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James Webb Space Telescope: A Cryogenic Approach

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Abstract: James Web Space Telescope (JWST) is a milestone to space exploration. JWST is concerned to observe the universe in infrared spectrum, provide unprecedented insight into the early universe, study formation of galaxies and birth of stars, give significant understanding of planetary system and discover signs of life on other planets. To sustain the hostile environment of space, cryogenic cooling system is used to keep telescope operational even at extremely low temperature just above absolute zero. Three-stage Pulse Tube precooler and a single Joule-Thomson cryocooler is used to generate cooling effect for effecting cooling of instruments and detectors. These instruments and detectors are responsible for providing data of astronomical phenomena and capturing high quality pictures of the planet, galaxies, stars, black holes and other astronomical objects.
Keywords: Cryogenic, cryocooler, infrared, compressor, universe, JWST

I. INTRODUCTION

The James Web Space Telescope (JWST) is a collaborative program of National Aeronautics and Space Administration (NASA), Canadian Space Agency (CSA) and European Space Agency (ESA) to focus on observing the universe in the infrared Spectrum. JWST is equipped or facilitated with state-of-the-art cryogenic cooling system for its mission, this cooling system allows instruments and detector to remain safe at extremely low temperatures to prevent interference from the infrared radiation radiated by telescope. James Web Space Telescope is named after James E. Webb, a former NASA Administrator.

On December 25-2021, JWST was launched on Ariane 5 Rocket. JWST is designed for exceptional insights into the early universe, birth of stars, formation of galaxies, the planetary systems and new life on another planet. Advanced scientific instruments were equipped inside this telescope that will allow us to observe deep space more effectively than any other telescope built before.

JWST has its two sides of operation, one hot side and another cold side, and are critical components of its design. The cold side keeps the instruments and detectors operational and safe at cryogenic temperature with cryogenic cooling system, while the hot side protects the telescope from radiation and heat radiated by the sun. Together, they allow JWST to achieve its mission of observing the deep space and universe in the infrared spectrum. JWST is more powerful than Hubble Space Telescope and it will transform our understanding of universe in detail and accurately.

II. DESIGN

JWST’s cryogenic cooling system is designed to work in two main parts, a sunshield and a cryocooler. The sunshield is designed with five layers of Kapton material along with aluminium coating to reflect sunlight and protects the telescope by blocking heat and radiation from the sun. The cryocooler is responsible for cooling the instruments and detectors to a cryogenic temperature or the temperature just above absolute zero (0 Kelvin). The design of a cryocooler consists of a compressor, cold head or expansion device, and heat exchanger that work together to circulate refrigerant throughout the system. The compressor compresses the refrigerants, circulates this pressurized refrigerant throughout the system to a place where it absorbs heat from the instruments and detectors. The cold head or expansion device cools the incoming refrigerant to an extremely low temperature. The heat exchanger removes the excess heat from the system to the surrounding. To power the cryocooler solar panels are used, this panels generate enough electricity to keep the entire system operational.

The JWST has a huge 6.5-meter diameter primary mirror which consists of 18 hexagonal segments that makes it a hundred times more powerful than the Hubble Space Telescope (HST). It has been optimized for examining early universe phenomena, distant galaxies, and formation of planets and stars by capturing and analysing infrared light. To achieve its mission, JWST is equipped with the most advanced instruments such as Near-Infrared Camera, Near Infrared Spectrograph, Mid Infrared Instruments, Fine Guidance Sensor and Slitless Spectrograph. These instruments work together to capture and analyse data providing extensive understanding of planet formation, evolution of galaxies, and birth and death of celestial bodies.

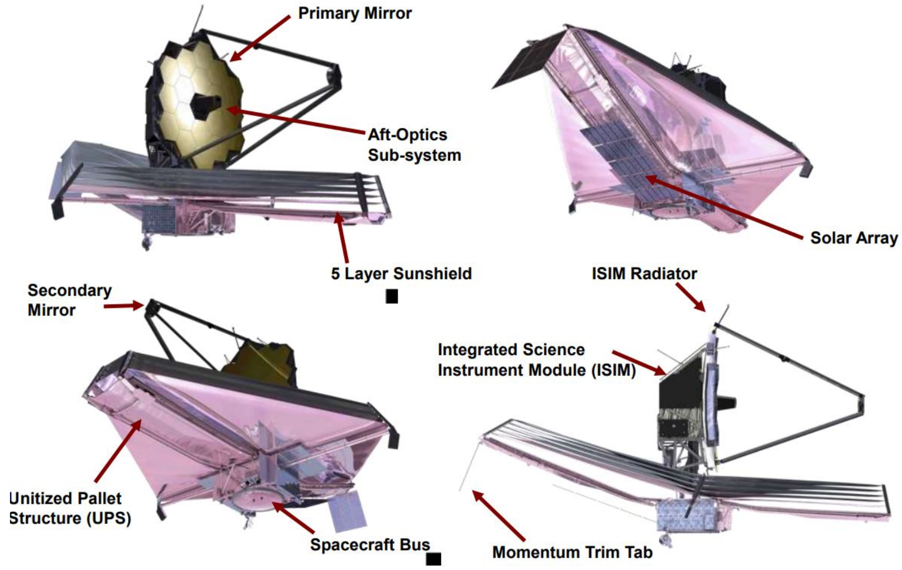

Fig. 1 Detail Design Features of JWST/Source: NASA

III. WORKING MECHANISM

The side facing the sun is the hot side that receives direct sunlight. The hot side is responsible for protecting sensitive instruments and sensors of telescope by intercepting heat and radiation from the sun. Instruments and detectors of the telescope are kept at the cold side (opposite of the hot side), where temperature is expected to be extremely low, just above zero Kelvin. To maintain this temperature cryogenic cooling system is installed in JWST, which includes a cryocooler. A cryocooler is the mechanical device that maintains low temperature due to compression and expansion of gases.

Each component of JWST serves a specific function, which is described below.

1) Sunshield: It is the crucial component having capability of withstanding extreme temperature variations, that protects the telescope from heat and radiation radiated by the sun and is composed of five layers of Kapton material with aluminum coating. To protect the telescope from heat and radiation, the layers of Kapton are designed to arrange in a form of tennis court-sized sunshade.
2) Primary Mirror: It is another crucial component consisting of 18 hexagonal segments. These hexagonal segments are assembled to form a mirror with a diameter of 6.5 meters. The primary mirror collects and reflects light from distant objects in space.
3) Sun-Facing Side Radiator: It is located at the hot side of JWST that dissipates heat to the surrounding efficiently, permitting the sensitive instruments and detector to operate at optimal temperature. To regulate the amount of heat dissipated into surrounding space, a radiator is composed of a series of louvers that efficiently radiates heat at specific wavelengths corresponding to thermal emission of the telescope.
4) Instruments: The instruments used in JWST are Near Infrared Camera, Mid infrared Instrument, Near Infrared Spectrograph, Slitless Spectrograph and Fine guidance sensor. This instrument performs specific functions like imaging, spectroscopy, guiding the telescope etc.
5) Fine Steering Mirror: It plays a crucial role in maintaining precise pointing and stability of the telescope and operates by reflecting a small portion of the incoming light from the primary mirror. This reflected light reaches to the control system, and the control system continuously monitors telescope’s position and alignment.
6) JWST Cryocooler: It is the crucial component of the cryogenic cooling system. It is a two-stage pulse tube cryocooler that can operate at very low temperature below 40 Kelvin and is designed to cool instruments of telescope enabling to operate at that temperature. A cryocooler works by compression and expansion of a gas or refrigerant. Design of a cryocooler involves a compressor, cold head or expander and heat exchanger. Compressor compresses the refrigerant to a particular pressure and circulated the refrigerants throughout the system, cold head or expander cools the refrigerants to a very low temperature and heat exchanger dissipates the excess heat to the surrounding space from the system. A pulse tube in the cryocooler is used to generate cooling effect that is utilized to cool the telescope’s instruments.

IV. CRYOCOOLERS AND THEIR APPLICATIONS

Mid-infrared Instrument cryocooler of JWST has an integrated architecture. It consists of a three-stage Pulse Tube precooler and a single stage Joule-Thomson cryocooler, comprising two major units Cooler Compressor Assembly (CCA) and Cold Held Assembly (CHA). CCA is located on the sun facing side of JWST, acts as a heat pump, and it consists of a precooler and pump. Precooler produces cooling power at around 14 Kelvin temperature using helium gas as a refrigerant, and pump having high efficiency circulates cooled helium refrigerant to Mid-Infrared Instruments (MIRI). To cool helium gas, the precooler uses pulse tubes and two cylinder horizontally opposed pump by exchanging heat with regenerator in acoustic manner. [3]

The Joule-Thomson and Pulse-Tube cryocooler control electronics (CCE) use identical flight software and control board and have a similar architecture. In contrast to the Joule-Thomson, Pulse-Tube cryocooler control electronic power has been scaled up two times. Physically, each cryocooler control electronics is divided into top subassembly and bottom subassembly. Signal processing, digital, and analogue data acquisition, capacitor bank, housekeeping converters, control circuitry are housed into top subassembly, and EMI filters, switching power amplifiers and high-power DC-DC converter are housed into bottom subassembly. In the case of Pulse-Tube cryocooler circuit electronics' top subassembly houses the valve drivers and heaters. [4]

To prevent image blurring problems, primary and the most important challenge of the cryocooler is preserving low vibrations. This can be accomplished by employing Joule-Thomson effect cooling in CHA and pulse tube cooling within CCA, having no moving parts except for two finely tuned piston pumps in the CCA. These pumps operate in perfect opposition to each other to control and minimize vibration. The control of vibration is achieved through advanced sensing mechanism with the use of two redundant pairs of piezoelectric accelerometers mounted on Pulse-Tube and Joule-Thomson compressors. The data transferred and fed by the sensors to the low noise charge amplifier adjust harmonic content of the compressor drive waveforms through a proprietary control algorithm, responding autonomously and dynamically to vibrations in the compressors and structure dynamics. For the health monitoring system and on-orbit debugging of the cryocooler, a comprehensive diagnostic database is accessible. This database includes telemetry data, and telemetry data includes several parameters like system and safety mode, temperature of heater and electronics, voltage of compressor, waveforms, voltage of secondary power supply, vibration measurement and control parameters etc. and these are accessible to the users for diagnostic and troubleshooting purpose. [3] [4]

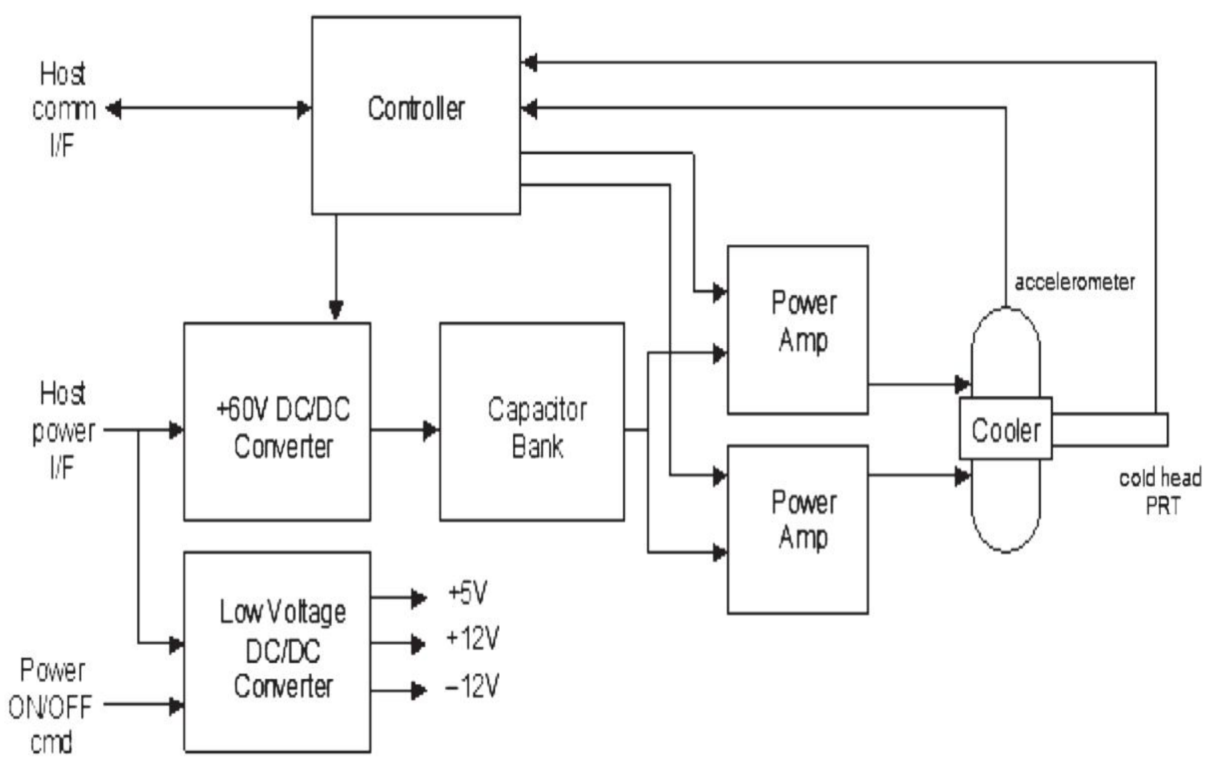

Fig. 2 Block Diagram of Joule-Thomson CCE [4]

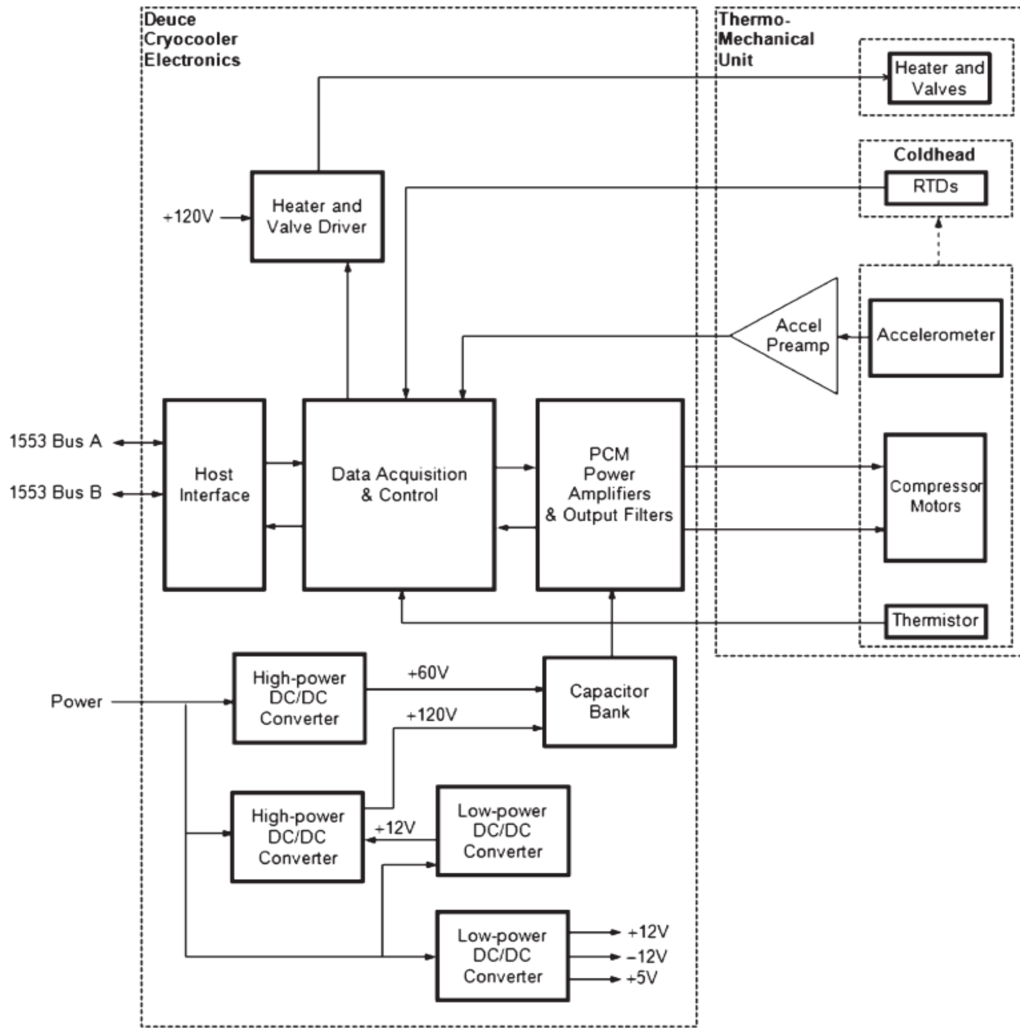

Fig. 3 Block Diagram of Pulse-Tube CCE [4]

V. THERMAL TEST AND PERFORMANCE

The first test comprises a thermal vacuum test of a one-third scale model of sunshield, that validated flight model, offering a praising compromise between the scaling of conductive and radiative sunshield modelling parameters, which has ability to scale with size, and smallest chamber fill factor differently for attested model validation data. Two thermal vacuum tests took place subsequently on a full-scale engineering model of the core section of observatory, that was crucial for validating the accuracy of the thermal model and thermal leak channels between base of OTIS and warm spacecraft. The Core 1 test analyzed full scale demonstrator model of the region between cryogenic OTIS and warm spacecraft, while Core 2 test identified a high-fidelity Engineering Test Unit. Detailed critical radiative and conductive heat flows representation of observatory thermal model is validated by Core 2 test. To confirm directional activity of heat dissipation prior to Core 2 test, an engineering model test of IEC thermal radiator reflector was conducted. All the flight components of the observatory underwent thermal testing in following three configurations: cryogenic test of the Integrated Science Instrument Module (ISIM) in Goddard Space Flight Center's Space Environment Simulator (SES), cryogenic test of combined OTIS (integration of ISIM and OTE – Optical Telescope Element) at Johnson Space Center's modified Chamber A facility, and thermal testing of Spacecraft Element (SCE) in Northrop Grumman M4 thermal vacuum chamber. The ultimate verification of the thermal performance of observatory was rendered feasible through these experiments including demonstrated thermal models for the ISIM, OTIS, and SCE. [5]

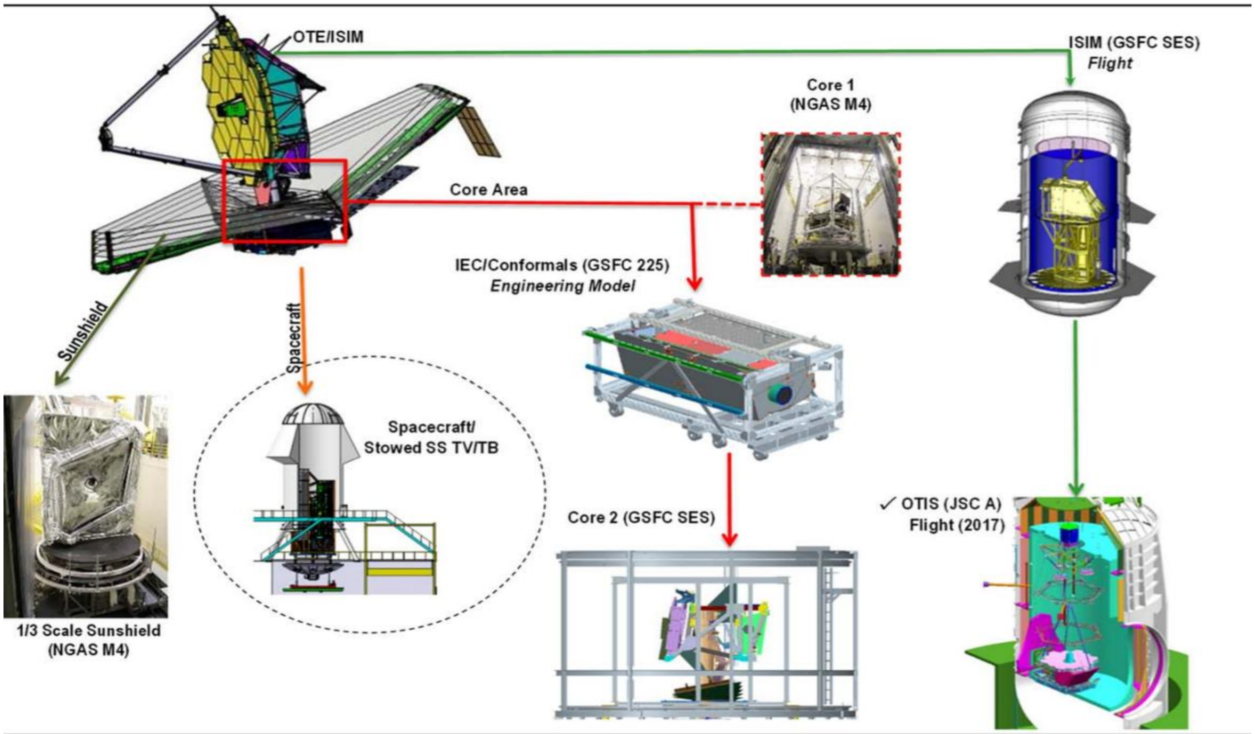

Fig. 4 Thermal Test of JWST [5]

VI. OPERATION AND LOCATION

By using telemetry data, scientists and engineers can monitor and adjust the cryogenic cooling system from the ground control station to ensure proper operation of the entire system. The JWST is designed to be positioned at the second Lagrange point, also called L2 which is situated on the opposite side of earth from the Sun. This L2 is a gravitational balance point, which is located at approximately 1.5 million kilometres away from the Earth. At second Lagrange Point, gravitational forces of the Sun and Earth are balanced. Since L2 is free from the interference caused by Earth's atmosphere and heat and light from the Sun, it permits for a stable and clear view of universe. This aids the major advantage to place James Web Space Telescope in L2 orbit and enables the telescope to capture high quality images and data of astronomical phenomena. The entire system and mechanism of the JWST is autonomously operated, and is designed to be extremely efficient, reliable, and durable to sustain hostile environments of space.

Fig. 5 Location of Earth from the Sun/ Source: NASA

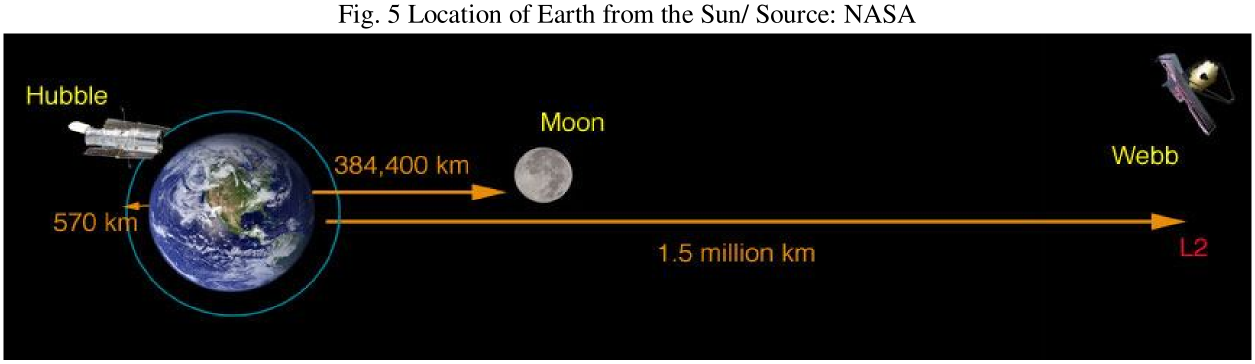

Fig. 6 Location of JWST from Earth/ Source: NASA

VII. CONCLUSIONS

The cryogenic approach utilized by the James Webb Space Telescope (JWST) is a crucial aspect of its mission to capture unprecedented views of the cosmos. By utilizing cryogenic cooling systems, the telescope can operate at extremely low temperatures, minimizing interference from thermal emissions and enabling the detection of faint infrared signals from distant objects. The development, design, and testing of the cryogenic system and its components were integral to ensuring the success of the JWST mission. JWST represents a significant breakthrough in space exploration and holds great promise for providing transformative insights into the origins and evolution of the universe.

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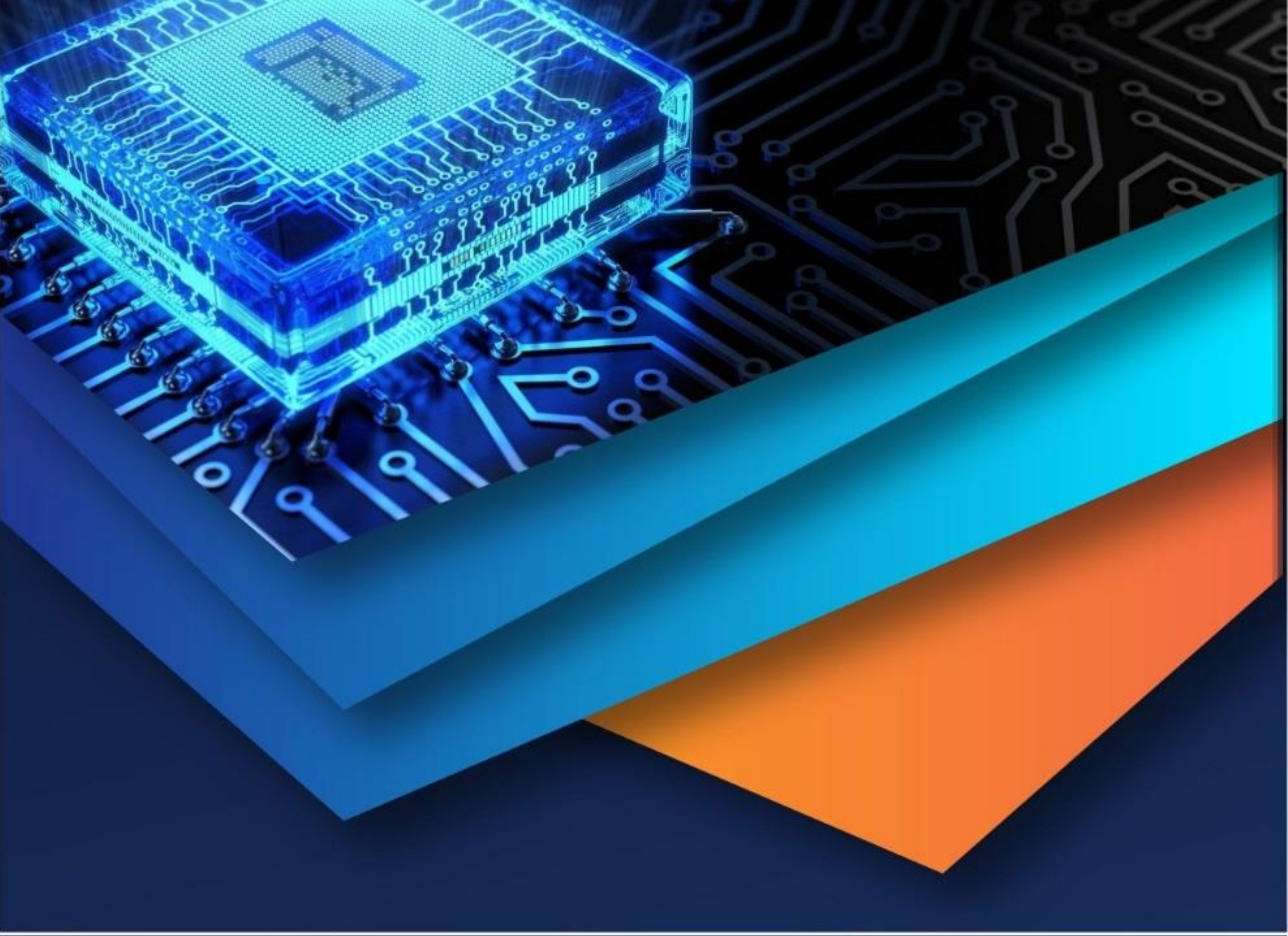

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