desirable to put the maximum number of solar arrays on the satellite during the design and production and to have the highest efficiency in these cells.

If we look at the solar cells and their manufacturers, which are currently space-qualified and used in various CubeSat projects, we first come across the European company AZUR Space and its products. The company, which started its activities with the German satellite AZUR in 1964, has gained an important place in the CubeSat market, as in other satellites. Solar cells of this company are also used in our project. Another global firm in this field is Spectrolab Corporation. Spectrolab, Inc., a wholly owned subsidiary of The Boeing Company, is the supplier of the Highest-Efficiency Multijunction Solar Cells for Spacecrafts, with proven reliability drawn from 65 years of space heritage. In addition to these, EXA DMSA company also has Deployable Multifunction Solar Array products. In addition to these companies, there are companies such as Hemu Group, which produces panels in accordance with the wishes of the customers using solar cells and components of well-known brands.

1.2.6 CubeSatellites research history at Türkiye

With the increasing interest in space technology in our country, decisions have been taken by the government to support universities and industrial organizations in this area. As a result, the development of a pico satellite, which is also supported by TUBITAK, has been raised. For the development of this pico satellite, Istanbul Technical University academicians, took the initiative and started these studies which improving the appropriate knowledge, experience and infrastructure in the field of space engineering. In order to support these studies, two laboratories named “Space Systems Design and Testing Laboratory” and “Small Satellites Communications Laboratory” have been established. In Figure 1.9, ITUpSAT-1, the first Turkish-made CubeSat, can be seen. This 1U sized satellite was designed, developed and tested in

the ITU SSDTL laboratory. It was launched from India on September 23, 2009 and has become one of the sources of pride of our country (İlarslan, Aslan, & Çelebi, 2013).



Figure 1.9 : ITUpSAT-1, the first Turkish-made CubeSat (Credit: ITU-SSDTL Laboratory).

The experience which were gained here and the trained manpower have allowed our country to make a rapid breakthrough in this field. TURKSAT 3USAT satellite, which is the first domestic communication satellite of Turkey, is a 3U-sized satellite designed by ITU USTTL for TURKSAT. The satellite was placed into orbit on April 26, 2013 (Ümit, et al.). This study was followed by two 2U-sized satellites developed within the scope of the QB50 project conducted by VKI as a European Union project. The first of these is “BeEagleSat”, developed together by ITU and the Turkish Air Force Academy. The second CubeSat was the “HavelSat” jointly developed by ITU and Havelsan.

These two satellites were followed by the UBAKUSAT satellite developed by ITU for the Ministry of Transport and Infrastructure, which is 3U in size. Along with these studies, new commercial initiatives have also started to emerge. One of the most successful examples of them is “Gumush Aerospace & Defence Company”, which was founded by a team that worked in ITU laboratories. The 3U-sized satellite ASELSAT, launched on January 24, 2021, was developed in partnership with ITU and GUMUSH. Another successful commercial enterprise established in our country is the Plan-S company. the company, which was founded in 2021, was able to successfully launch its first satellite, the 3U-sized Connecta T1.1 satellite, into orbit on May 25, 2022. The company, which aims to establish a satellite team (constellation), already has Connecta

T1.2 and Connecta T1.3 satellites in progress. In addition, Grizu-263 satellite, which is the first satellite in the pocket cube class in our country, was developed by Zonguldak Bülent Ecevit University and launched into orbit in 2022. Some of the CubeSat projects launched in our country and currently in progress are shown in Figure 1.10.



Figure 1.10 : Some of the cubeSat projects launched or ongoing in our country.

If we look at the continuing projects currently in our country, it is expected that the 3U-sized SharjahSat-1 satellite developed by ITU, Sabancı University and University of Sharjah (from the United Arab Emirates) will be launched in the first quarter of 2023. We can say that our country has achieved great success in high value-added space exports with this project. This success of project was continued with a 16U CubeSat project received and started at 2022 from Pakistan.

The 6U satellite PIRISat is one of the ongoing CubeSat projects developed by STM is aimed to use a space based Automatic Identification System on. In addition, one of the ongoing projects is the 3U sized n-ART One satellite, the details of which are not very well known. In the same way, there is a study called SSS-2B with a size of 3U, which was undertaken by TUBITAK Space Technologies Research Institute within the scope of the APSCO project (Kacmaz, Karakaya, Tola, & Atas, 2020).

1.3 Thesis Purpose and Overview:

This thesis study was completed as a result of a project carried out in the ITU-SSDTL (Istanbul Technical University- Space Systems Design and Testing Laboratory), which has made a major breakthrough in the field of CubeSats in our country in the last fifteen years. With the project supported by the Turkish Exporters Assembly, it is aimed to develop, test and produce multifunctional solar panels for use in nano and micro satellites with domestic facilities. After reaching the desired level in the following processes, it is aimed to be space-qualified by using it in a satellite project carried out in our laboratory. In this way, foreign dependency is reduced in an important subsystem component in a critical issue such as satellite technologies, while a process in which a transition from import to export will be aimed.

The existing knowledge in the ITU-SSDTL Laboratory has provided great opportunities, while getting me and my friends excited about the successful execution of this process. In addition, the support given to this project by our TUBITAK-MAM (The Scientific and Technological Research Council of Türkiye-Marmara Research Center) with the help of this research center, which contributes to this field with its current studies in our country, has increased the success of the project and paved the way for future studies.

In this study, after the documents prepared together with the literature study, the acceptance of the project support was approving by TIM (Turkish Exporters Assembly). After that the material procurement process was started. While determined the project process, the planning, integration, testing and analysis processes are determined with precision and are carried out within a calendar. At the first stage, some soldering experiences were made with the existing solar cells, and the experiences gained from this provided convenience in the integration of the actual cells. Cold-welding method and epoxy bonding methods were also used during the integration of solar cells to solar panels. Silver epoxy was preferred with a material called Areldite 2014-2 as epoxy. Various measurements were taken by performing Suction (Strain), Electro-Luminescence (EL) and Space Environmental tests of the produced panels. After the comparisons about the qualification of the data obtained from these measurements, it was seen that the expected impacts in the product outputs was achieved, and it made a positive contribution to future studies.



2. BACKGROUND

This thesis will provide a brief for introduction to the production processes, tests and results of multifunctional solar panels for nano and micro satellites and will shed light on future studies in this area in our country. In this study, issues such as efficient, undamaged and accurate integration, testing, verification of solar cells, which are obtained as a result of various researches, are discussed.

2.1 Solar Cells and Panels (PVA):

Solar panels (PhotoVoltaicArrays-PVA) are a key technology for generating electrical power in the space environment and powering the satellite's systems. Together with the developing semiconductor material technology, we provide most of our energy needs in space, thanks to solar panels whose efficiency is increasing day by day. The most important requirement in solar panels is that the cells can operate with an efficient, consistent and stable performance. Solar panels can be used in the Solar system with sufficient efficiency up to the outer orbit of Jupiter. Beyond that, radioisotope thermoelectric generators (RTGs) or other technologies should be used. Fortunately, since the orbits of our CubeSats are usually in the inner solar system, solar panels can provide our satellite's energy needs (Vertat & Vobornik, 2014).

The power generated by the solar panel is simply calculated as seen in Equation 2.1:

$$P = \eta_n \cdot S \cdot A \cdot \sin\varphi \quad (2.1)$$

Where;

η_n [%] is nominal sun energy conversion efficiency of used solar cells,

S [W/m²] is sunlight power density,

A is the area of solarcells on panels,

and φ [°] is the angle of sunlight irradiance measured from the panel base plane

This equation gives a simple value power generated calculation by solar panels. Normally, factors such as changing temperature, aging of solar panels and loss of

efficiency directly affect power generation and they should be included in the process when calculating generated power.

For larger mass satellites, Smart Solar Panels (SSPs) can be used to maximize the efficiency of the solar panels. The main purpose of SSPs is to keep the surface of the solar panels perpendicular to the sun's photons and to clean the surface of the panel from the influence of dust and other pollutants. With these two methods, the efficiency of solar panels can be maximized. In addition, by using the ADCS system, it is possible to actively direct the solar panels to the sun rays at the maximum level.

Since passive ADCS methods are generally used in CubeSats, it is aimed to obtain maximum energy source by covering all possible surfaces of the satellite with solar panels. Because the electrical energy to be obtained from PVA varies depending on the size of the panel surface and how long it is in contact with the sun's photons. The electrical energy capacity to be produced from these panels should be determined by detailed calculations and simulated on the ground, and the power of the satellite should be determined. Because cutting off the energy supplied to critical systems during the mission can have fatal consequences. For this reason, with an effective power management, it should be determined which system will work when, which system will stop when and which systems will be given priority.

If we need to give an example about the effect of the efficiency of solar panels on production, it will be enough to look at the image in the Figure 2.1. In the image on the left, you can see the calculations obtained from the CubeSat covered with cheap silicon-based solar panels with an efficiency of around 12%, while on the right, you can see the calculations obtained from solar panels covered with modern gallium arsenide with an efficiency of 27%. In the measurements made by placing the on the six walls of the CubeSat, the surface areas of both solar panels (54.6 cm²) are equal to each other (Vertat & Vobornik, 2014).

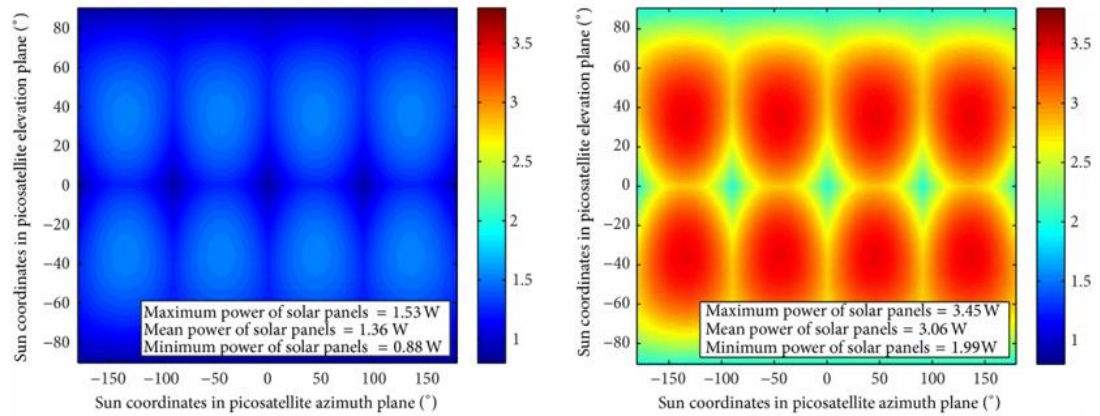


Figure 2.1 : View of the comparative solar panel simulation.

Solar panels are connected in series with each other. The higher output voltage of connecting panels in series results in higher efficiency of subsequent switched regulators. Also, the output voltage is more suited to the final voltage of Li-Ion or Li-Pol batteries, which helping to activate a safe direct battery charging mode in non-standard situations. In case of failure of any cell, there are protection circuits on the panels in order not to lose all other cells.

Solar panels are produced specifically for each satellite design. Different methods are used when mounting solar cells to solar panels. While designing the solar panel for the satellite, first of all, the energy need of the satellite should be calculated and the number of solar panels to be used and their locations should be determined. Then the process should be continue with the selection of suitable efficient solar cells. PVA production is a sensitive process. It is imperative to comply with certain standards and parameters in the production of PVA. In this way, the efficient operation of the satellite's only energy source can be guaranteed. It would be right to examine the requirements and parameters determined by the standards for PVA design.

2.2 PVA Design Requirements:

Requirements for PVA (Photo Voltaic Assembly) detail design performance, qualification, fabrication, and acceptance testing need to be determined. While determining these inputs, solar array specification, mission specification, ground test program and satellite design should be taken into consideration. All these requirements are specified in the design specification ECSS-E-ST-20-08C developed by ECSS and are universally accepted parameters (ESA Requirements and Standards Division, 2012).

2.2.1 Parts, materials and processes (PMP) parameters:

These parameters were determined with the help of the document ECSS-E-ST-20-08C_REV-1, Photovoltaic Assemblies and Components, prepared by the European Space Standardization Cooperation (ESA Requirements and Standards Division, 2012).

2.2.1.1 Outgassing:

Outgassing is the release of a dissolved, trapped, frozen, or absorbed gas in the material as a result of a change in environment (temperature, vacuum, etc.) (Prentice-Hall Physics Series, 1938).

Two measurements determine this parameter, which is also important in terms of space materials and tests. These; Recovered Mass Loss-RML and Collected Volatile Condensable Material (CVCN). RML is how much of the mass of the material is lost in the space environment, while CVCN is the amount of substance expelled from a condensed sample. In this parameter, the RML value of the materials to be used is 1% or less, and the CVCN value when heated to 125 °C during vacuum is required to be 0.1% or less.

2.2.1.2 Toxicity:

If any material harmful to human health is used in the production of PVA, this is the parameter that should be specified.

2.2.1.3 Flammability:

It is the parameter that tells that if any flammable material is used in the production of PVA, it should be specified its.

2.2.1.4 Corrosion:

It is a parameter that indicates that the supplier and the customer must agree on preventing corrosion during storage and use.

2.2.1.5 Magnetism:

It is the parameter that determines that permanent magnetic materials should not be used and that the use of non-magnetic materials is appropriate.

2.2.1.6 Erosion:

It is the parameter that determines the necessity of an erosion level that can tolerate the PVA materials without deterioration by the specifications.

2.2.1.7 Atomic oxygen (ATOX):

ATOX is produced by the photo-decomposition of molecular oxygen in the upper atmosphere by solar radiation with a wavelength less than or equal to 243 nm. Low-Earth-orbiting (LEO) atomic oxygen not only erodes the outer surfaces of polymers on the spacecraft but can also cause surfaces to deteriorate inside components on the spacecraft, where openings to the space environment exist. Atomic oxygen flow is dependent on altitude, solar activity, orbital inclination, and time (Rooij, 2010).

This parameter is a parameter that shows the tolerance level against deterioration caused by ATOX environment without deterioration in the performance of PVA.

2.2.2 PVA design parameters:

These parameters were determined with the help of the document ECSS-E-ST-20-08C_REV-1, Photovoltaic Assemblies and Components, prepared by the European Space Standardization Cooperation (ESA Requirements and Standards Division, 2012).

2.2.2.1 Cell integration:

This parameter indicates that solar cells should be configured to withstand all phases by the requirements of the task, can be replaced in case of any damage, and there should be a repair method that can be applied if needed.

2.2.2.2 Stringing:

This parameter specifies that if the block diode is used in the panel design, the plus end of the strings should be connected with the block diode with the panel. For performance measurement, each string should be measured separately. This parameter determines how the directories will be made in general.

2.2.2.3 Cell interspacing:

This parameter determines the minimum distance that should be left between cells. Thermal expansion and contraction, panel geometry and ESD requirements are the factors that determine this distance.

2.2.2.4 Sectioning:

This parameter is used to test the technique of linking strings together. For this, the negative ends of the arrays can be connected to represent the flight panels.

2.2.2.5 Reverse bias protection:

This parameter refers to the use of shunt diodes to protect solar cells exposed to reverse polarity. AOCS failure shadowing, self-shadowing, and power management are types of reverse bias.

2.2.2.6 Insulation:

This parameter is used for items to be electrically isolated from each other.

2.2.2.7 Derating:

It is the parameter related to the decrease of the current with temperature, that is, the decrease of the voltage ratio.

2.2.2.8 Redundancy:

It is a parameter related to backup. The details of this parameter are determined by ECSS-Q-ST-30 and ECSS-Q-ST-30-02 design specifications.

2.2.2.9 Fault tolerance:

It is a parameter that determines what the fault tolerance of the produced PVA will be and what values it will change depending on.

2.2.2.10 Fatigue resistance:

It is the parameter that indicates the necessity of verifying the effects of fatigue in the design of PVA with analysis and tests.

2.2.2.11 Adherence to substrate:

It is the parameter that describes the correct adhesion of the solar cells to the solar panel, remaining connected to the panel while fulfilling all task requirements, and being able to be tested and repaired/replaced when necessary.

2.2.2.12 Adhesive uniformity:

It is the parameter that states that the thickness limits of the adhesive used during the manufacture of PVA should be determined. When producing PVA, a controlled application process on individual samples must be guaranteed. The importance of this parameter was understood during the Suction or Strain Test and interpreted in the relevant section.

2.2.2.13 Electrostatic discharge (ESD):

It is a parameter that indicates that PVA, which is surrounded by a low-density plasma environment formed by high-energy electrons and protons in the spacecraft during and after launch, should not be affected by sudden discharge electrons. PVA must be able to withstand the charging environment and operating conditions specified in the tasks.

2.2.2.14 Electromagnetic compatibility (EMC):

It is the parameter that indicates that the PVA should be designed to meet specific EMC requirements.

2.2.2.15 Repairability:

It is a parameter that indicates that PVA should have the ability to disassemble, repair and replace parts up to the component level.

As you can see, there are a lot of parameters that need to be considered in the design of a solar panel. Considering that these panels are the life source of satellites in space, the necessity of these parameters for PVAs developed for satellites that have been dealing with for years will be understood once again. In the development studies carried out within the scope of the thesis, these parameters and the frameworks drawn by the design specifications were adhered to. In this way, it is aimed to use domestic solar panels that are both universally valid and verified and suitable for use in our country in the future.

2.3 ITU SSDTL Laboratory and Its Capabilities

With the increasing interest in space in our country, the "Space Systems Design and Testing Laboratory" and "Small Satellites Communications Laboratory" were established at the Faculty of Aeronautics and Astronautics of Istanbul Technical University to design pico satellites. Additionally added their existing facilities which eligible for improving small satellite to other laboratories (Vibration Labs of Mechanical EElectronic Labs of Electrics Electronics Faculties) at ITU, it has gained a rapidly growing structure in the fields of Nano/Micro satellite development and testing. In this way, it also hosted the development and testing stages of many nano/micro sized satellites developed in our country.

The fact that the design, development and testing processes of the recently developed SharjahSat-1 3U CubeSat of the United Arab Emirates were carried out at ITU SSDTL demonstrates the international recognition of the laboratory.

There is a 1000 class clean room measuring 25 square meters in the laboratory. There is a TVAC (Thermal Vacuum Chamber) unit used in the tests for vacuum and thermal control and various measurement equipment in the clean room. You can see whose visuals belongs to this clean room are shown in Figure 2.2. The clean room, which was first used for the verification of the design, development and testing phases of the ITUpSat-1 satellite, after it was subsequently used in many satellite projects, subsystem development projects (ITU SSDTL Laboratories, 2022).



Figure 2.2 : View of clean room established at the ITU-SSDTL laboratory (Credit:ITU-SSDTL).

Owing to the TVAC unit shown in Figure 2.3, it is possible to simulate the vacuum and temperature parameters that satellites will be exposed to in space environmental conditions. Owing to thermal cycling tests, how satellites and subsystems will behave

in space after launch and mission performance efficiencies can be predicted. TVAC unit, which is frequently used in solar panel development processes, has been used.



Figure 2.3 : TVAC unit located in the ITU-SDTL laboratory.

If we look at the general properties of the Thermal Vacuum Chamber unit;

- 350 lt Volume
- 10–5 Pascal Pressure
- -60 °C – 125°C Temperature Range
- 1-3 degree/min. Temperature Control (ITU SSDTL Laboratories, 2022)

ITU SSDTL Laboratory also has equipment and measurement tools to support external nano/micro satellite development, integration and testing processes. In addition, since the ITU SSDTL laboratory is located in an educational institution (Istanbul Technical University), it is frequently used in trainings, thus serving our country in terms of training qualified manpower. It is a great chance to have such a laboratory at the university level in our country. I would like to thank the forward-thinking people who brought this service to our country.

2.4 TUBITAK Marmara Research Center and Its Laboratory Capabilities:

TUBITAK MAM Research Center is another government institution that is competent in producing solar panels working in the field of space in our country. Solar energy

research, which started in the 2000s within the Research Center, gained momentum with the project of creating a Photovoltaic Module Production Line.

The National Solar Power Plant Development Project (MILGES), which was initiated with the support of the state in 2014, has enabled the work in this field to progress at a higher level. In the MILGES project, TUBITAK MAM Energy Institute, ODTÜ GUNAM (Center for Solar Energy Research and Applications) and Bereket Enerji Uretim A.Ş. are the executive partner institutions. The work continues at full speed within the scope of the project, which aims to localize the needs of solar energy equipment and to provide an infrastructure that paves the way for exports (TUBITAK Marmara Research Center, 2014).

After TUBITAK MAM's knowledge and experience in the field of solar energy was further increased with the terrestrial solar panel development project, the space qualified solar panel development project for the satellite named IMECE continued with the goal of producing materials for space by going to the upper league. Solar panel design and production processes are carried out in the Photonic Technologies Laboratory located in the research center. In this laboratory, both high-efficiency solar cell research activities based on heterojunction silicon technology and new generation cost-effective solar cell research activities based on nano-structured silicon, organic and perovskite technologies are carried out. In addition, thanks to the Mechanical Testing Laboratories located in the center, resistance tests of solar cells integrated into the solar panel can be performed (TUBITAK MAM Research Center, 2018).

Within the scope of the thesis, TUBITAK MAM Research Center was visited and its experiences were benefited from and laboratory facilities were used.

3. DESIGN AND TESTING OF MULTIFUNCTIONAL 1U SIZED SOLAR PANEL

In this section, the design stages of solar panels, which are aimed to be developed for nano and micro satellites, are mentioned. This thesis study has emerged as a result of a project carried out in the ITU-SSDTL Laboratory and it is thought that it will become more beneficial for our country by being developed. The importance and requirements of the project have been explained in detail in the previous sections. According to the detailed literature research done before starting the project, it was decided which methods should be tried in solar panel production.

After the literature review, detailed project planning and scheduling processes were started, and a project document was created and presented to the Turkish Exporters Assembly for their support for the project. After the acceptance of the project and the signature of the relevant protocol, the project work started.

3.1 Method and Material Selection Processes

In this study, two different method processes were selected. The first method choice was a method selection regarding how solar cells will be connected to each other. As a result of the researches, it was decided to try the conventional soldering and cold-welding methods in order to create a coupon to connect the solar cells with each other.

The second method choice is related about how method will be useful for mounting solar cells to the solar panel. In this study, three methods were initially considered for this method. These; mounting with epoxy-based adhesive materials, mounting with silver epoxy-based adhesive materials and mounting with double-sided tape. Due to the busy schedule of the project, only epoxy-based adhesive material (Arelidite 2014-2) could be used. The other two methods will be tested in future works and compared with the necessary tests. These studies and tests were recommended in the future studies section.

It is aimed to make an effective trade-off while determining the materials to be used in the thesis. In this way, it is aimed to achieve the most effective results with a limited budget. First of all, I would like to give information about the selection study of solar cells. The main criteria

taken into account in the solar cells foreseen to be used within the scope of the project are cost effectiveness, being space-qualified, and ease of procurement process.

In this context, when the solar cells owning space-qualified in the sector are examined, it is seen that the 3G30A solar cells belonging to AZUR Space are widely used. To give a few examples of companies that use this solar cell in their panels; ISISPACE corporation, EXA R&D Institution (Ecuadorian Space Agency) and DHV corporation use solar cells of Azur Space firm in their solar panels. You can see the visuals of the panels belonging to these companies from left to right in Figure 3.1, from left to right in order of corporation.

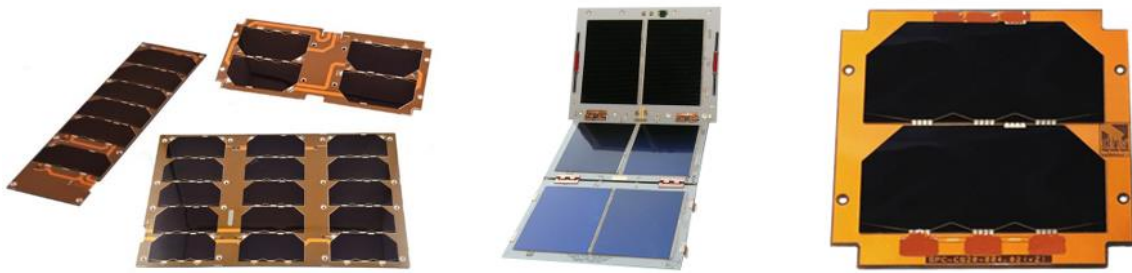


Figure 3.1 : Example solar panels produced by some corporations.

3.2 Selected and Used Solar Cells:

In our study, Triple Junction GaAs Solar Cell Assembly solar cells with model number 3G30A manufacturing by AZUR Space company were used in terms of widespread use advantage and compliance with trade-off selection criteria. These solar cells which has 30% efficiency advanced, are type of a triple junction solar cell. Upper layer consists of Indium Gallium Phosphide (GaInP), middle layer consists of Gallium Arsenide (GaAs) and bottom layer consists of Germanium (Ge). It is equipped with external silicon bypass diode, interconnectors and cover glass Design and mechanical data of the 3G30A solar cell was shown in Table3.1 (AZUR Space, Solar Power GmbH, 2010).

Table 3.1 : Design and mechanical data of 3G30A solar cell.

Properties	Data
Base Material	GaInP/GaAs/Ge on Ge substrate
AR-coating	TiO _x /Al ₂ O ₃
SCA Dimensions	40.15 x 80.15 mm ± 0.1 mm
Cell Area	30.18 cm ²
SCA Average Weight	≤ 118 mg / cm ²
SCA Thickness	280 ± 25 μm
Coverglass type	CMX 100 AR
Coverglass thickness	100 μm
Interconnectors (2x front side/ 1x diode)	Kovar, silver coated
Dimensions (interconnector)	6.5 x 7.53 mm
Interconnector thickness	25 μm
Bypass protection	External Si diode

As seen in Table 3.1, an external silicium diode was used in the cell with the aim of bypass protection. This diode is called a bypass diode. When the sun's photons reach the cells, voltage and current occur on the cells. When the voltage is constant, the changes in the current reduce the power of the cell depending on the intensity of the sun's photons or whether the panel is exposed to the sun.

Bypass diodes are connected in parallel to create a current diagram in case of this current change or failure of the cell or panel. In this way, even if one or a part of the cells fails, the remaining solar cells in the panel will continue to produce power at full capacity. Considering that solar panels are our only energy source for CubeSats, the importance of this bypass diode will be understood once again. As an extra, electric data was shown in Table 3.2 (AZUR Space, Solar Power GmbH, 2010).

Table 3.2 : Electrical data (SCA) of 3G30A solar cell.

Properties	Unit	BOL	2.5E14	5E14	1E15
Average Open Circuit Voc	[mV]	2690	2606	2554	2512
Average Short Circuit Isc	[mA]	519.6	517.9	513.4	501.3
Voltage at max. Power Vmp	[mV]	2409	2343	2288	2244
Current at max. Power Imp	[mA]	502.9	501.7	499.1	485.1
Average Efficiency η_{bare} (1367 W/m ²)	[%]	29.3	28.4	27.6	26.3
Average Efficiency η_{bare} (1353 W/m ²)	[%]	29.6	28.7	27.9	26.6

Within the scope of the project, it is aimed to produce a 1U cube sizes satellite panel. In this context, twenty solar cells were supplied. The supplied solar cells are shown in Figure 3.2. It is foreseen that the 3G30A solar cell with Triple Junction will be sufficient in all design, production, integration and testing phases. In addition to these solar panels, experience has been gained by working with demo solar cells provided by TUBITAK MAM. In addition, old solar

cells that have completed their economic life in the laboratory were also used for experimental purposes within the scope of the study.



Figure 3.2 : Supplied and used solar panels.

3.3 Selected and Used Adhesives:

As a result of the researches, it was foreseen to use the adhesives named Araldite 2014-2 and Araldite AV 138M & Hardener HV998 produced by Huntsman company as epoxy-based adhesive. Since the adhesive named Araldite AV 138M & Hardener HV998 could not be supplied, Araldite 2014-2 adhesive was used in the production and testing processes. In addition to these adhesives, a silver epoxy named EPO-TEK H20E-PFC, produced by Epoxy Technology firm, was supplied to be used with the aim of as a different method. Production and testing processes could not be carried out with this silver epoxy during the ongoing processes within the busy of the project schedule. This topic is covered in the future works section.

Let's talk about the main reasons for using Araldite 2014-2 adhesive for mounting solar cells in solar panels. This adhesive is a high temperature resistant adhesive brought by space environmental conditions, and also properties of chemical resistant is sufficient. Also, gap filling with non-sagging up to 5 mm thickness is very distinguishing and special advantage from the others.

3.4 Design And Testing Processes

After the material selection and supply, studies was started in order to have detailed information and application experience about the development of solar panels and the applied methods. The

studies started with old solar cells, which were in the laboratory and procured for old projects but could not be sent to space. In this way, the newly procured and suitable cells for use in space were prevented from being damaged in the process of gaining experience. In addition, experience has been gained in solar panel production, testing and verification methods through experiments with demo cells developed by TUBITAK MAM. Most of the development processes and testing phases took place in the ITU-SSDTL Laboratory. TUBITAK MAM laboratory and facilities have also been used to a great extent.

3.4.1 Design processes:

3.4.1.1 Conventional soldering method:

First, conventional soldering practice were carried out on old solar panels in the laboratory. As a result of these trials made with the classical soldering method, since the classical soldering is very difficult for solar panels, the cell is damaged locally when the soldering machine is heated too much, but the solder does not melt when it is underheated, so healthy soldering could not be made. However, as a result of long efforts, two of the old cells were soldered to each other and a test coupon was prepared as seen in Figure 3.3. Although it was not a very successful soldering process, it was a very useful work in terms of mounting on the panel and gaining experience. In later studies, the soldering process was further improved. However, as will be discussed in detail in the results section, the cold-welding method is a more accurate and successful method than the soldering method.

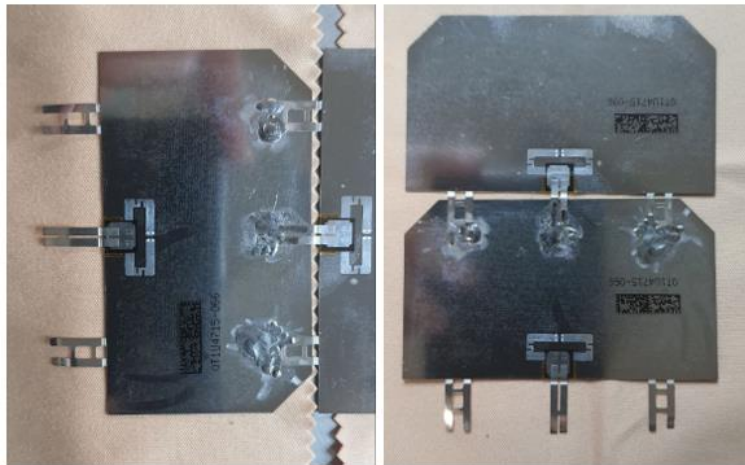


Figure 3.3 : First try coupons with conventional soldering method.

After the first soldering experiences, by trying different methods and increasing the hand sensitivity, as can be seen in the Figure 3.4, the solders were more smooth. However, partial deterioration and faults in solar cells was observed in both visual inspections and Electro-

Luminescence tests due to the heat of the soldering iron. For this reason, it can be easily said that the classical soldering method is not very successful in the process of combining solar cells into coupons before mounting them on the panel.



Figure 3.4 : Last try coupons with conventional soldering method.

3.4.1.2 Cold-welding method:

As the name suggests, Cold-welding method is a some welding method. It is a solid state welding process that requires little or no heat or fusion to join two or more metals. With this method, solar cells are stringed into coupons. In this way, coupon are obtained with an effortless and effective method. However, an extra device is needed to apply this method. In Figure 3.5, you can see the double coupon produced at TUBITAK MAM facilities for this study.

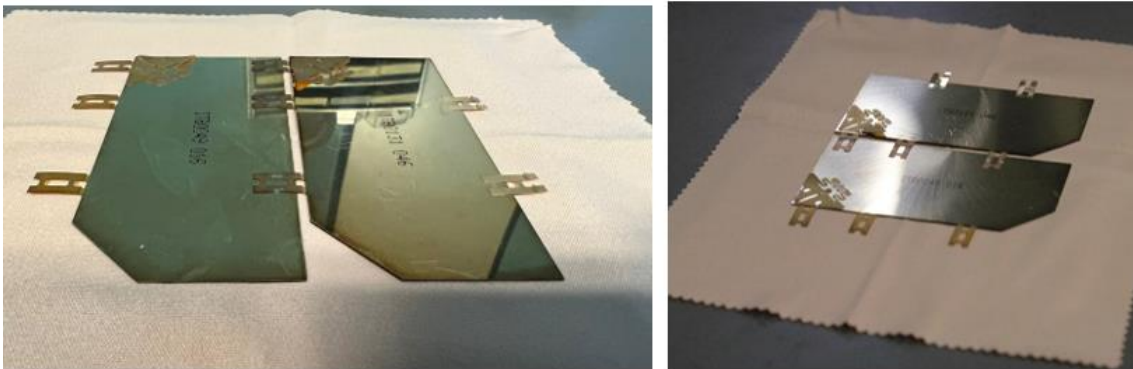


Figure 3.5 : Test coupons produced with the cold-welding method.

3.4.2 Solar panel design process:

For panel production, a suitable for 1U size panel platform, and double coupon shown in Figure 3.6, supplied from TUBITAK MAM and combined with the cold-welding method, was used.



Figure 3.6 : Test coupons developed at TUBITAK MAM.

Areldite 2014-2 adhesive was used for mounting the coupon to the panel and EPX brand manual application gun produced by 3M company was used to apply this adhesive. Compatible apparatus for the application gun has been provided and made ready for use as seen in the Figure 3.7.

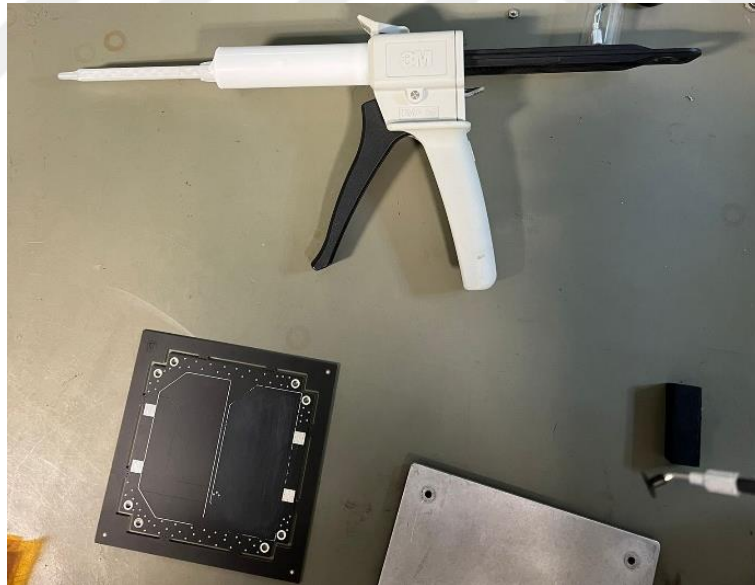


Figure 3.7 : 1U panel base and 3M brand adhesive application gun.

By turning the prepared solar panel coupon upside down, with the help of the application gun, adhesive drops were left at regular intervals as seen in the Figure 3.8.



Figure 3.8 : A view of adhesive application for mounting coupon to solar panel.

This application is a process that requires experience. If the adhesive cannot be left at equal intervals and the amount of adhesive released is not equal, breakage or deterioration occurs in the cells during the suction test. Figure 3.9 shows the state of the trial panel made for this sensitivity measurement after the suction test. While the adhesive drops are equally spaced and of equal volume in the upper cell, the adhesive drops are equally spaced in the lower cell, but they are not of equal volume. This wrong application resulted in the breaking of the cell below after the suction test.

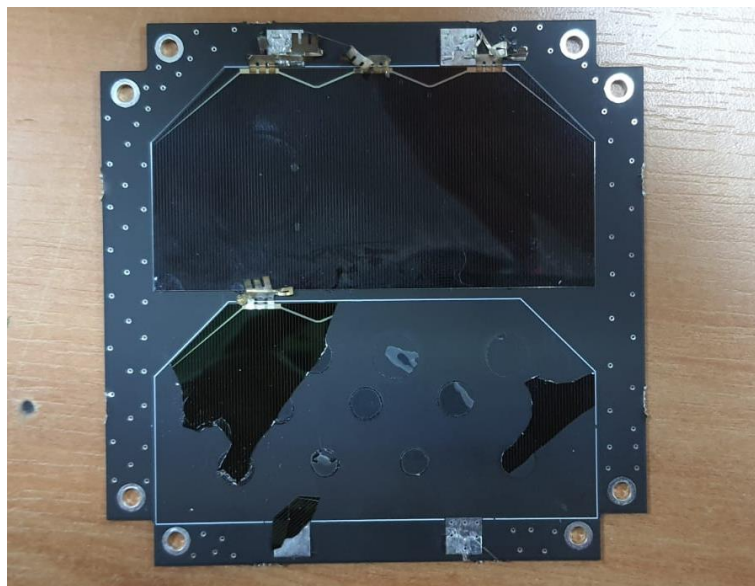


Figure 3.9: Solar cells that break (lower cell) and remain intact (upper cell) after suction test.

In Figure 3.10 you can see the successful gluing (mounting) processes of the double coupon to the solar panel. After the panel assembly process, the cleaning process was performed and visual inspections and Electro-Luminescence were tested, and it was made ready for the tests in the TVAC unit, where the space environmental conditions were simulated.

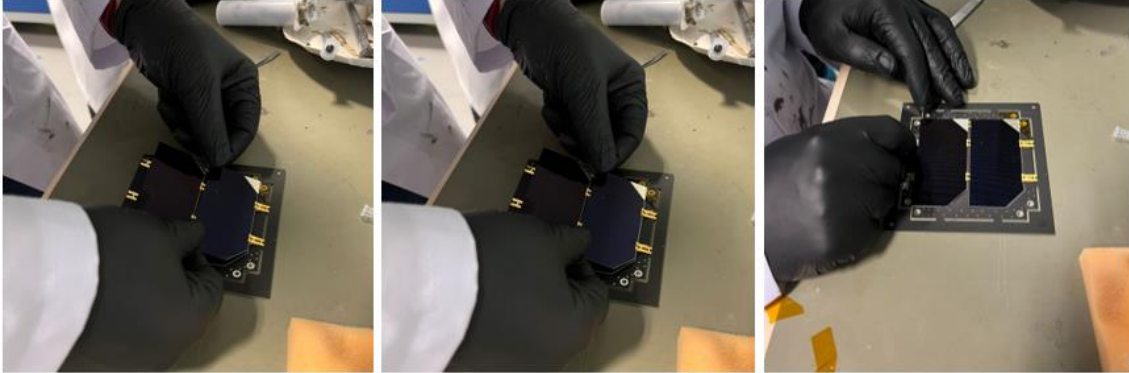


Figure 3.10 : Mounting phase of the double coupon on the panel board.

3.4.3 Panel PCB card design:

Within the scope of the project, a genuine printed circuit board including magnetorquer was designed and produced by the engineers of ITU-SSDTL Laboratory to be used in a 1U CubeSat. In this way, it is aimed to make a positive effect to the ADCS system with the presence of magnetorquer feature in the panels. You can see the top view of the designed PCB card in the Figure 3.11.

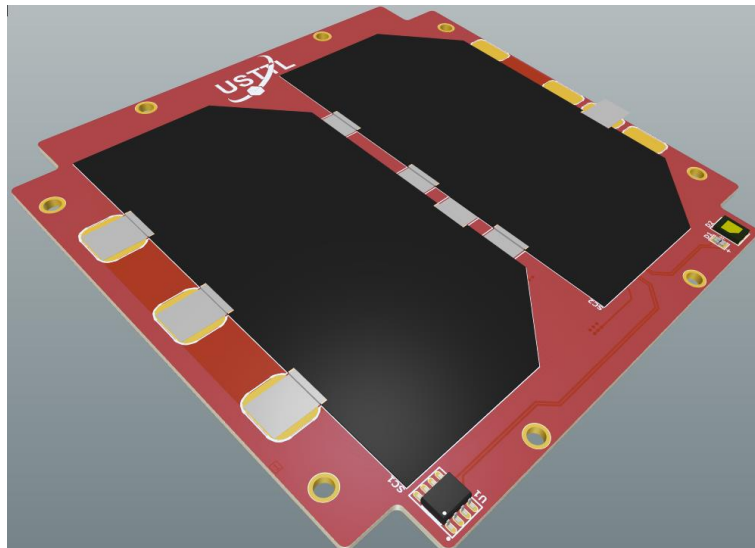


Figure 3.11 : Top view of the developed PCB.

3.4.3.1 Technical details of the PCB:

While keeping compactness, the design of the panel also aims to implement improved functionality. Therefore, the panel was populated with several peripherals: solar cells,

temperature sensor, photodiode and a coil that is embedded inside the panel. All of these peripherals can be connected over single panel connector. Compact design and the design of the coil inside the panel, required the panel PCB to have 4 layers. While bottom and inner layers are used for the coil connections, the top layer used for the connections of other peripherals. You can see the layers and schematic diagram of the PCB in Figure 3.12.

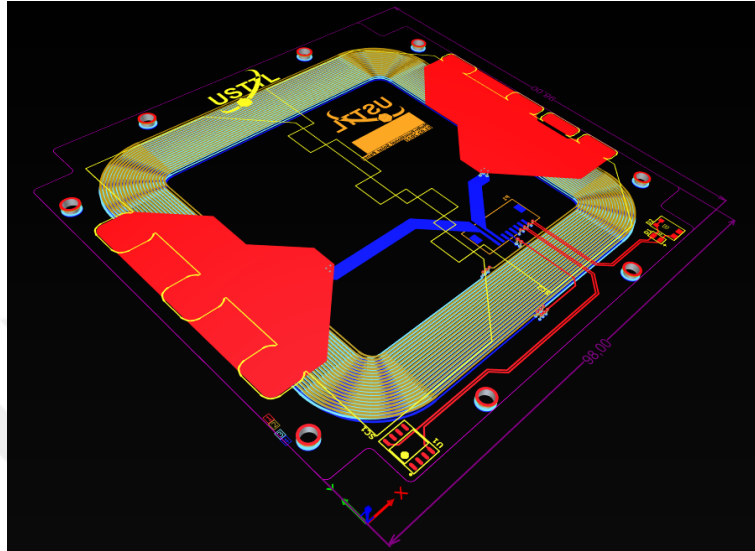


Figure 3.12 : Schematic view and layers of the developed PCB.

3.4.3.2 Peripherals of the PCB:

Solar cells: The panel includes 2 Azur Space 3G30A solar cells connected in series. The voltage and current of the single cell being 2409mV and 502.9mA respectively, with two cells connected in series, a power generation level of 2.42 watts can be reached.

Temperature sensor: The panel includes one Texas Instruments LM335A precision temperature sensor. Extended operating temperature range of -55°C to $+150^{\circ}\text{C}$ enables the sensor to be used in very harsh environments. Linearity and low impedance of the signal output, enables the sensor to reach up to 0.5°C temperature accuracy.

Photodiode: The panel has an option to use one of the two different photodiodes: Vishay Semiconductors VEMD1060X01 or VEMD5060X01. Even though each sensor has very distinct and different properties only a single photodiode can be populated at the same time. The technical properties of these photodiodes as shown in the Table 3.3.

Table 3.3 : Technical properties of photodiodes VEMD1060X01 and VEMD5060X01.

Photodiode	VEMD1060X01	VEMD5060X01
Angle of Half Sensitivity	± 70	± 65
Sensitive Wavelength	350 to 1070nm	350 to 1070nm
Radiant Sensitive Area(mm ²)	0.23	7.5
Size (LxWxH in mm)	2x1.25x0.85	5x4x0.9

Coil: To increase total number of coil inductance the tracks of the coil separated in to 3 layers, two of them being inner layers of the panel. The coil consists of 60 turns in total. Where each layer has 20 turns.

3.4.4 Testing processes

While determining the test stages, the previously stated design specifications were adhered to. In this way, an effective testing process has been experienced.

3.4.4.1 Visual inspections:

Before Visual Inspections, the panels should be carefully cleaned with a special cotton swab and special alcohol solution as shown in the Figure 3.13.

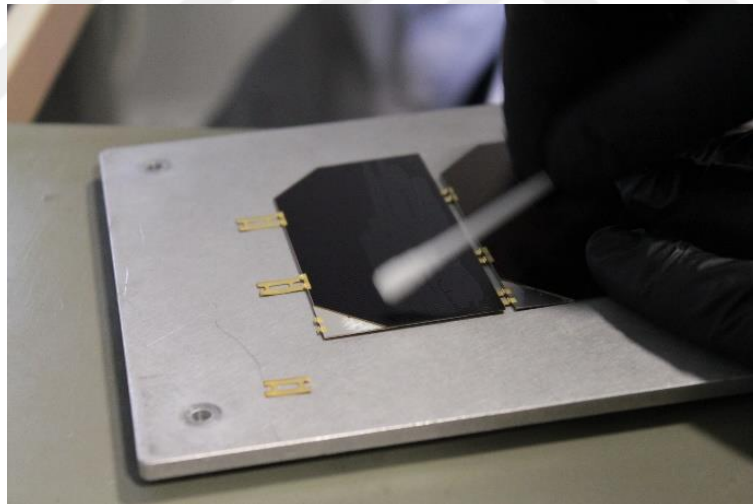


Figure 3.13 : Preparing cells for visual inspections by cleaning.

Solar cells are examined under a 15X microscope to detect any defects or damage. You can see the visual inspection process in the clean room in the Figure 3.14. This visual inspection is important in terms of detecting any errors or defects before proceeding with the assembly process (Khorchef & Kimber, 2019).

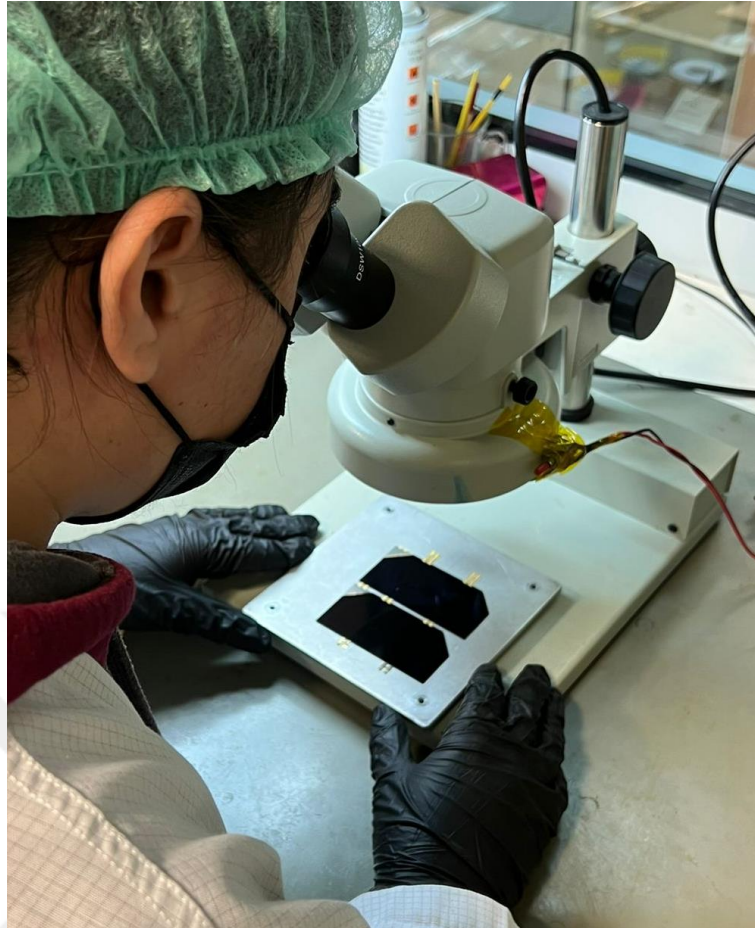


Figure 3.14 : A view from visual inspections process.

3.4.4.2 Electro-luminescence (EL) test:

Electro-luminescence test; enables the determination of the damages or defects that occur during the manufacture or assembly of solar panels on a cell basis. Thanks to this test, which is an x-ray of the panels, it provides early detection of future problems with damage and defect detection. In these tests; we energize the solar panel and turn it into the infrared heaters we know. Yes, we burn the solar panel like a lamp, and in this way, these micro-cracks that cause loss of efficiency are detected. The EL test alone does not give us information about the strength of the panel but gives detailed information about the damage status of the cells in the panel. Fractography can also be done using electro-luminescence to analyze the crack pattern.

EL tests were started with the help of a two-cell panel prepared with old solar cells and a power supply as shown in the Figure 3.15. The cells were powered with a voltage of 2.5V and a current not exceeding 0.1A per cell. These data should not exceed the working voltage called VOP in the datasheet of the cells. This test can damage cells even if it is a little. To prevent this, cells can be tested at lower powers with advanced imaging systems. Since we did not have such an opportunity in this study, these tests were carried out at a visible level in a dark environment.

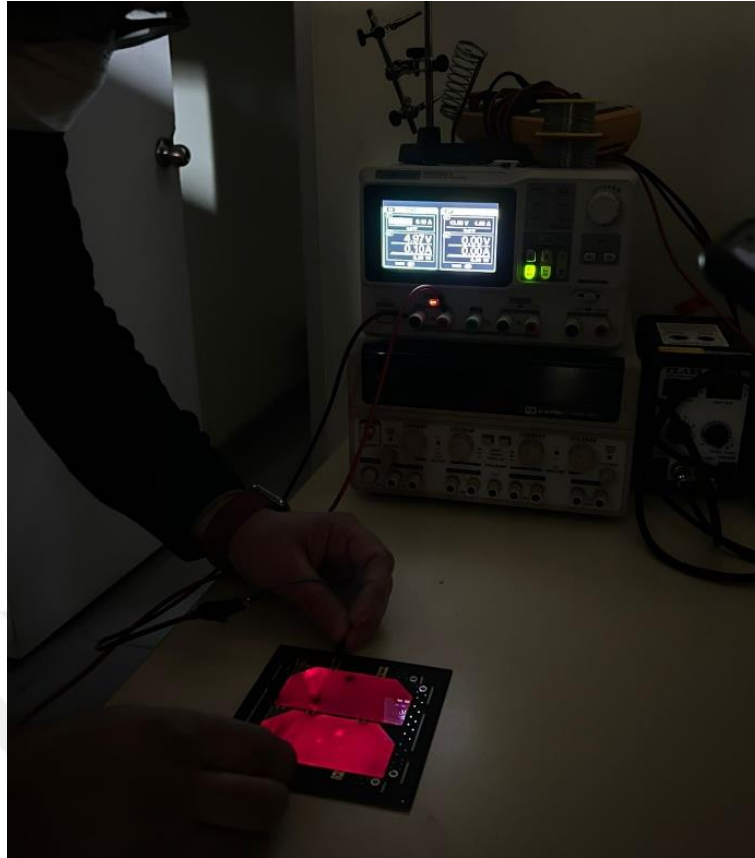


Figure 3.15 : EL tests setup with old solar cells and a power supply.

In the EL test in Figure 3.15, the damaged areas in the cells are seen. EL tests are recommended control tests before and after solar panel installation. Thanks to this test, it is aimed that the cells to be used in the real model of the satellite are undamaged and perfectly located.

The EL test is also performed before and after the space environmental conditions (TVAC) test. In Figure 3.16, you can see the EL test image (left) taken before the panel undergoing the test in the TVAC test unit and the EL test image (right) taken after the TVAC.

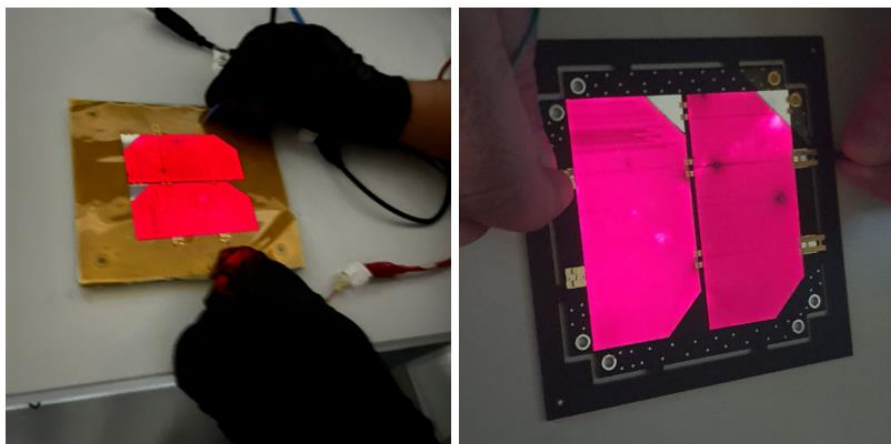


Figure 3.16 : EL test image taken before the TVAC test (left) and the EL test image taken after the TVAC test (right).

3.4.4.3 Suction or strain tests (before TVAC tests):

These tests were carried out in the Mechanical Systems Laboratory at TUBITAK MAM Research Center. The purpose of these tests is to check whether the solar cells are correctly mounted on the panel. For this, the tensile machine in the Laboratory was used. This tensile machine has the same structure as the classical tensile testing machines in terms of working logic. As seen in Figure 3.17, it has heads called suction heads in order to grasp the solar cells.

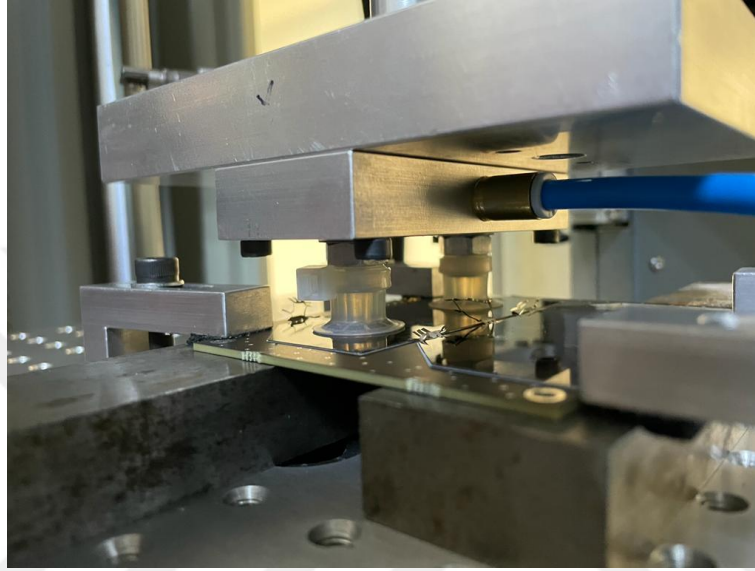


Figure 3.17 : Suction test setup.

Thanks to these suction heads, the holder head adheres to the solar cells and applies a force in the direction of separating them from the panel. If the force is continued until the breaking point, either the cells are broken or they are separated from the panel. Sometimes, it can be observed that the suction heads were separated from the cells after a certain point.

In our study, strain test was first performed on the demo solar panel prepared by TUBITAK MAM personnel. Here, we learned how the process was done and took part in a real test.

First of all, the demo solar panel was rigorously connected to the tensile machine and made ready for strain test. Afterwards, the test was started by running the tensile test machine. Figure 3.18 shows the connection of the panel to the tensile machine and the start of the test.

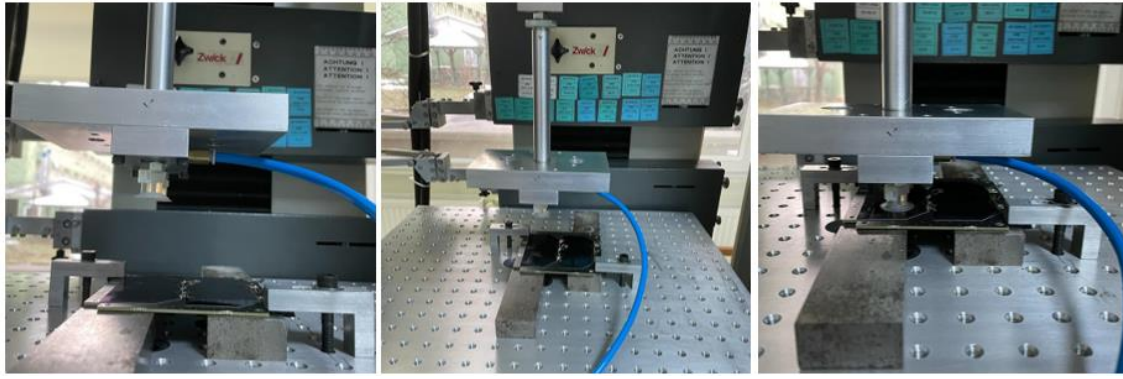


Figure 3.18 : The image of connection of the panel to the tensile machine.

In the tensile test, a 1kN Load Cell was used. During the test, it is seen that the adhesion strength of the panel withstands up to 25 N. As a result of this test performed with a speed of 1mm/min, suction heads could hold onto the panels up to 25N. These heads were then separated from the cells, but the cells remained intact on the panel without breaking.

Later, with the help of TUBITAK MAM personnel, a two-cell coupon, which was previously combined with the cold-welding method, was mounted on the panel using Areldite 2014-2 adhesive. While mounting, the volume and spacing of the adhesive drops were adjusted in accordance with the design specifications for the upper cell as mentioned before, while the volume of the adhesive drops corresponding for the lower solar cells was not taken into consideration. After waiting for the curing time, the panel was made ready for the tensile test. The test conditions applied to this panel are the same as the test conditions applied to the demo panel. The adhesion strength applied to the panel was brought to 25N, and after waiting for a while, it was observed that the cell at the bottom of the panel was broken.

The fact that the cell was broken at a holding strength of 25N was an instructive experiment in terms of how sensitive the cells should be while mounting them to the panel. As can be seen in the Figure 3.19, while the lower cell is broken and dispersed to a great extent, there is no problem in the upper cell.

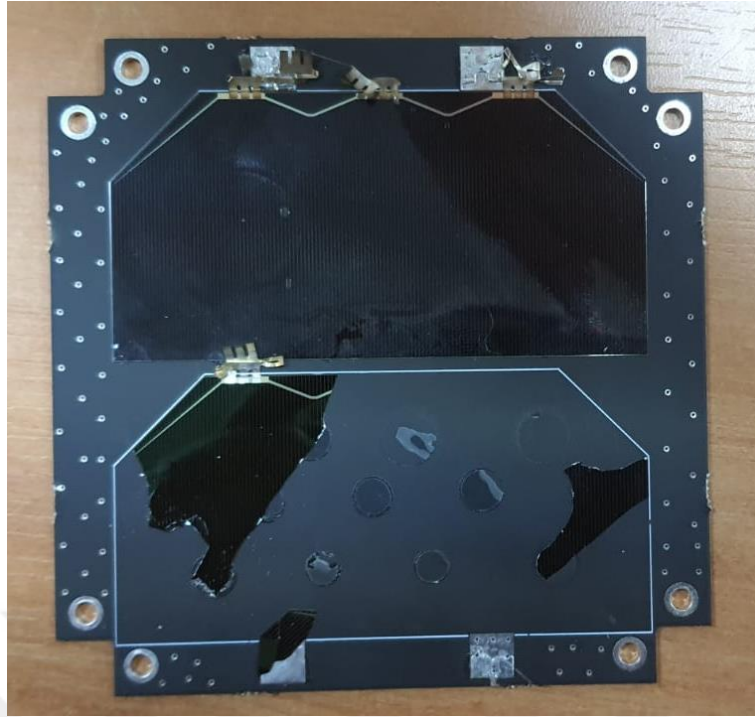


Figure 3.19 : The state of the produced panel after the suction test.

3.4.4.4 Space environmental conditions (TVAC) tests:

An orbiting satellite and its subsystems must be resistant to harsh space conditions. These harsh environmental conditions are vacuum, radiation, and temperature changes. For two of these challenging conditions (vacuum and extreme temperatures), test units called thermal vacuum chambers (TVAC) have been developed. In TVAC, satellites are put to the test by simulating space environmental conditions (Ümit, et al.).

There is a thermal vacuum chamber within ITU USTTL with a volume of 350 lt, which can decrease to 10^{-5} Pa pressure and can change the ambient temperature between -60°C and approximately $+125^{\circ}\text{C}$. All manufactured and ready-made systems are tested one by one at this TVAC before the satellite is launched. All systems are tested individually or together as a system in TVAC at varying ambient temperatures. The problems that arise are corrected and the satellite system is made ready for flight without any problems (Ümit, et al.).

We tested our solar panels, which were developed for a 1U satellite in the future, in this TVAC unit in the ITU-SSDTL laboratory. In this way, a test was carried out by the design specifications on how the produced solar panels will behave in space environmental conditions and the suitability of their use as a satellite subsystem.

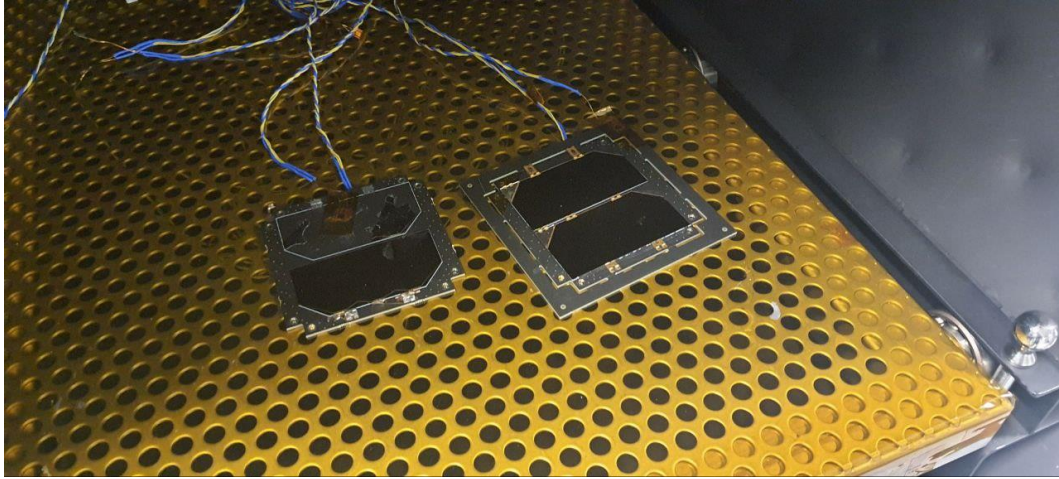


Figure 3.20 : Image of the demo panel and the manufactured panel being placed on the TVAC unit.

The prepared test coupons were placed in the TVAC room as seen in the Figure 3.20. The solar panel, the one which was damaged after the suction test, was also included in the test process for data collection. The system was made ready for testing by connecting sensors to the solar panels placed in the TVAC room to take measurements from four points (each panel has two measurement points). During the test starting from 0°C, the solar panels were tested to make two cycles between -30 °C and 70 °C. During the test, measurements were taken every five seconds and recorded. During the test cycle, which lasted approximately fourteen and a half hours, 10342 pieces of data were obtained.

After the successful TVAC test, the solar panels were removed, cleaned for the Electro-Luminescence test, and passed through visual inspections. The images of the EL test of both coupons are shown in Figure 3.21.

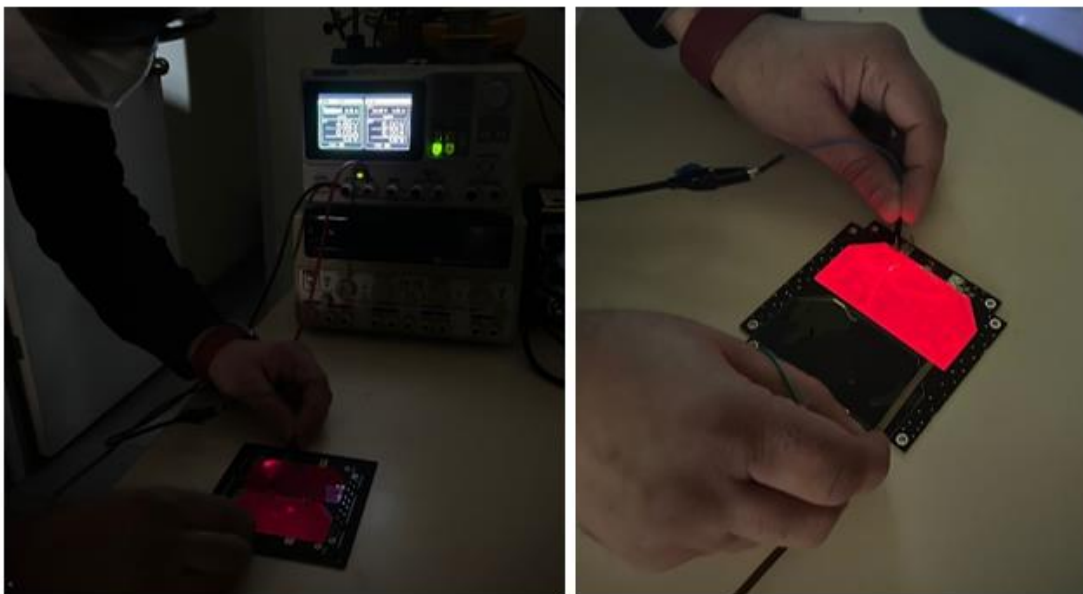


Figure 3.21 : EL testing for each panel after the TVAC test.

3.4.4.5 Suction or strain tests (after TVAC tests):

Solar panels that pass the TVAC test are subjected to a tensile test once again to test the suitability of their adhesion strength. After the TVAC test, the panels were taken back to TUBITAK MAM to repeat the tensile test. As in the previous tests, the tension device and panels were prepared and the tests were started. This time in the test carried out on the demo panel, the holding strength was increased up to 80N.

Since these demo panels have been tested many times before, they were not tested at a higher holding strength. No problems were observed in the 80N adhesion strength applied on the panel. In this state, it can easily be said that it was much higher than the value specified in the design specifications.

After the tensile test of the demo panel, the panel whose lower cell was broken in the previous strain test was subjected to the tensile test in the same way. Although the holding strength was increased up to 100N in the tensile test, no faults or defects occurred in the cell. it can easily be said that a result far above normal design specifications was obtained.

4. RESULTS & DISCUSSIONS

Within the scope of the thesis, two of the production process methods (conventional solder method and cold-welding method) related to the assembly of solar cells, which were determined at the beginning, were applied. In these two methods, an important knowledge and experience infrastructure has joined our laboratory and ourselves, and it will have a positive effect in future studies. When we compare these two methods with each other, the conventional solder method is easier to apply and it is a method familiar to many people dealing with electronics. However, partial deterioration in solar cells was observed in both visual inspections and Electro-Luminescence tests due to the heat of the soldering iron. For this reason, it can be easily said that the classical soldering method is not very successful in the process of combining solar cells into coupons before mounting them on the panel.

The other method, Cold-welding, is a bit more difficult to apply than the other method, as it is done with less used, additional experience and not commonly used equipment. However, when the necessary equipment is provided and after a short experience, this method is in a structure that can be easily learned and applied.

In the other method, no matter how careful the cells are, they are affected by heat. However, since there is no such problem in the cold-welding method, much more successful results have been obtained compared to the other method. It is foreseen that this method will be used directly in future studies.

Although three different methods were originally thought to be used to mount the coupons on the solar panels, only one of them could be used due to the project schedule constraints. The coupons are mounted on the panel only with epoxy-based adhesive (Arelidite 2014-2). Trials of bonding with silver epoxy-based adhesive and double-sided tape are left for future studies.

As a result of the tests carried out, it can be said that the Arelidite 2014-2 adhesive selected for assembly performed better than expected. The success of this adhesive has been proven, especially when the panels after TVAC can withstand 80N and 100N adhesion strength, respectively. After the experiment in which the sensitivity of the bonding process was measured during the assembly process, the solar cell (lower cell) that was not adhered with the appropriate

method was separated and broken in the panel. A good experience has been gained with this trial, which shows how important it is to comply with the design specifications in the production process.

The results obtained from tensile test applied on demo panel before the TVAC test and the test report received from TUBITAK MAM given are shown in the Figure 4.1.

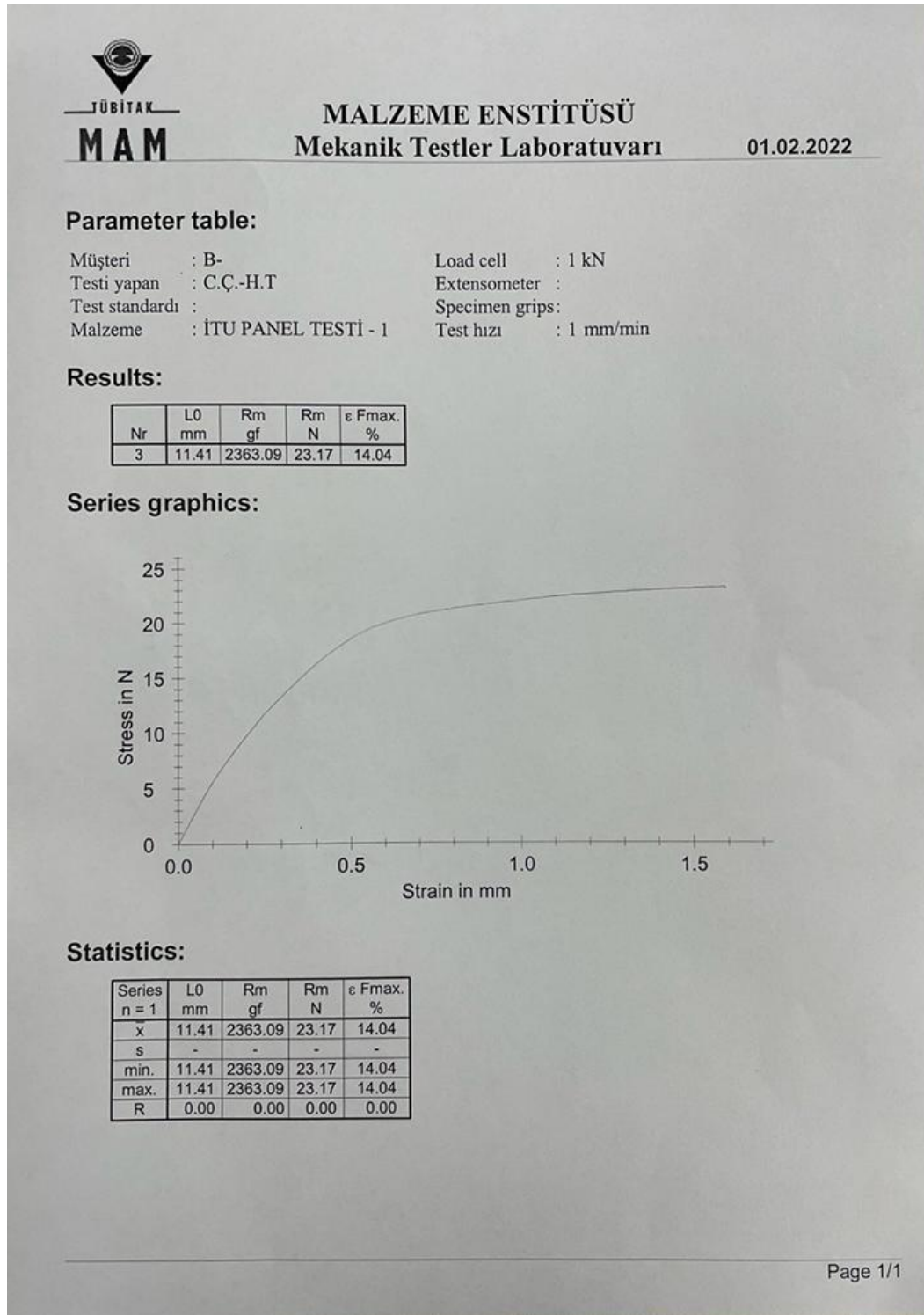


Figure 4.1 : Suction test report made to the demo panel before TVAC test.

The results obtained from tensile test applied on panel produced before the TVAC test and the test report received from TUBITAK MAM given are shown in the Figure 4.2 The lower cells of this panel, which were not fully adhered with the appropriate method, were broken and damaged at 25N holding strength.

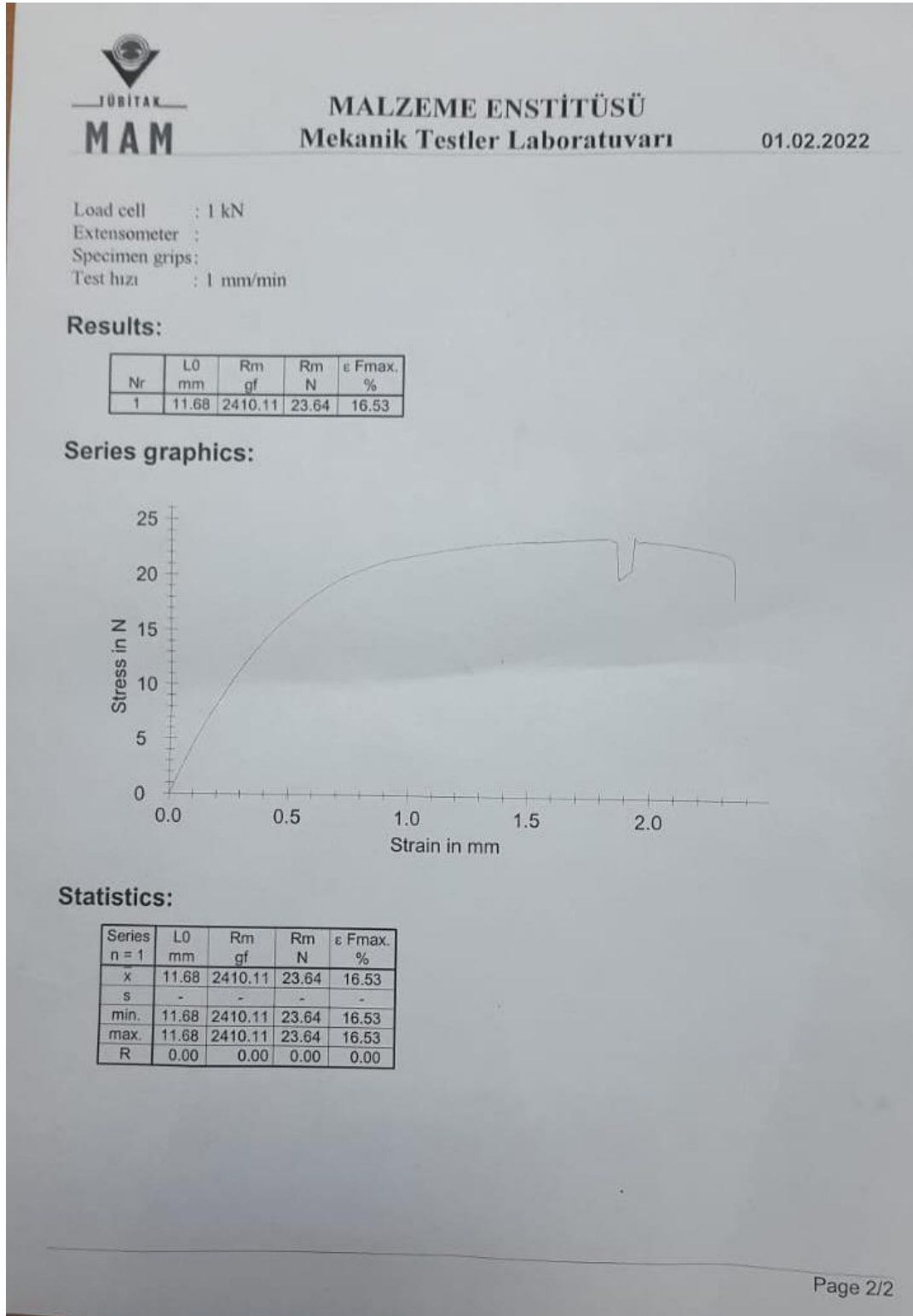


Figure 4.2 : Suction test report made to the produced panel before TVAC test.

The results obtained from tensile test applied on demo panel after the TVAC test and the test report received from TUBITAK MAM given are shown in the Figure 4.3. The panel was tested by increasing the adhesion strength to 80N and its was tested for this value. This value is well above the 25N value determined in the design specifications, and we can say that the demo panel prepared successfully passed the current tests.

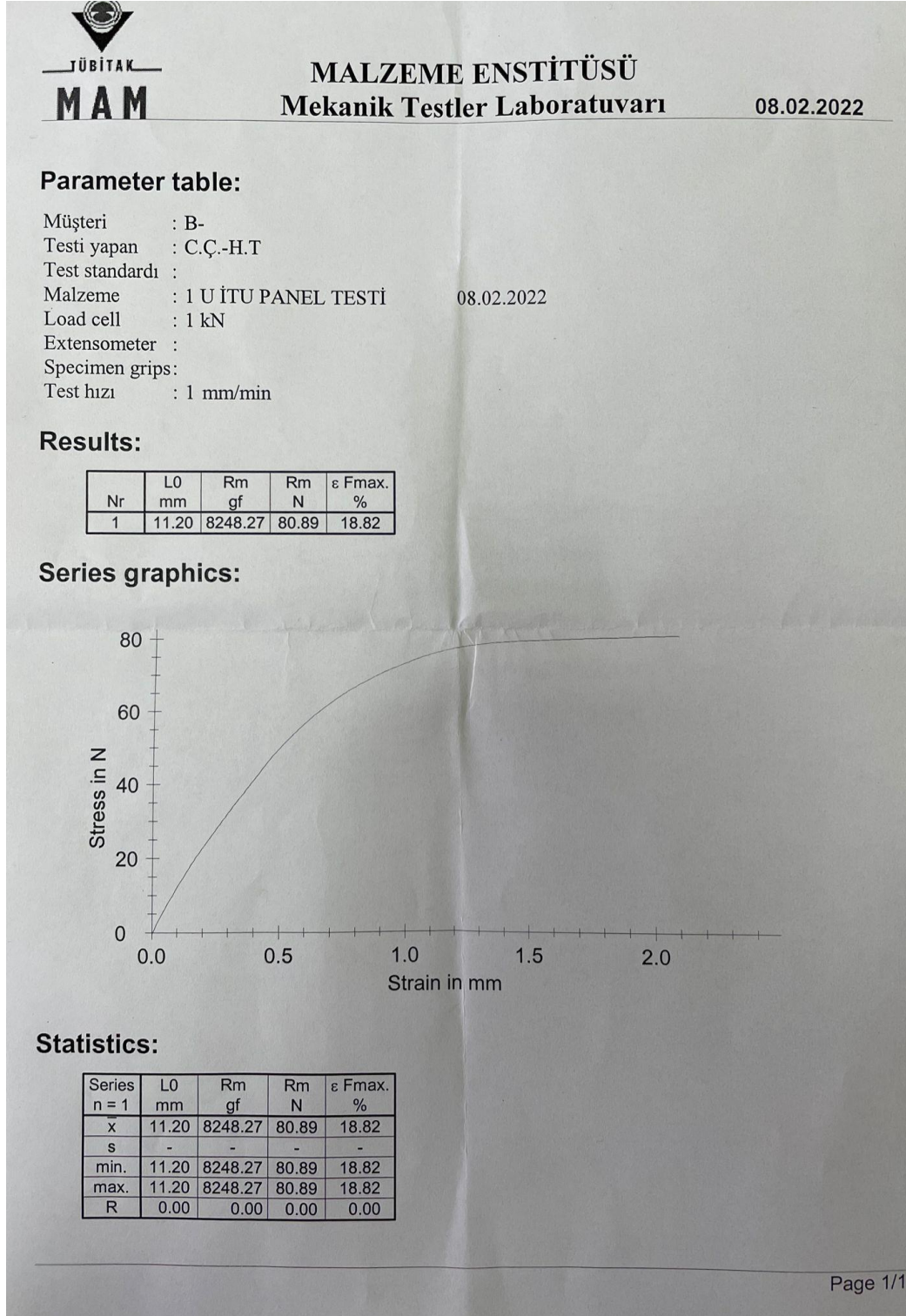


Figure 4.3 : Suction test report made to the demo panel after TVAC test.

The results obtained from tensile test applied on panel produced after the TVAC test and the test report received from TUBITAK MAM given are shown in the Figure 4.4.

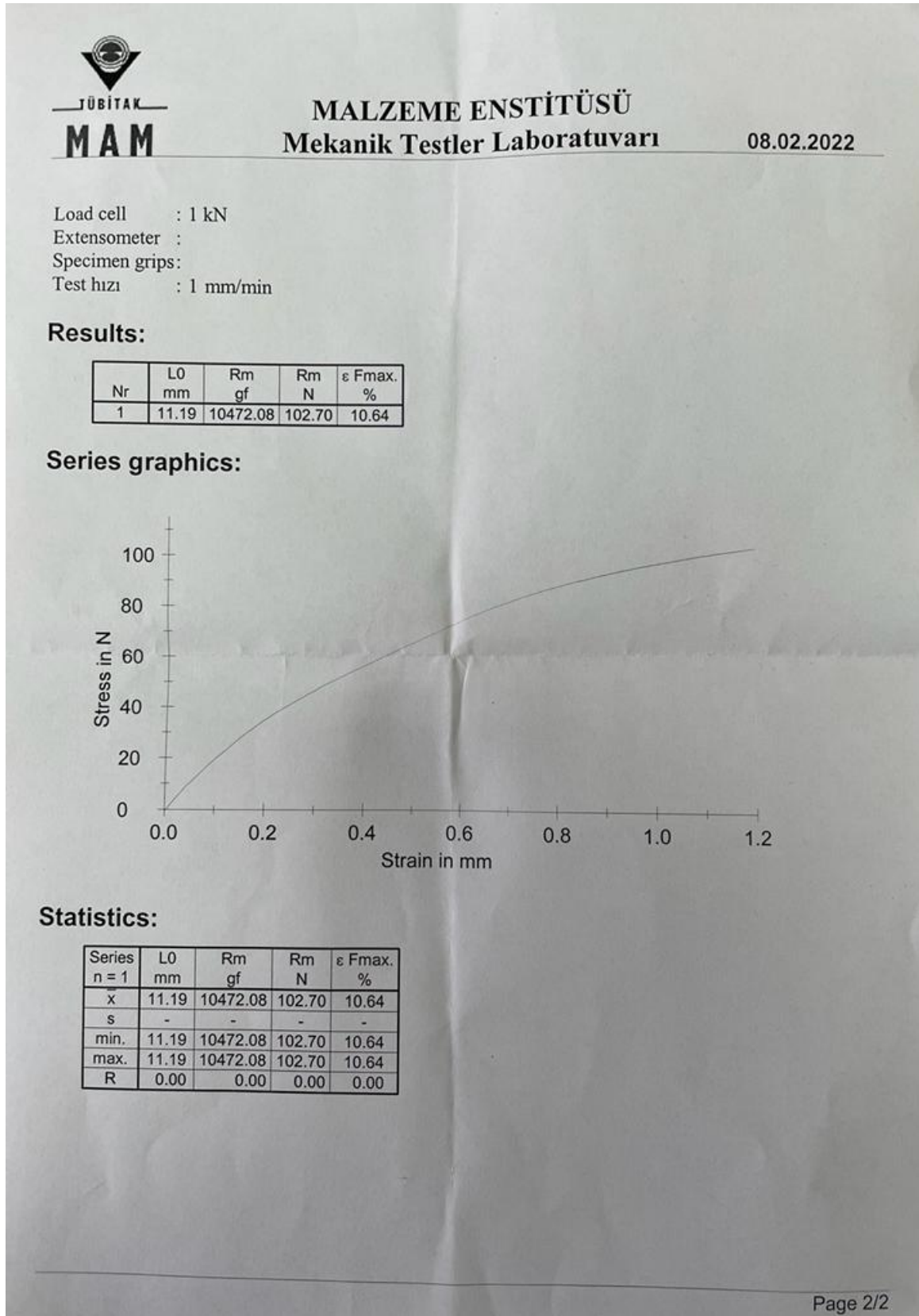


Figure 4.4 : Suction test report made to the produced panel after TVAC test.

Although the bottom cell of the produced panel was broken in the first suction test, the upper cell adhered with the correct method passed TVAC and other tests. The panel was tested by increasing the adhesion strength to 100N and its was tested for this value. This value is well above the 25N value determined in the design specifications, and we can say that the demo panel prepared successfully passed the current test.

A portion of the data taken during the test cycle, which lasted approximately fourteen and a half hours, is shown in Table 4.1. Since a lot of data (10342) was obtained during the test, a limited number of information taken at regular intervals is included here. As a result of the data obtained from the TVAC test, the graph showing the time-dependent temperature change seen in Figure 4.5 was obtained. Here, it is seen that the four measurement points connected to the solar panels follow the shroud temperature linearly and there is no problem.

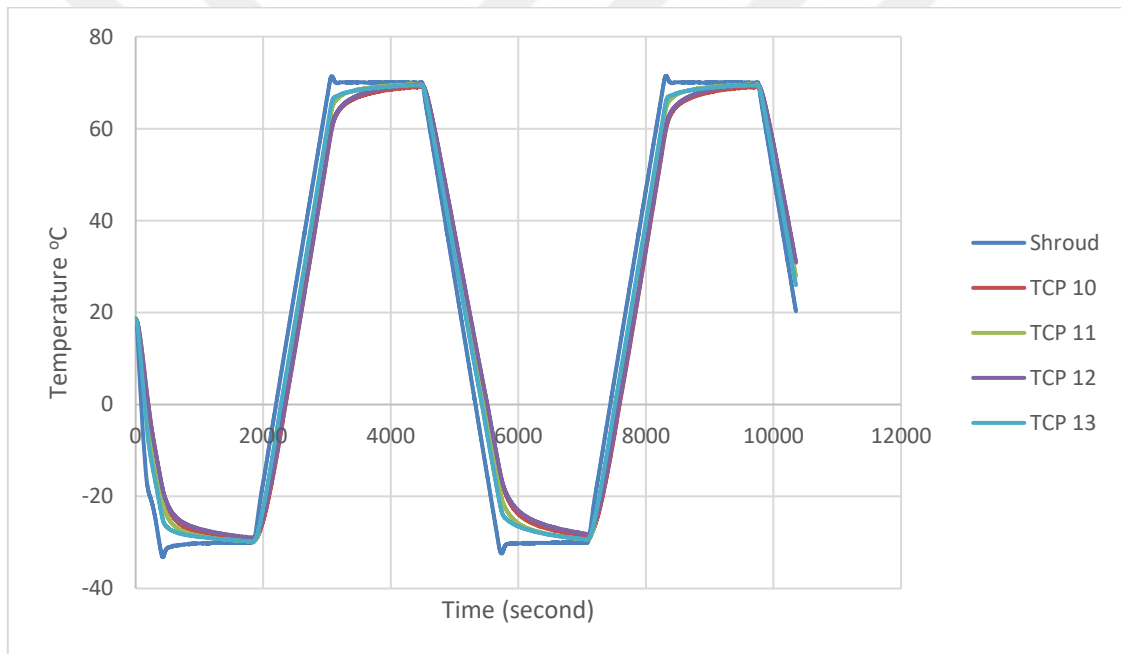


Figure 4.5 : The graph showing the time-dependent temperature obtained from TVAC test data.

After the successful TVAC test, the solar panels were cleaned and passed through visual inspections. Then Electro-Luminescence test was performed. After the controls, there was no additional damage or deterioration in the coupon, which was prepared with the appropriate method, both after the suction tests and after the TVAC tests. Although a solar cell was completely broken after the suction tests on the coupon, where the correct method was not applied during the bonding process, we can say that the upper solid solar cell passed the TVAC test successfully. In other words, there was no loss in the strength and efficiency of the cells

after the heat cycles in which the space environmental conditions to which the cells were exposed were simulated during the TVAC test.



Table 4.1 : Data taken during the TVAC test applied to both panels.

Date	Time	PT100 Int. Fluid	T Set Point	PT100 T _{Shroud}	PT100 T _{D.U.T}	P Full Range	T Cryo	T Cryo Stage	P Pirani Cryo	L.S: P Suction	L.S: P Discharge	H.S: P Suction	H.S: P Discharge	PT100 10 - TCP 10	PT100 11 - TCP 11	PT100 12 - TCP 12	PT100 13 - TCP 13
3.02.2022	22:18:34	18,6	0,72	18,7	18,07	0,01	65,15	13,75	0,02	2,45	12,68	1,95	10,72	18,12	18,52	18,56	18,5
3.02.2022	22:20:29	9,6	-1	16,2	17,57	0	64,05	13,91	0,02	1,97	13,05	1,75	11,21	17,63	17,73	18,07	17,62
3.02.2022	22:29:34	-15,2	-10	-9,8	13,92	0	59,15	14,46	0,02	2	10,9	1,37	10,77	7,68	4,85	7,46	1,57
3.02.2022	22:39:29	-24	-20	-21,1	10,86	0	54,85	13,29	0,02	1,5	10,87	0,82	9,12	-5,23	-8,56	-5,44	-12,73
3.02.2022	22:51:34	-35,2	-30	-32	7,11	0	51,65	13,62	0,02	1,42	9,95	1,62	9,38	-16,7	-19,81	-16,59	-23,26
3.02.2022	23:50:34	-31,2	-30	-30,1	-6,42	0	48,55	12,71	0,02	1,53	10,41	1,46	8,46	-28,16	-28,83	-27,41	-28,94
4.02.2022	00:50:49	-30,9	-30	-30	-16,02	0	48,55	13,19	0,02	1,27	10,28	1,65	9,49	-29,53	-29,78	-28,88	-29,78
4.02.2022	00:55:39	-25,3	-25,2	-27,6	-16,34	0	48,55	13	0,02	4,11	10,54	1,31	7,95	-29,21	-29,36	-28,67	-29,15
4.02.2022	01:05:49	-14	-15,03	-16,3	-16,13	0	48,75	13,91	0,02	4,59	10,37	0,96	8,32	-24,9	-23,74	-24,05	-21,89
4.02.2022	01:10:49	-8,6	-10,03	-11,2	-15,71	0	48,75	12,81	0,02	4,76	10,57	1,29	7,7	-21,43	-19,81	-20,47	-17,46
4.02.2022	01:21:04	2,4	0,2	-0,8	-14,34	0	48,95	12,74	0,02	5,05	9,73	1,27	8	-12,91	-10,37	-11,86	-7,46
4.02.2022	01:31:39	13,6	10,8	9,9	-11,91	0	49,25	13,29	0,02	5,3	9,85	1,4	8,09	-2,7	0,29	-1,77	3,24
4.02.2022	01:41:09	23,7	20,3	19,4	-8,85	0	49,65	13,29	0,02	5,52	10,21	1,29	7,83	6,4	9,6	7,17	12,5
4.02.2022	01:50:54	34	30,03	29,1	-4,84	0	50,15	13,52	0,02	5,74	10,59	1,28	7,73	16,05	19,41	16,5	22,05
4.02.2022	02:01:04	44,8	40,2	39,3	0,49	0	50,95	13,1	0,02	5,97	9,7	1,32	7,92	26,21	29,81	26,52	32,19
4.02.2022	02:10:54	55,3	50,05	49	6,42	0,01	51,95	13,78	0,02	6,16	9,81	0,73	8,15	35,96	39,81	36,25	42,03
4.02.2022	02:21:09	66,2	60,3	59,3	13,82	0,01	53,05	14,27	0,02	6,35	10,05	1,31	7,9	46,31	50,41	46,66	52,37
4.02.2022	02:30:54	76,6	70	69	22,02	0,01	54,15	13,07	0,02	6,54	10,52	1,29	7,72	56,26	60,61	56,78	62,22
4.02.2022	03:26:54	75,6	70	70	50,56	0	56,55	13,39	0,02	5,04	9,83	0,74	8,18	67,79	69,03	68,28	68,81
4.02.2022	04:31:24	75,5	70	70,1	64,38	0	57,55	13,36	0,02	4,23	10,06	1,27	7,69	69,07	69,63	69,55	69,5
4.02.2022	04:41:24	63,7	60,02	61,5	63,2	0	57,45	12,64	0,02	1,75	10,73	1,17	8,89	65,53	64,77	65,82	63,79
4.02.2022	04:51:19	52,8	50,1	51,5	60,93	0	57,05	13,03	0,02	1,42	10,72	1,27	9,2	57,94	56,35	58,16	54,83
4.02.2022	05:01:24	41,8	40	41,4	57,77	0	56,55	12,97	0,02	1,7	11,11	1,46	9,32	49,36	47,14	49,61	45,48
4.02.2022	05:10:54	31,6	30,5	31,8	54,11	0	55,95	13	0,02	1,48	10,26	1,15	9,05	40,99	38,53	41,26	36,62
4.02.2022	05:21:24	20,4	20,02	21,3	49,67	0	55,15	13,36	0,02	1,96	10,64	1,52	9,72	31,63	28,92	31,92	26,87
4.02.2022	05:31:24	10	10,02	11,2	45,03	0	54,35	13,32	0,02	1,88	10,52	1,48	9,1	22,85	19,81	23,08	17,62

Table 4.2 (Continue) : Data taken during the TVAC test applied to both panels.

Date	Time	PT100 Int. Fluid	T Set Point	PT100 T _{Shroud}	PT100 T _{D.U.T}	P Full Range	T Cryo	T Cryo Stage	P Pirani Cryo	L.S: P Suction	L.S: P Discharge	H.S: P Suction	H.S: P Discharge	PT100 10 - TCP 10	PT100 11 - TCP 11	PT100 12 - TCP 12	PT100 13 - TCP 13
4.02.2022	05:36:24	4,5	5,02	6,1	42,56	0	54,05	13,62	0,02	1,52	10,29	1,25	9,12	18,42	15,25	18,76	12,99
4.02.2022	05:41:24	-1,5	0	1	40,19	0	53,65	13,71	0,02	1,69	10,99	1,25	9,09	13,99	10,79	14,34	8,46
4.02.2022	05:46:24	-6,6	-5	-3,9	37,62	0	53,25	13,52	0,02	1,85	11,03	1,56	9,5	9,65	6,43	9,92	4,03
4.02.2022	05:51:24	-12	-10	-9	35,15	0	52,85	13,1	0,02	1,62	10,83	1,66	9,88	5,41	1,98	5,59	-0,41
4.02.2022	05:58:24	-19,3	-17	-16	31,6	0	52,45	13,16	0,02	1,57	11,1	1,61	9,58	-0,5	-4,32	-0,3	-7,04
4.02.2022	06:06:29	-27,9	-25,08	-24,1	27,55	0	51,95	12,97	0,02	1,69	10,81	1,18	9,3	-7,86	-11,64	-7,65	-14,52
4.02.2022	06:11:29	-33,2	-30	-29,1	24,98	0	51,65	13,16	0,02	1,81	11,54	1,32	9,41	-12,28	-16,2	-12,07	-19,15
4.02.2022	07:11:09	-31,1	-30	-30,1	3,65	0	50,25	13,49	0,02	1,33	11	0,85	8,42	-26,69	-27,98	-26,04	-28,1
4.02.2022	08:07:34	-31	-30	-30	-9,27	0	49,85	12,45	0,02	1,31	10,21	1,28	8,63	-28,69	-29,36	-28,15	-29,36
4.02.2022	08:17:29	-19,1	-20,07	-21,3	-10,12	0	49,95	13,32	0,02	4,39	10,05	1,2	7,44	-26,79	-26,49	-26,15	-25,57
4.02.2022	08:27:34	-8,5	-10	-11,2	-10,12	0	49,95	13,19	0,02	4,75	10,46	1,22	7,48	-20,8	-19,28	-19,84	-17,04
4.02.2022	08:32:34	-3,2	-5	-6,1	-9,8	0	49,95	13,16	0,02	4,89	10,69	1,43	7,98	-16,91	-14,93	-15,95	-12,2
4.02.2022	08:37:34	2,2	0,02	-1,1	-9,27	0	50,05	13,94	0,02	5,04	10,99	0,55	7,83	-12,59	-10,26	-11,65	-7,36
4.02.2022	08:47:34	12,9	10,02	9	-7,48	0	50,45	13,62	0,02	5,27	9,36	1,42	8,04	-3,23	-0,1	-2,19	2,75
4.02.2022	08:57:34	23,5	20,03	19,1	-4,74	0	50,75	13,07	0,02	5,49	9,56	1,28	7,72	6,3	9,6	7,17	12,4
4.02.2022	09:07:34	34	30	29,1	-1,04	0	51,15	13,88	0,02	5,72	9,92	1,01	8,4	16,05	19,71	16,7	22,25
4.02.2022	09:17:34	44,7	40	39,1	3,55	0	51,75	13,62	0,02	5,94	10,33	1,31	7,85	25,91	29,81	26,52	32,19
4.02.2022	09:27:34	55,3	50,02	49	9,08	0	52,25	13,94	0,02	6,17	10,94	0,92	8,27	35,86	40,01	36,44	42,23
4.02.2022	09:37:34	65,9	60,02	59,1	15,7	0	53,05	13,39	0,02	6,36	9,37	1,32	7,97	46,01	50,31	46,56	52,27
4.02.2022	09:47:34	76,6	70	69	23,4	0	53,85	13,03	0,02	6,52	9,46	0,86	8,27	56,16	60,61	56,88	62,41
4.02.2022	11:50:14	75,4	70	70,1	64,78	0	57,65	13,91	0,02	4,38	8,29	1,58	8,58	69,07	69,63	69,55	69,5
4.02.2022	12:00:14	64,1	60,03	61,6	63,69	0	57,55	13,07	0,02	1,31	9,98	1,24	9,77	65,53	64,67	65,82	63,79
4.02.2022	12:10:14	52,8	50,05	51,4	61,32	0	57,25	13,58	0,02	1,4	10,48	1,38	9,89	57,84	56,16	58,06	54,73
4.02.2022	12:20:14	42	40,05	41,4	58,16	0	56,65	12,61	0,02	1,41	10,69	1,76	10,2	49,27	47,14	49,51	45,38
4.02.2022	12:30:14	31,6	30,03	31,3	54,31	0	55,95	13,49	0,02	1,36	9,89	1,37	9,89	40,59	37,93	40,86	36,13
4.02.2022	12:41:14	19,7	20	20,3	49,67	0	55,05	12,51	0,02	1,76	10,84	1,51	9,85	30,84	27,93	31,04	25,99



5. CONCLUSION & FUTURE WORKS

In this thesis, a multifunctional solar panel that can be used in nano and micro satellites was designed and tested in accordance with design specifications. Literature researches mentioned about satellites, CubeSats, the beginning philosophy of CubeSats, their widespread impact today, studies conducted in this field in our country and studies specific to solar panels were presented.

While determining the design parameters, both these literature studies and the limitations imposed by the CubeSat design specifications were always taken into consideration. The test methods performed were also successfully completed by adhering to them. Within the scope of the thesis, it is seen as a plus value that a new cooperation on solar panels has been started with the support received from TUBITAK MAM research center as ITU-SSDTL. All production processes and tests were performed on type B cells. In future studies, it is envisaged that the same production and testing processes will be repeated for A-type cells in a project where the panels will be space-qualified.

Although it was aimed to try at the beginning of this thesis, silver epoxy-based adhesive panel mounting method and double-sided tape panel mounting method couldn't be tried. As Future Works, it was aimed to try these untested methods in the coming days and to share the results in an academic article.

In the next stage of this thesis, the main aim will be to ensure that at least one panel of a 1U satellite to be sent into space is one of the panels produced within the scope of this study and by providing space history to solar panels produced here to ensure that they are space-qualified.

Afterwards, by being mounted the panels produced according to the success of this study on a 1U or 3U sizes satellite, the overall success of the panels should be focused. It is among the targets that all nano and micro satellites that will be developed in our country from now on will be covered with solar panels produced as a result of this project and an effective export success will be achieved with these panels.



REFERENCES

- Air Force Space Command.** (2014). SPACE AND MISSILE SYSTEMS CENTER STANDARD. *TEST REQUIREMENTS FOR LAUNCH, UPPER-STAGE AND SPACE VEHICLES*. Air Force Space Command.
- Aslan, A., Sözbir, N., & Öz, İ.** (2021). *Uydu Haberleşmesi 101*. Retrieved Ağustos 2022, from <https://uydu.turksat.com.tr/sites/default/files/2022-01/Uydu-Haberlesmesi-101.pdf>
- AZUR Space, Solar Power GmbH.** (2010). *30% Triple Junction GaAs Solar Cell Assembly*. Retrieved from Azur Space: http://www.azurspace.com/images/products/0003401-01-01_DB_3G30A.pdf
- California Polytechnic State University.** (2022). CubeSat Design Specification (1U-2U) REV 14.1 CP-CDS-R14.1. Retrieved 2022 July
- ESA Requirements and Standards Division.** (2012). ECSS-E-ST-20-08C Rev.1. *Space engineering - Photovoltaic assemblies and components*. (E. Secretariat, Ed.)
- İlarslan, M., Aslan, A. R., & Çelebi, M.** (2013). Turkish University Consortium for Space Technologies and Education (UTEB) Prospects for Turkey. (pp. 1099-1102). 6th International Conference on Recent Advances in Space Technologies (RAST).
- Introduction: The history of the CubeSat by Bob Twiggs and Jordi Puig-Suari.** (2020). In C. Cappelletti, S. Battistini, & B. Malphrus (Eds.), *CubeSat Handbook* (Vol. 1, pp. xxi-xxviii). Academic Press. doi:<https://doi.org/10.1016/B978-0-12-817884-3.09983-5>.
- ITU SSDTL Laboratories.** (2022). *ITU SSDTL*. Retrieved from Laboratories: <https://usttl.itu.edu.tr/en/laboratuvarlar/>
- Kacmaz, S., Karakaya, I., Tola, C., & Atas, O.** (2020). SSS-2B Küp Uydusunun Tasarımı ve Yapısal Analizi. 8. *ULUSAL HAVACILIK VE UZAY KONFERANSI* (pp. 1-16). Ankara: Türk Hava Kurumu Üniversitesi.
- Khorchef, N., & Kimber, R.** (2019). AlSat-1B Solar Array Assembly Design and Flight Qualification. (pp. 1-7). European Space Power Conference (ESPC). Retrieved July 2022
- KULU, E.** (2022). *Nanosat Database*. Retrieved August 2022, from <https://www.nanosats.eu/#figures>
- Kulu, E.** (2022, July). *Nanosats Database*. Retrieved from <https://www.nanosats.eu/database>
- Kulu, E.** (2022, July). *NanoSats Database*. Retrieved from <https://www.nanosats.eu/#figures>
- Maini, A., & Agrawal, V.** (2011). *Satellite Technology Principles and Applications* (2nd. Edition ed.). John Wiley & Sons Ltd., Publication. Retrieved August 2022
- Mauro, G., Lawn, M., & Bevilacqua, R.** (2018, February). Survey on Guidance Navigation and Control Requirements for Spacecraft Formation-Flying Missions. *JOURNAL OF GUIDANCE, CONTROL, AND DYNAMICS*, 2. doi:10.2514/1.G002868
- NASA.** (2013). GENERAL ENVIRONMENTAL VERIFICATION STANDARD (GEVS). (N. G. CENTER, Compiler)
- NASA.** (2021). *State-of-the-Art of Small Spacecraft Technology*. Retrieved July 2022, from 6.0 Structures, Materials, and Mechanisms: <https://www.nasa.gov/smallsat-institute/sst-soa/structures-materials-and-mechanisms>
- NASA.** (2021). *Technical Standards of NASA*. (P. Gill, Ed.) Retrieved July 2022, from <https://standards.nasa.gov/nasa-technical-standards>
- NASA.** (2022). *State-of-the-Art of Small Spacecraft Technology*. Retrieved July 2022, from 9.0 Communications: <https://www.nasa.gov/smallsat-institute/sst-soa/communications>

- NASA Ames Research Center, Small Spacecraft Systems Virtual Institute.** (2021). *State-of-the-Art Small Spacecraft Technology*. California: NASA. Retrieved July 2022, from <https://www.nasa.gov/smallsat-institute/sst-soa>
- NASA CubeSat Launch Initiative.** (2017). CubeSat-101 Basic Concepts and Processes for First-Time CubeSat Developers. Retrieved July 2022, from https://www.nasa.gov/sites/default/files/atoms/files/nasa_csli_cubesat_101_508.pdf
- Nguyen, Q., Yuknis, W., Pursley, S., Haghani, N., & Albaijes, D.** (2008). A HIGH PERFORMANCE COMMAND AND DATA HANDLING SYSTEM FOR NASA'S LUNAR RECONNAISSANCE ORBITER. *AIAA SPACE 2008 Conference & Exposition* (pp. 1-8). American Institute of Aeronautics and Astronautics.
- Prentice-Hall Physics Series.** (1938). *Procedures in Experimental Physics*. Prentice-Hall Inc.
- Rooij, A.** (2010). *CORROSION IN SPACE*. doi:10.1002/9780470686652.eae242
- Suari, J., Turner, C., & Ahlgren, W.** (2011). Development of the Standard CubeSat Deployer and a CubeSat Class PicoSatellite. 1, pp. 347-353. IEEE Aerospace Conference .
- TUBITAK MAM Research Center.** (2018). *Fotonik Teknolojiler Laboratuvarı*. Retrieved July 2022, from <https://me.mam.tubitak.gov.tr/tr/laboratuvarlar/fotonik-teknolojiler-laboratuvari>
- TUBITAK Marmara Research Center.** (2014). *TUBITAK MAM MILGES*. Retrieved July 2022, from <https://ee.mam.tubitak.gov.tr/tr/hakkimizda/milli-gunes-enerjisi-santrali-milges-projesi>
- Ümit, M., Baş, M., Akyol, İ., Uludağ, M., Ecevit, A., & Aslan, A.** (2012). TURKSAT 3USAT KÜP UYDUSU İÇİN ELEKTRİK GÜÇ SİSTEMİ TASARLANMASI. IV. *ULUSAL HAVACILIK VE UZAY KONFERANSI* (pp. 1-12). İstanbul: Hava Harp Okulu Komutanlığı.
- Vertat, I., & Vobornik, A.** (2014). Efficient and Reliable Solar Panels for Small CubeSats. *International Journal of Photoenergy* (pp. 1-8). Hindawi Publishing Corporation. doi:<http://dx.doi.org/10.1155/2014/537645>

CURRICULUM VITAE

Name Surname : Süleyman SOYER

EDUCATION :

- **B.Sc.** : 2018, Istanbul Technical University (ITU), Faculty of Aeronautics and Astronautics, Department of Aeronautical Engineering
- **B.Sc.** : 2013, Anadolu University, Faculty of Open Education, Department of Economics
- **A.S.** : 2006, Turkish Air Force, NCO High Vocational School, Department of Aviation Elektrik & Electronic (Avionic)

PROFESSIONAL EXPERIENCE AND REWARDS:

- 2006-2010, MALATYA, Turkish Air Force, 7th Air Force Basement, Air Sergeant
- 2010-2020, ISTANBUL, Turkish Air Force Academy, Air Sergeant&Teaching Assistant
- 2020-2022, KAYSERI, Turkish Air Force, 12nd Air Logistic Basement, Air Sergeant
- 2010, MERIT Award (with team), “Spain CanSat Competition” organized by European Space Agency
- 2012, 1st Degree (with team), “NASA Annual Cansat Competition, Texas, USA” organized by NASA, AIAA, AAS-American Astronautical Society
- 2012, “Science and Achievement Award of Turkish Armed Forces, General Staff” given by Commander of Turkish Armed Forces, General Necdet ÖZEL
- 2013, “Outstanding Service Award” given by Commander of Turkish Air Force Academy, Major General Muhittin Fatih SERT
- 2016, “Vecihi HÜRKUŞ Sergeant Honorary Award” (organized by Turkish Air Force) given by Commander of Turkish Air Forces, General Abidin ÜNAL

PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- **Telli H., Ayan E., Soyer S., Gulsever E., Ozcan S.,** 2015. An Investigation of C-130 Aircraft Base Drag Reduction With Aftbody Modifications, *AIAA Aviation 2016*
- **Soyer S.,** 2011. Small Space Can: CanSat, *Recent Advances in Space Technologies 2011*
- **Soyer S., et all,** 2011. Mission Analysis and Planning of a CANSAT, *Recent Advanced in Space Technologies 2011*
- **Kızılkaya M.Özgür, Soyer S.,** 2017. CanSat Descent Control System Design and Implementation, *Recent Advanced in Space Technologies 2017*

OTHER PUBLICATIONS, PRESENTATIONS AND PATENTS:

- **Soyer S., Aslan A.R., Karabulut B., Çatal E., Sarıca A.K., Öztekin O.** 2022: A Study on the Development of Multifunctional Solar Panels for Nano and Micro Satellites. International Graduate Research Symposium-IGRS 2022, June 1-3, 2022, Online Session Istanbul Technical University, Istanbul, Turkey.

