



# AMITY UNIVERSITY

---

## UTTAR PRADESH

---

### Amity Institute of Applied Sciences

#### Synopsis of Major Project

**Title:** Advanced Cathode Materials for Intermediate Temperature Solid Oxide Fuel Cells.

**Name of internal guide:** Dr. G. N. Pandey

**Name of external guide:** Dr. Raghvendra Pandey (A.R.S.D. College, University of Delhi)

Programme: - M.Sc. (AP)		Year/Semester: - 2022/IV-Sem	
S. No.	Enrolment No.	Name	Signature
1.	A4450020010	Paras Saini	

**Summary (short): -**

Fuel cells are devices for electrochemically converting chemical energy into electrical energy and heat without the need for direct combustion as an intermediate step, giving much higher conversion efficiencies than conventional energy systems. Solid oxide fuel cells (SOFCs), based on an oxide-ion conducting electrolyte, have several advantages over other types of fuel cells, including relatively inexpensive materials, low sensitivity to impurities in the fuel, and high efficiency.

**Resource requirement: -**

Research Papers, Lab Equipment's, Software's to analyse Data.

**Schedule of work completion: -**

**Scheduled Date of Commencement:** 10/01/2022

**Schedule Date of Completion:** 21/05/2022

**Signature of Student:**

Paras  
Deepak 21/05/22

**Signature of internal guide:**

**Name of Programme Leader:** Dr. Deepak Tripathi

**Approval by Board of Faculty**

Member	Signature	Remark (Approved / Not Approved)

# **Major Project**

*Submitted to the Amity University Uttar Pradesh In partial fulfillment of  
requirements for the award of the Degree of*

**(M.Sc.-Applied Physics)**



*By*

**Paras Saini**

**Enrollment No: A4450020010**

*Under the Supervision of:*

#### **Internal Faculty Guide**

**Dr. G. N. Pandey**  
Department of Applied Physics,  
Amity Institute of Applied Sciences,  
Amity University, Uttar Pradesh, Noida

#### **External Faculty Guide with affiliation:**

**Dr. Raghvendra Pandey**  
Assistant Professor  
Department of Physics,  
Atma Ram Sanatan Dharma College,  
University of Delhi

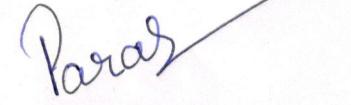
**Amity Institute of Applied Sciences, AUUP,  
Sector 125, Noida – 201303 (India)**

**DECLARATION**

I, .....**Paras Saini**...., student of ...**M.Sc.-Applied Physics (Batch 2020-22)** ...hereby declare that the **Major Project (STMJ600)** titled “...**Advanced Cathode Materials for Intermediate Temperature Solid Oxide Fuel Cells.....**” which is submitted by me to the **Department of Applied Physics**, Amity Institute of Applied Sciences, Amity University, Uttar Pradesh, Noida, in partial fulfillment of requirement for the award of the degree of **M.Sc. -Applied Physics.**, has not been previously formed the basis for the award of any degree, diploma or other similar title or recognition.

Noida

Date: **23/05/2022**



**Paras Saini**

Name and Signature of student

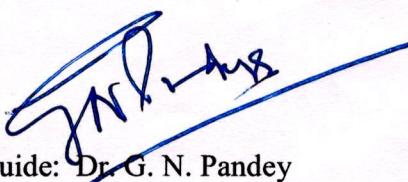
## **CERTIFICATE**

On the basis of declaration submitted by .....**Paras Saini**....., student of ...**M.Sc.-Applied Physics (Batch 2020-22)**....., I hereby certify that the **Major Project (STMJ600)** titled “...**Advanced Cathode Materials for Intermediate Temperature Solid Oxide Fuel Cells.....**” which is submitted to Department of .....**Applied Physics**..., Amity Institute of Applied Sciences, Amity University, Uttar Pradesh, Noida, in partial fulfillment of requirement for the award of the degree of ...**M.Sc.-Applied Physics**..., is a faithful record of work carried out by him under my guidance and supervision.

To the best of my knowledge this work has not been submitted in part or full for any Degree Diploma to this University or elsewhere.

Noida

Date: **23/05/2022**



Guide: Dr. G. N. Pandey

Department of.... **Applied Physics**.....,  
Amity Institute of Applied Sciences,  
Amity University, Uttar Pradesh, Noida



## Department of Physics

भौतिकी विभाग

A.R.S.D. College, University of Delhi

आत्मा राम सनातन धर्म कॉलेज, दिल्ली विश्वविद्यालय

Dhaula Kuan, New Delhi-110021

धौला कुआं, नई दिल्ली-११००२१



**Dr. Raghvendra Pandey**

Assistant Professor

Phone: +91-9560111832, Fax: 011-24111390

E-mail: [raghvendra@arsd.du.ac.in](mailto:raghvendra@arsd.du.ac.in)

## CERTIFICATE

This is to certify that Mr. **Paras Saini**, a student of M.Sc. Applied Physics from Amity University, Uttar Pradesh, Noida, has done his six months major project work titled "*Advanced Cathode Materials for Intermediate Temperature Solid Oxide Fuel Cells*" under my supervision in our Green Energy Physics & Solid State Ionics Research lab.

During the period he has shown keen interest in his assignment and was regular in attendance.

**Place:** New Delhi

**Date:** 19/05/2022



(Raghvendra Pandey)  
Assistant Professor  
Department of Physics,  
A.R.S.D. College, University of Delhi  
Dhaula Kuan, New Delhi-110021, India

## Acknowledgment

*“Help demands no recompose; to clouds of heaven, by men to earth”.*

I would like to express my special thanks of gratitude to my guides **Dr. G. N. Pandey** and **Dr. Raghvendra Pandey** for their able guidance and support in completing my project successfully.

Mainly I would like to thank my parents who were supportive all these days in all my hard situations.

Last but not least, I would like to thank all those good hearts who were there to help me without any expectation.

I would like to say special thanks to Ms. Hera Tarique who helped me a lot in finalizing my project in limited time frame.

# Table of Contents

## DECLARATION

## CERTIFICATE

## ACKNOWLEDGMENT

<b>TABLE OF CONTENT .....</b>	<b>6-7</b>
-------------------------------	------------

<b>ABSTRACT .....</b>	<b>8-9</b>
-----------------------	------------

1. Introduction .....	9-10
2. Fuel Cell .....	10-12
2.1. History of Fuel Cell	
2.2. Types of Fuel Cell	
3. Phosphoric Acid Fuel Cell (PAFC).....	12-14
4. Polymer Electrolyte Membrane Fuel Cell (PEMFC).....	14-15
5. Alkaline Fuel Cell (AFC) .....	16-17
6. Molten Carbonate Fuel Cell (MCFC) .....	17-19
7. Solid Oxide Fuel Cell (SOFC) .....	19-23
7.1. History of Solid Oxide Fuel Cells	
7.2. Working of Solid Oxide Fuel Cell	
8. Materials Selection in SOFC .....	23-31
8.1. Cathode Material	
8.2. Anode Material	
8.3. Interconnect Material	
8.4. Electrolyte Material	
i. Zirconia Based Electrolyte	
ii. Bismuth based electrolytes	
iii. LaGaO <sub>3</sub> -based perovskite electrolyte	
iv. Hexagonal Perovskite based electrolyte	
8.5. Application of Solid Oxide Fuel Cells	

8.5.1. Solid Oxide fuel cell – gas turbine combined system	
9. Synthesis Method .....	32-35
9.1. Solid- State Reaction Method	
10. Characterization Methods .....	35-44
10.1. Powder X- ray Diffraction	
10.2. Scanning Electron Microscope (SEM) spectroscopy	
10.3. Fourier Transform Infrared Spectroscopy (FTIR)	
10.4. Raman Spectroscopy	
10.5. Electrochemical Impedance Spectroscopy (EIS)	
11. Preparation of Samples .....	45-47
12. Characterization Data Analysis .....	47-55
12.1. XRD Analysis	
12.2. SEM Analysis	
12.2.1. EDS Analysis	
12.3. Raman Analysis	
12.4. FTIR Analysis	
12.5. Impedance Spectroscopy Analysis	
13. Results .....	56
14. Future Work .....	57
<b>References .....</b>	<b>58-60</b>

# **Advanced Cathode Materials for Intermediate Temperature Solid Oxide Fuel Cells**

## **Abstract: -**

Worldwide environmental concern has compelled researchers to search new technologies for clean and green energy generation. Now a days, Solar Cells, Fuel cells, batteries, supercapacitor etc. have emerged as some of the clean energy conversion and storage technologies. Out of these, fuel cells are, currently, used for green and clean energy generation. There are several types of the fuel cells depending upon the electrolyte used and its operating temperature. In these types of fuel cells, Solid oxide fuel cells (SOFCs) are very imperative because the use of solid electrolyte which leads to easy transportability and high efficiency. In SOFCs, the conductivity of oxide ion in the electrolyte is very vital to improve the performance and efficiency of the fuel cell at intermediate temperature. The yttria stabilized zirconia is the most used material as oxide ion conducting material, but it's high operating temperature and high cost gives extreme motivation to find the alternate materials which provides higher conductivity at intermediate temperature, increases the efficiency, and reduces the making cost of fuel cell. Using perovskites as an electrolyte in SOFC is attractive option and many researchers' have been working towards it. Recently, hexagonal perovskite materials  $Ba_3NbMoO_{8.5}$  and  $Ba_7Nb_4MoO_{20}$  have gained much attention to the scientist's because of their use as oxide ion conducting materials.<sup>[1][2][3]</sup> In the present work hexagonal perovskite materials system  $Ba_7Nb_4MoO_{20}$ ,  $Ba_7Nb_{3.9}Mo_{1.1}O_{20}$ ,  $Ba_7Nb_{3.8}Mo_{1.2}O_{20}$ ,  $Ba_7Nb_{3.7}Mo_{1.3}O_{20}$  and  $Ba_7Nb_{3.6}Mo_{1.4}O_{20}$  were synthesize via Solid State Reaction Method and characterized by X- ray Diffraction, Raman spectroscopy and Fourier-Transform Infrared (FTIR) spectroscopy for phase formation and structural analysis. Scanning Electron Microscope (SEM) spectroscopy, Energy-dispersive X-ray spectroscopy (EDS) were performed to study the morphology and investigate the composition of the synthesised samples. Impedance spectroscopy (EIS) was performed to study the electrical behaviour of the samples. Here, we increase the Molybdenum (Mo) content and decrease the of Niobium (Nb) content in same ratio i.e., " $Ba_7Nb_{(4-x)}Mo_{(1+x)}O_{20}$ ", ( $x = 0.0, 0.1, 0.2, 0.3,$  and  $0.4$ ) (BNM) and explored the possibility for ion conduction in the system. The electrical conductivity of host material was found to the order of  $\sim 10^{-3}$   $Scm^{-1}$  at  $\sim 650$   $^{\circ}C$ . This shows its

application in solid electrolyte for SOFCs. Therefore, in a variety of energy-related technologies, hexagonal perovskites may prove advantageous for forming new ionic conductors.

## 1. Introduction: -

In the world, the electricity demand continuously increasing every year. So, it is necessary to find different methods to generate electricity in a fast and environmentally friendly manner. The Fuel Cell is a reliable method to generate electricity in a fast manner while not making drastic effects on environment and it does not produce any type of pollution (even noise pollution because it does not have any moving part). An electric current is generated using the fuel cell when a chemical reaction occurs among the precursors. Fuel-Cell is a word which is made up of two words. The first is fuel and the second is cell. Fuel is a material that gives heat energy or thermal energy on burning. [4] [5] [6] A cell is a single source of electrical energy in which chemical reaction is used to produce current (or flow of electrons through the circuit).

There are three components in a cell. Anode, Cathode, and Electrolyte. Anode and cathode are electron conducting material which are also known as Electrodes. [4] [5] The Anode is a reducing or negatively charge electrode which releases electrons to the external circuit. The Anode is oxidized during the electrochemical reactions.

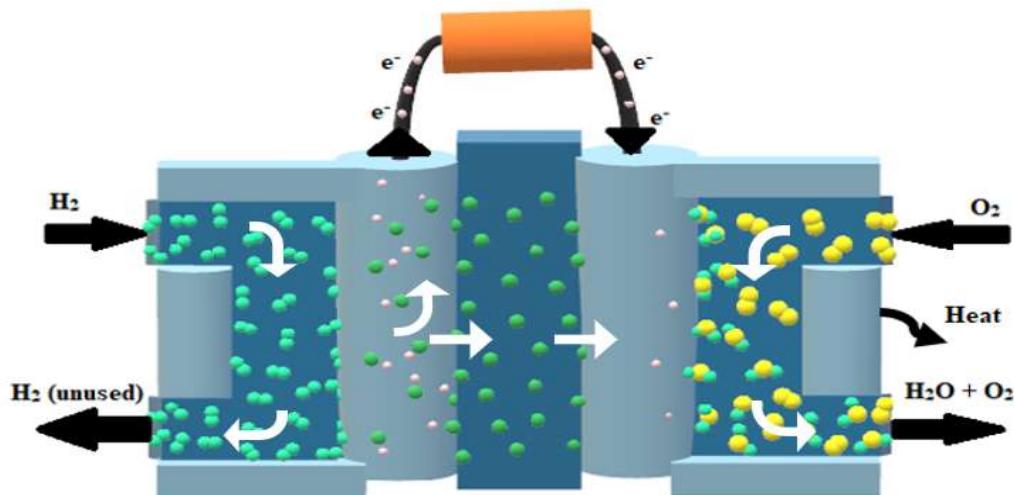


Fig1.: - Fuel Cell

Whereas Cathode is reducing or positively charge electrode which takes electrons from the external circuit. The cathode is reduced during the electrochemical reactions. [4] [5] [6]

Electrolytes serve as a medium to allow the movement of charge (ions) between the anode and the cathode of a cell. It does not allow electron to move between the anode and the cathode of a cell.

An electrochemical reaction produces electricity in a fuel cell just like a battery. Both fuel cell and batteries transform chemical energy into electrical energy, as well as thermal energy as a byproduct of the process. Energy is kept in a closed reservoir in a battery, and when it runs out, it must be dumped or recharged. To recharge, an external source of electricity is used to reverse the electrochemical process. The cell produces electrical energy for a short time because once the precursors are exhausted inside the cell the chemical Reaction is completed in the cell, therefore, the flow of electrons stops. We call this as the discharging of cell. So, to overcome this fuel cell was made, Fuel-Cell is an electrochemical cell which converts the chemical energy of a fuel (H and O) into electricity by the pair of redox reactions. If the Fuel cell is connected to a source of hydrogen and oxygen (usually air), a fuel cell can continue to run indefinitely.

There are various varieties of fuel cells, however they all have a common design. The fuel cell can be classified into five main types based on the electrolyte with which they function, are as follows-Phosphoric Acid Fuel Cell (PAFC), Polymer Electrolyte Membrane Fuel Cell (PEMFC), Alkaline Fuel Cell (AFC), Molten Carbonate Fuel Cell (MCFC), and Solid Oxide Fuel Cell (SOFC). A fuel cell unit is made up of a stack that would be made up of many individual cells.

## **2. Fuel Cell: -**

Fuel-Cell is a word which is made up of two words. The first is fuel and the second is cell. Fuel is a material that gives heat energy or thermal energy on burning. A cell is a single source of electrical energy in which chemical reaction is used to produce current (or flow of electrons through the circuit). Due to their greater efficiency, fuel cells have been found to be the most important source of energy in the power industry. Fuel cells with low and high temperatures are both suitable for application in this area. Fuel cells such as SOFC and MCFC are operate at high temperatures. SOFC and MCFC fuel cells can be used in three main application such as Residential application, Combine-cycle power generation plant and Tri-generation but SOFC is preferable to use in Combine- cycle power generation plant.

Nowadays, transportation plays an extremely important role. The current methods of transportation are not suitable for the environment because of pollution. [4] [5] [6] Therefore, the technology needs to be changed. Some demonstration work is going on to install PEM fuel cell technology in vehicles. This fuel cell is suitable for transportation vehicle because low operating temperature and it don't require pure hydrogen used as a fuel. [4] [5] [6] Similarly, we can use SOFC fuel cell, but due to high operating temperature it can't be used directly. Extensive research work has been going on to reduce the operating temperature of this cell. There is large use for fuel cells in equipment's such as portable power source which happens to be one of the important applications is military equipment's to run and it also can be used in construction work as a local power source to run the equipment.

## 2.1. History of Fuel Cell: -

William Grove, in 1839, is known for the demonstration of the first fuel cell. William Grove review the paper of William Nicholson and Anthony Carlisle and he thought that he could recompose water by connecting electrodes in a series circuit, which is known as a gas battery. This device is also known as the Grove cell. [4] [5] [6] This device is operated by separated platinum electrodes in Hydrogen and Oxygen which is submerged in a diluted sulfuric acid electrolyte solution. The water and gasses are sealed inside the containers. William Grove observed that when current flow, the water level goes up in both the tube. [4] [5] [6]

In 1893, Friedrich Wilhelm Ostwald was one of the fathers of physical chemistry. He contributes significantly to understand fuel cells theoretically, Ostwald did some experiments with fuel cell components, and he determined their roles in the fuel cell. [4] [5] [6]

In the early 1900s, Emil Baur of Switzerland and his several students carried out numerous experiments on various types of the fuel cell. [4] E. Baur work on high temperature devices. E. Bauer and H. Preis of Switzerland did an experiment with Solid Oxide Fuel Cell (SOFC). At that time in 1930, they found limitations of solid oxides like bad chemical stability and electrical conductivity. [4] [5] [6]

In 1934, G. H. J. Broers and J. A. A. Ketelaar uses the fused salts as an electrolyte. They introduce the new fuel cell known as the Molten Carbonate Fuel Cell (MCFC). [14] [6] In later it became one of the most common forms of fuel cells used in commercial manufacturing.

In the 1940s, O. K. Davtyan conducted several experiments to boost electrolyte's mechanical strength and conductivity. Many of his ideas did not give the expected result. But Bauer's and Davtyan's work led to the essential basic research for today's Molten Carbonate Fuel Cell (MCFC) and Solid Oxide Fuel Cell (SOFC) devices. [4] [5] [6]

In August 1959, Francis Thomas Bacon demonstrated the first workable fuel cell, which is a combination of 40 cells which can generate power of 6KW. [5] In space travel, the first-time application of a fuel cell was seen which was used in space flight in the Gemini and Apollo mission in the early 1960 as producing electric power and drinking water. [4] [5] [6]

## 2.2. Types of Fuel Cell: -

The fuel cell can be classified into five main types based on the electrolyte in which they function, are as follows-

- i. Phosphoric Acid Fuel Cell (PAFC)
- ii. Polymer Electrolyte Membrane Fuel Cell (PEMFC)
- iii. Alkaline Fuel Cell (AFC)
- iv. Molten Carbonate Fuel Cell (MCFC)
- v. Solid Oxide Fuel Cell (SOFC)

## 3. Phosphoric Acid Fuel Cell (PAFC): -

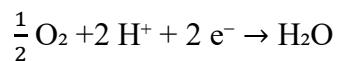
Phosphoric Acid solution is used as an electrolyte in this type of fuel cell, so it called as Phosphoric Acid Fuel Cell (PAFC).



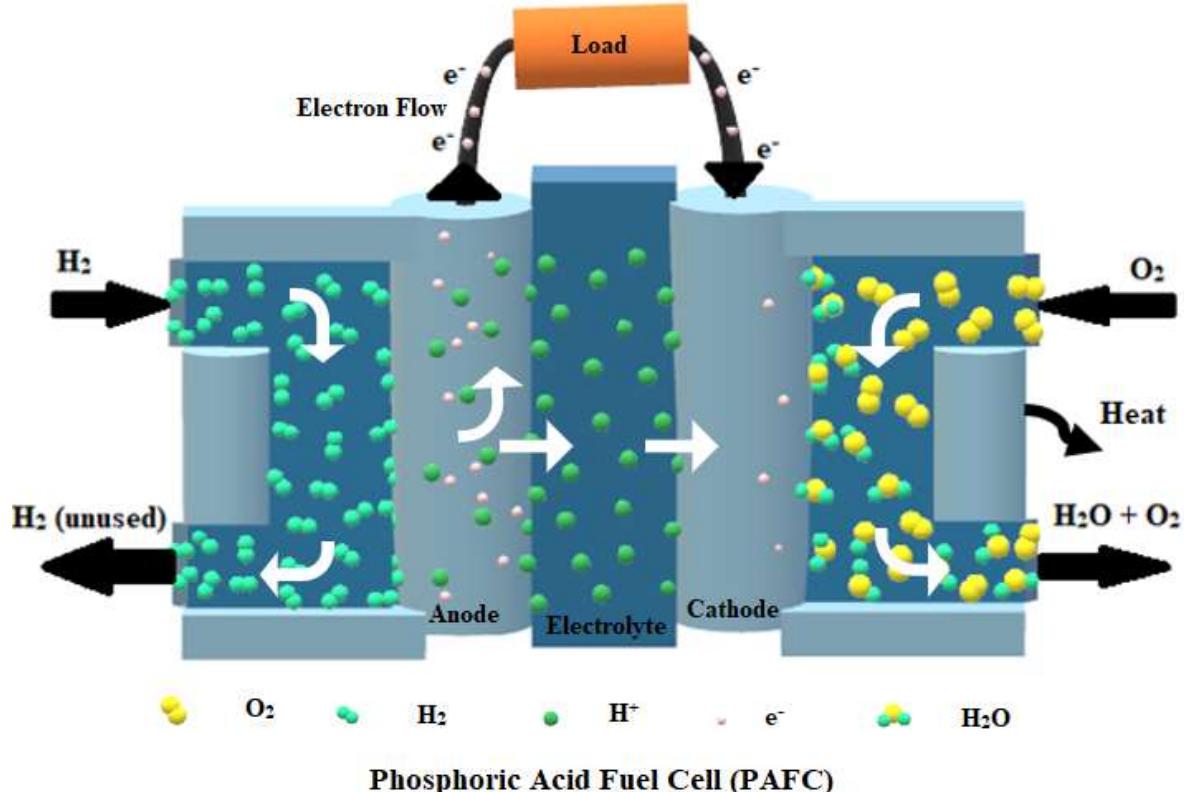
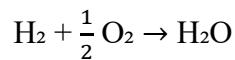
The phosphoric acid dissociates (in an aqueous solution) into hydrogen ions and phosphoric ions. A hydrogen ion be a charge carrier. Despite its chemical stability and ease of handling, phosphoric acid has an extremely low vapour pressure, even at 200 degrees

Celsius (473K).<sup>[7]</sup> This means the fuel cell exhaust gas cannot easily discharge together with phosphoric acid in the electrolyte layer. If any minute discharge takes place then in long term, this can degrade the performance of the cell. <sup>[7]</sup>

Hydrocarbon or fuel gases which consists primarily of hydrogen is supplied at the fuel electrode and at air electrode, air is supplied. When an electrochemical reaction occurs, an electric current is generated. <sup>[7]</sup> At fuel electrode, hydrogen undergoes electrochemical reaction. The hydrogen ions move through electrolyte toward the air electrode. <sup>[7]</sup> At air electrode, electron travels through external circuit and hydrogen ions, moves through electrolyte from fuel electrode. Oxygen supplied from outside, react and combine with hydrogen and produces water. As shown in the following reactions: -



So, the fuel cell reaction produces  $\text{H}_2\text{O}$ , as the following Reaction: -



*Fig.2: - The working principle of PAFC is described.*

In Phosphoric Acid Fuel Cell, there are two porous electrodes inside the Phosphoric Acid Fuel Cell (PAFC) (one electrode is the fuel electrode where hydrogen or fuel gases supplied, and the other electrode is the air electrode where Oxygen supplied) formed mainly by carbon materials.<sup>[7]</sup> Between the fuel electrode and air electrode, there is layer of electrolyte which consist of a highly concentrated phosphoric acid solution. The catalytic layers are formed by the carbon material, little metal catalyst, and material that repels water used in electrodes where reactions occur.<sup>[7]</sup> When single Phosphoric Acid Fuel cell was used, it gives 0.7V of voltage. So, for large scale power generation "cell Stack" are used. A cell Stack is a series of stacked cells assembled in a series of several hundred or thousand cells and interconnected to form a power plant.<sup>[7]</sup> Hydrogen and oxygen undergo an electrochemical reaction which generate heat, so the fuel cells are placed at periodic intervals between cooling plates to reduce the effects of the heat. To keep the operating temperature of cells at about 473K (nearly 200°C) cooling water is passed through them.<sup>[7]</sup>

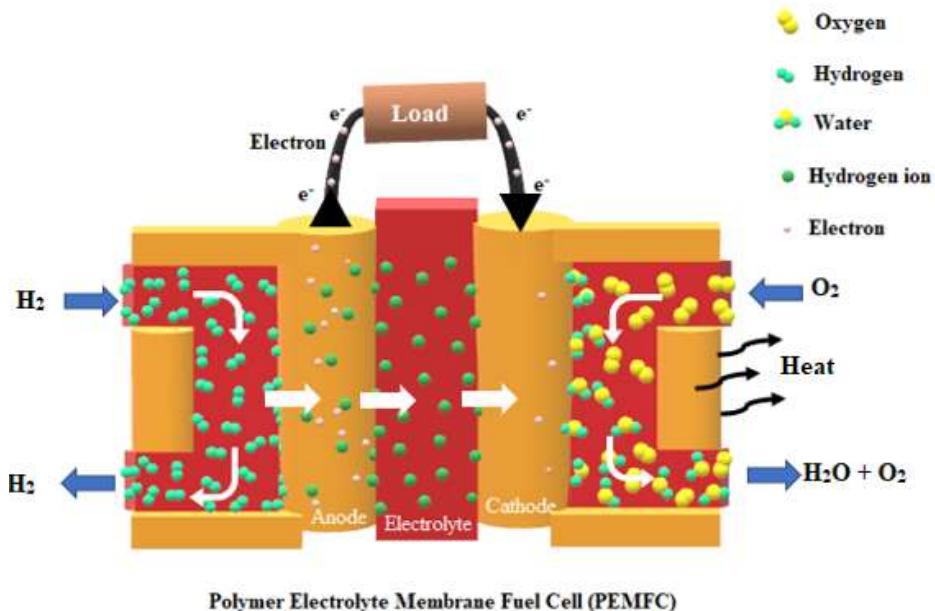
### ***3.1. Features of Phosphoric Acid Fuel Cell:***

Unlike alkaline fuel cells, Phosphoric Acid Fuel Cell do not suffer from degeneration of the electrolyte caused by CO<sub>2</sub> gas. The operating temperature of a phosphoric Acid Fuel Cell is about 200 °C.<sup>[7]</sup> If fuel cell is constructed in such a way that it does not come in direct contact with phosphoric acid. We can use other material such as copper or iron. To reduce the heat, which is generated by the electrode reactions, we can use different types of highly heat resistant materials. And the fuel cells can be placed at periodic intervals between cooling plates to reduce the effects of the heat.<sup>[7]</sup>

## **4. Polymer Electrolyte Membrane Fuel Cell: -**

Polymer Electrolyte Membrane Fuel Cell is also known as Polymer Membrane Fuel Cell (PMFC) or Membrane Fuel Cells (MFC). In fuel cell (PEMFC), proton conducting membrane is used as an electrolyte. This type of fuel cell is called Proton Exchange Membrane Fuel Cell because of the proton-based nature of this fuel cell electrolyte membrane.

Hydrogen or fuel gases which consist primarily of Hydrogen (Ethanol, Methanol, and acids) is supplied at the fuel electrode (known as anode) and Oxygen or air is supplied at air electrode (also known as cathode). [5] As a result, when an electrochemical reaction occurs, an electric current is generated. At fuel electrode, Hydrogen undergoes an electrochemical reaction, which resulting in electrons and Hydrogen ions (Proton). [5] The Hydrogen ions moves through the electrolyte toward the air electrode (or towards the cathode).

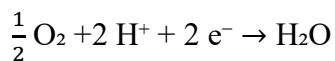


*Fig.3: - The working principle of PEMFC is described.*

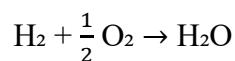
The reaction occurs at fuel electrode: -



And electrons move through the external circuit towards the cathode. At cathode (the air electrode), electrons and hydrogen ions (which moves through electrolyte from fuel electrode) and oxygen which is reduced by the electron, from outside, reacts and combine to produce water and heat. [5] It shown in the following Reactions: -



So, the fuel cell reaction produces  $\text{H}_2\text{O}$ , as the following Reaction: -

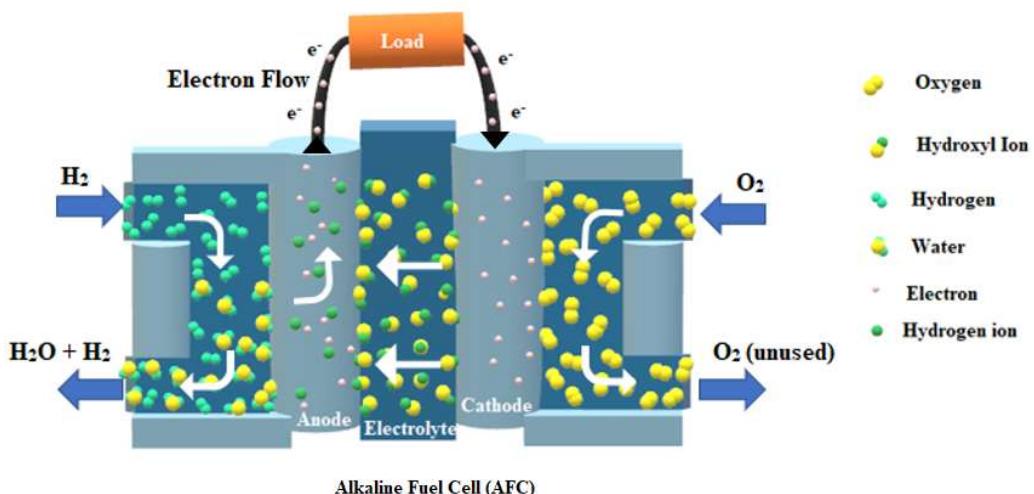


## 5. Alkaline Fuel Cell (AFC): -

Alkaline Fuel Cell is the cells which uses alkaline aqueous solution as an electrolyte. This Fuel cell operates at below 100 °C. Alkaline Fuel Cell have high electrical efficacy in all types of fuel cell, but in this fuel cell we can only use very pure gases. In alkaline KOH electrolytes that used in AFCs, oxygen reduction occurs much rapidly comparing with acid fuel cells. [8]

There are two porous electrodes inside the alkaline Fuel Cell (AFC), (One electrode is the fuel electrode or Anode where pure gases are used primarily Hydrogen supplied and other electrode is the air electrode or cathode where Oxygen supplied). Between fuel electrode and air electrode, there is the chamber of electrolytes which consists of alkaline aqueous solution. [8] The catalyst and material which repels water used in electrodes, where reactions occur at the time of construction such that, it must be designed in such a way that the reaction gas can be supplied effectively.

The main work begins in the 1920 where Alkaline Fuel Cell attracts much attention because of low operational temperature and excellent Reaction. Then in 1950-60s, the American space agency uses it as power supplies in space vehicles. [8] They use pure hydrogen and oxygen for generate electricity and provide power to the space vehicles.

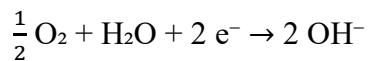


*Fig.4: - The working principle of AFC is described.*

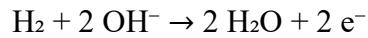
The catalyst layer, in AFC can be made up of platinum or nickel or non-precious metal and alkaline aqueous solution or liquid KOH use as an electrolyte. The fuel hydrogen and oxygen using in this fuel cell because of carbon dioxide. [8] If the CO<sub>2</sub> present in the fuel cell, it will deteriorate the aqueous electrolyte.

In Alkaline Fuel cells, OH<sup>-</sup> ions are involved in the relevant reactions. As the Oxygen is reduced at the cathode, they are moved to the Anode via the electrolyte, and the electron moves through the external circuit toward the cathode. The Hydrogen is recombined with OH<sup>-</sup> ions to form water.

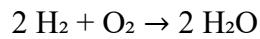
The Reaction occurs at the fuel electrode (at Anode): -



And the Reaction occurs at the air electrode (at the cathode): -



So, the fuel cell reaction produces H<sub>2</sub>O, as the following Reaction: -

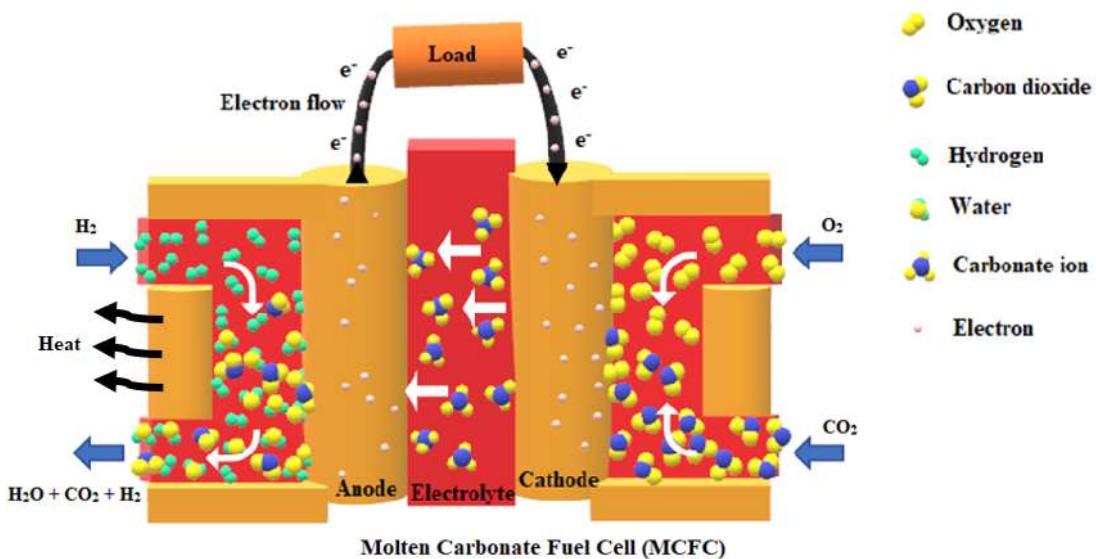


## **6. Molten Carbonate Fuel Cell (MCFC): -**

In this Fuel Cell, A molten Carbonate electrolyte operates with in a temperature range of 550- 750°C, So this is a high temperature fuel cell. When the electrolyte is at a lower temperature, the conductivity of the electrolyte is very poor and electrolyte results vaporized at the higher temperature, which resulting in a lower operating temperature interval. [9] For electrode material we can use could be cheap non-noble catalysts which provides major advantage of high temperature fuel cell. Molten Carbonate Fuel Cell have nickel-based anodes, which can be alloyed with Al and Cr for microstructural stability. In Molten Carbonate Fuel Cell, Cathode is made up of LiNiO<sub>2</sub>. [9]

Molten Carbonate Fuel Cell can be operated in pressurized conditions and atmospheric conditions. By comparing with other fuel cell, atmospheric Molten Carbonate Fuel Cell which work with low current densities. Due to high polarization and ohmic losses at cathode and electrolyte respectively. [9] Power density is increased by using pressurized system, which is economically feasible.

In Molten Carbonate Fuel Cell, electrical and thermal efficiency are more than 60% and 90% respectively, via theoretically.



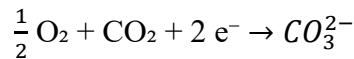
*Fig.5: - The working principle of MCFC is described.*

In this fuel cell, there are two electrodes, first is anode or fuel electrode, where we supply Hydrogen as a fuel, other is cathode or air electrode where we supply Air + Carbon dioxide ( $CO_2$ ) in mostly time we use Oxygen with  $CO_2$ ). At cathode, Oxygen is reduced with  $CO_2$  to make  $CO_3^{2-}$ , on other hand, at anode Hydrogen is oxidizes which produce hydrogen ion (proton) + electron. [9] Electron is travel through external circuit and reach towards cathode and  $CO_3^{2-}$ . Carbonate ions moves through electrolyte from electrolyte from Anode to cathode. The hydrogen ion is recombined with  $CO_3^{2-}$  (carbonate ions) which produce water and  $CO_2$ .

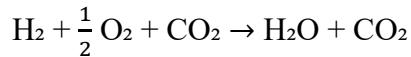
The Reaction which occurs at Anode is as follows: -



The Reaction which occurs at Cathode is as follows: -

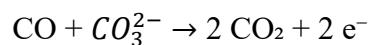


So, the final Reaction can be written as follow: -

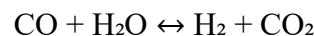


The advantage of high temperature operation is that we can use Carbon monoxide (CO) as a fuel in the Molten Carbonate Fuel Cell. Because in low temperatures, carbon monoxide works as a poison at low temperatures.<sup>[9]</sup> We use CO as a directly fuel by direct oxidation at the Anode or by water gas shift reaction.

The Reaction which occurs if we use CO at the Anode is as follows: -



And the Reaction which occurs with water gas shift is as follows: -



Loss of electrolyte and cathodic dissolution are two principal causes of performance degradation during cell life. Fuel gas vaporization is principally responsible for electrolyte loss. The second reason is that the corrosion reaction with metal depletes the electrolyte during the fuel cell's operation.<sup>[9]</sup> The degradation of atmospheric MCFC performance is primarily caused by electrolyte loss and corrosion.<sup>[9]</sup> The careful management of electrolytes could decrease this problem by improving the structure of electrolytes in the fuel cell.

## 7. Solid Oxide Fuel Cell (SOFC): -

The Solid Oxide fuel cell is the fuel cell in which the electrolyte is made up of solid oxide material (or solid oxide ceramic electrolyte) because of this we also called as a ceramic fuel cell. The solid oxide fuel cell is consisting of two porous electrodes of ceramic material and one electrolyte made up of solid oxide ceramic material.<sup>[10] [11]</sup> A Solid oxide electrolyte is typically used in Solid Oxide fuel cell in place of the polymer electrolyte in PEMFC, which conducts negative oxygen ions ( $\text{O}^{2-}$ ) from cathode to Anode in place of positive hydrogen ion ( $\text{H}^+$ ). The operating temperature of the Solid Oxide fuel cell is very high in the range of 600-1000°C.<sup>[10] [11]</sup> At these temperatures range, the Solid Oxide fuel cell does not require

expensive catalyst (like platinum or other) material compared with other fuel cells. Other fuel cells should require platinum catalysts. [10] [11] There is no effect of carbon monoxide **on** electrodes which can degrade the fuel cell's performance because of high operating temperature. But many studies observed that the performance of fuel cells could be affected by sulfur poisoning. [10] Solid Oxide fuel cell has many varieties of application to use as a power source in vehicles and can also be used in power plant.

We can also use Solid Oxide fuel cell with the thermal power plant. Where SOFC is high temperature can heat water, which converts water vapors to rotate power plant turbine to generate electricity, which can further increase the fuel efficiency in the fuel cell to generate power. By using exothermic electrochemical oxidation to generate heat for endothermic steam reforming inside the Solid Oxide fuel cell. [10] [11] SOFC power system can increase efficiency.

Solid Oxide fuel cell can use working fossil fuel because of the outperform other fuel technologies. The other fuel cell requires Hydrogen as their fuel, because of this we need specific Hydrogen generating plants which will be more costly. But in Solid Oxide fuel cell, we can use hydrocarbons and other, which makes SOFC to generate electricity with low cost. [11] The benefits of SOFC goes beyond their fuel efficiency and fuel adaptability. It's a non-polluting clean energy, reliable and there is no moving part in Solid Oxide fuel cell. So, there is no noise pollution during power generation.

### 7.1. History of Solid Oxide Fuel Cells: -

It was in 1899 that Nernst discovered solid oxide electrolytes, which led to the idea of a solid oxide fuel cell and that electrolyte was Zirconia ( $\text{ZrO}_2$ ). He reported that as the temperature rises, the conductivity rises slowly and stay relatively low in pure metal oxide. But when it comes to the metal oxides mixtures, the conductivity rises as the temperature rises. [5] [6] [10] [11] He relates this electrolyte (metal oxides mixture) with aqueous salt solutions, he explains that when we take pure common salt and pure water, there conductivities are very low, and when we take the aqueous salt solutions, it has very high conductivity. Which shows similarly in case of metal oxides. After this Nernst identified many compositions which shows high conductivity and temperature rises and he patented them. Some of them are Yttrium Oxide and Zirconium Oxide.

In the early 1900s, Emil Baur in Switzerland and his several students carried out several experiments on various types of the fuel cell.<sup>[5] [6]</sup> E. Baur work on high temperature devices.

In 1905, 1<sup>st</sup> patent was filed on fuel cell which consists of solid electrolyte by Haber and his Co-worker. He used porcelain and glass (as a material) to make electrolyte of a fuel cell, and he used partially gold and platinum as electrode materials in the fuel cell. Haber established the fundamentals of solid electrolyte fuel cell.<sup>[4][5][10][11]</sup>

In 1916, Treadwell and Baur use ceramic solid metal as a electrolytes and metal oxide as electrodes material. Yttria stabilized Zirconia can used as an electrolyte in solid fuel cell.

E. Bauer and H. Preis of Switzerland did an experiment with Solid Oxide Fuel Cell (SOFC). At that time, they found limitations of solid oxide like bad chemical stability and electrical conductivity in 1930. They used Yttrium, Zirconia, Tungsten, lanthanum, and cerium as the materials in Solid Oxide Fuel Cell (SOFC). They found that there was problem with their design. It did not perform as they expected the result. The fuel cell was not that much electrically conductive because of material resistance.<sup>[5] [6] [11]</sup> They also found that there were unwanted chemical reactions occur between various gases and electrolyte.

In 1935, Schottky was emphasized that solid electrolytes are advantageous over liquid electrolytes because of they are more feasible for thin- layers. He pointed out that Yttria-Stabilized Zirconia can be used as an electrolyte in solid fuel cell.

In the 1940s, in Russia, O. K. Davtyan's conducted several experiments to uplift electrolyte's mechanical strength and conductivity.<sup>[10] [11]</sup> He mixed  $\text{WO}_3$  (Tungsten trioxide), glass and  $\text{Na}_2\text{CO}_3$  (Sodium Carbonate) with monazite sand. Many of his ideas did not give the expected result. He found that there was unwanted chemical reaction occur between various gases and electrolyte.<sup>[5] [6] [11]</sup>

But Bauer's and Davtyan's work led to the essential basic research for today's Solid Oxide Fuel Cell (SOFC) and Molten Carbonate Fuel Cell (MCFC) devices.

In August 1959, Francis Thomas Bacon demonstrated the first workable fuel cell, which is a combination of 40 cells which can generate power of 6KW. In space travel, the first-time application of a fuel cell was seen which was used in space flight in the Gemini and Apollo mission in the early 1960 as producing electric power and drinking water.<sup>[5] [6][10][11]</sup>

In 1960s, there were many patents were filed on the development of Solid Oxide Fuel Cell (SOFC) technology. At that time there was major problem in Solid Oxide Fuel Cell's was that they show poor efficiency.<sup>[5] [11]</sup> The electrolytes made of thick layer. Due to which Solid Oxide Fuel Cell internal resistance increases and it found high loss.

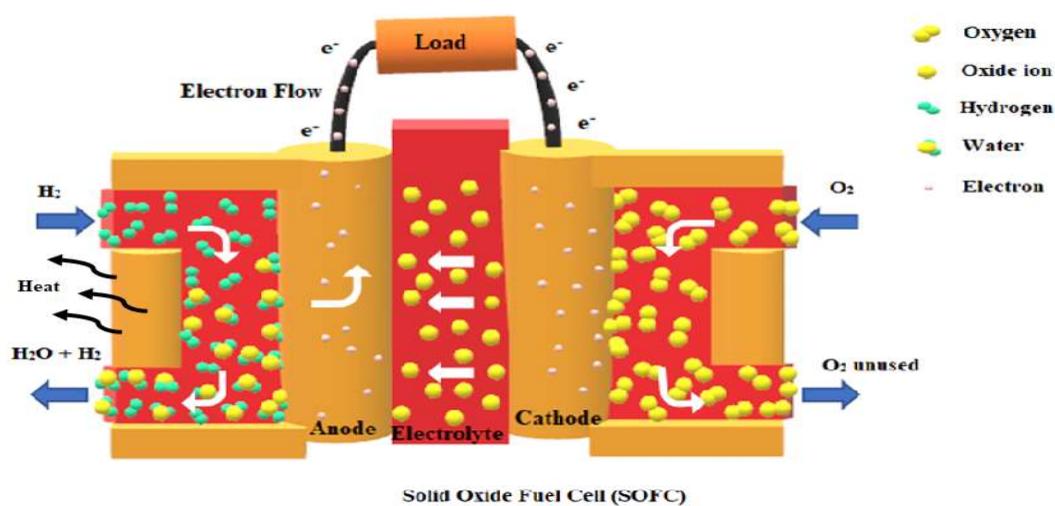
In 1970s, the development work was going on to reduce the thickness of electrolytes, which helps to increase the efficiency and due to reduce in thickness Solid Oxide Fuel Cells electrolytes internal resistance decreases which reduce the losses in Solid Oxide Fuel Cell (SOFC). [5] [6] [11] There are many types of designs of Solid Oxide Fuel Cell (SOFC) tried mainly most common are tubular design and planar design in SOFC, so that we can use large numbers of Solid Oxide Fuel Cell for commercial at the same time like in power plant, etc. [5] [6] [11]

In recent years, attention has been paid to a Solid Oxide fuel cell that is compatible with carbon monoxide and uses a stable electrolyte.

## 7.2. Working of Solid Oxide Fuel Cell: -

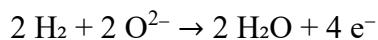
The Solid Oxide fuel cell has two electrodes along with solid oxide electrolyte is there in between both the electrodes. First electrode is cathode (which is also known as Air electrode). When air flows along cathode, the oxygen molecule acquire electrons and splitted into oxide ion at cathode and electrolyte interface. [11] The Oxide ions travel through solid oxide ceramic electrolyte and reach at the other electrode known as fuel electrode.

Fuel is flow along with Anode at fuel electrode or Anode (as fuel for solid oxide fuel cells, most commonly hydrogen and carbon monoxide are used). Which react catalytically with oxide ion, at Anode and electrolyte interface, which produce water ( $H_2O$ ), carbon dioxide ( $CO_2$ ), electrons, and heat. [10] [11] The electrons are move through external circuit towards cathode and the cycle is repeated. This is how Solid Oxide fuel cell is work.



**Fig.6: - Working of SOFC**

The Reaction that occurs at Anode is as follows: -



And at cathode is as follows: -



The Solid Oxide fuel cell operates at 600-1000°C, which is very high. At that temperature, this fuel cell does not need an expensive platinum catalyst, unlike fuel cells that operate at low temperatures like PEMFC. This allows us to use reformed gas (mostly Hydrogen based and carbon monoxide). [10] [11] The advantage of high temperature operation is that we can use carbon monoxide (CO) as fuel by direct oxidation at Anode.

So, the Reaction which occurs if we use CO at the Anode is as follows: -



Several studies have shown that sulfur poisoning is very dangerous for cells and requires the presence of absorbent beds to remove the sulfur.

The Solid Oxide fuel cell contains porous electrodes and these two separated by the solid oxide electrolyte (or which conducts oxygen ion). In Solid Oxide fuel cell, many different types of design have been observed but these two are 1. Planar design and 2. Tubular designs are very similar to each other. [10] [11] In planar design, A flat stack of components are assembled, and channels are built into the anode and cathode. So, that fuel (mostly Hydrogen based) and air (oxygen) can flow through of components surrounding a tabular cathode with components assembled in the form of tubes. [10] The tube has an interior containing air and an exterior containing fuel.

## 8. Materials Selection in SOFC: -

Solid Oxide fuel cell present a huge challenge when it comes to material selection. In order to work or perform in the cell, each material must have electrical properties. The material must be structurally and chemically stable. So that at the time of fabrication, it does

not face any problem and must be stable at high operating temperature because high temperature is required to achieve sufficient power output and current density from the fuel cell operation. [12] [13] [14] [15] Yttria- stabilized zirconia (YSZ) is the most common electrolyte used in Solid Oxide fuel cells, which operate up to 1000 °C.

The inter-diffusion and reactivity between electrodes and the electrolyte should be kept to minimum. In order to minimize the risk of thermal stress, which can lead to cracking in the components or mechanical failure. [14] The thermal expansion coefficients of each component in the fuel cell must be very close to each other so that the risk of fuel cell failure is minimized. [13] An oxidizing atmosphere must be present on the air side of the cell, and a reducing atmosphere must be present on the fuel side.

The materials chosen must fulfill the other requirements: -

1. To prevent reducing and oxidizing gases from mixing. The interconnect and electrolyte must be dense, and the electrodes should be porous, which allows gas to transport through the electrolyte-electrode interface.
2. All the components in the fuel cell must show high electronic conductivity except electrolyte, electrolyte must have high ionic conductivity along with negligible electronic conductivity.
3. In the fuel cell, both the fabrication and operation time, it is imperative to check chemical compatibility with adjoining components of the cell.
4. The stability is required for electrodes, electrolytes, and interconnect in the fuel cell, in the form of chemical, morphological, dimensional, and as well as phase. These all should be stable. So, during long term operation and the temperature of the operating cell should not be affected.
5. The components should have a mechanical shock as well as high thermal heat resistance capabilities.
6. The cost should be low and availability should be easy.

### **8.1. Cathode Materials: -**

The cathode which is also known as Air electrode. This electrode works in oxidizing environments at 1000°C, when Oxygen or air flow on it.<sup>[3]</sup> The reaction is oxygen reduction reaction is shown as: -



The oxygen gas is reduced to oxide ion (proton) by taking two electrons in this process. So, to make this cathode, material should be full-filling the requirements: -

1. The fuel cell must be highly electrically conductive, so the material which will be chosen must be highly electrically conductive in nature.
2. The material which will be chosen must be chemically and dimensionally compatible during fabrication and operation time with adjoining component of the cell.
3. The thermal expansion coefficient must match with other components (anode, electrolyte, and inter connection) of the fuel cells.
4. The material should have mechanical shock as well as high thermal heat resistance.

These are the requirement for cathode material. To most use cathode material in the Solid Oxide fuel cell is Lanthanum maganite ( $\text{LaMnO}_3$ ).<sup>[6] [12]</sup> To increase its conductivity  $\text{LaMnO}_3$  is doped with rare earth elements, and it must be porous so that the oxide ion can travel through electrode- electrolyte interface.  $\text{LaMnO}_3$  is a p-type perovskite.<sup>[12]</sup> The amount of Oxygen available in the material can be either excessive or deficient depending on the partial pressure of Oxygen in the ambient atmosphere.<sup>[6]</sup> An advantage is that it can be used with alternative electrolyte compositions since there are no limitations on fuel cell temperature (about 700°C).<sup>[12]</sup> Reducing the operating temperature will help reduce the operating cost, which makes material more readily available, which help to providing in additional cost savings.

## **8.2. Anode: -**

The Anode which is also known as fuel electrode. This electrode must work and should be stable in reducing environment at 1000°C when the fuel flows through it. The reaction is oxidation reaction takes place at anode is as follows: -



The oxygen ions come through electrolyte and recombines with hydrogen gas, which generates water ( $\text{H}_2\text{O}$ ), 2 electrons ( $2\text{e}^-$ ) and heat. The water flows outside the fuel cell as a product and electrons moves through the external circuit and reached at cathode where electrons help to break Oxygen ( $\text{O}_2$ ) in oxygen ions and the reaction going on. [12] [13] A metal such as nickel can be used as the fuel electrode in a Solid Oxide fuel cell due to the reducing conditions present on the fuel side.

The requirement of anode is almost similar to the requirements of cathode such as porosity, thermal expansion compatibility and electrical conductivity. The different requirement is that the material must show the reducing atmospheric function. [12] The combination of reducing atmospheric function, the electrical conductivity reducing condition requirements make materials more attractive to choose as a anode material. Because nickel is abundant and affordable. [12] A large part of the development has been devoted to it. But the thermal expansion of nickel is very high comparing with Yttria stabilized zirconia (YSZ) to pair them in pure form. So, it tends to sinter to close its porosity at operational temperature. That problem is fixed by the Ni- YSZ composite material of Anode. As a result, YSZ, Nickel (Ni) particles remain separated and do not sinter together. [12] [13] [14]

## **8.3. Interconnect: -**

During the Solid Oxide fuel cells technology, development process, the cells need to be connected and a way of collecting electrical current must be provided and this is done using the interconnects. [12] [13] [14] The interconnect protects the cathode from the reducing atmosphere of the anode as well as serving as an electrical contact on the cathode. Cells rely on this component as one of their most essential elements, the interconnection must satisfy the following requirements, are as follows: -

1. Electronic conductivity is nearly 100%.
2. Due to, the fuel is exposed to air (Oxygen) on one side while the oxygen is exposed to the fuel on other side, it can exist in both oxidizing and reducing atmospheres when the cell operates at its operating temperature.
3. To reduce direct Oxidant-fuel collision during cell operation, Oxygen and hydrogen have a low permeability.
4. Interconnectors should have a similar coefficient to fuel and air electrodes and electrolyte when it comes to thermal expansion.
5. The interconnector should be non-reactive with cathode, solid oxide electrolyte and the electric contact material

Solid Oxide fuel cells use lanthanum chromite ( $\text{LaCrO}_3$ ).  $\text{LaCrO}_3$  is p-type conductor. This material can be doped with rare earth elements (Mg, Ca, Sr, ...) to improve interconnect material conductivity. The other interconnect material which also can be used in Solid Oxide fuel cells is Yttrium chromate which is doped with calcium. [12] [13] [14] This material shows good thermal expansion in reducing the environment.

#### **8.4. Electrolyte: -**

The electrolyte, in the Solid Oxide fuel cell are composed of dense ceramic layer that conduct oxygen ions because of this SOFC is also known as ceramic fuel cell. Considering that electrolyte is in contact with both reducing (at Anode) and oxidizing environment (at cathode) it is important for the electrolyte to be stable in both the condition in the Solid Oxide fuel cell. When the Oxygen is converted into oxide ion (proton) it must travel through electrolyte to reduce the oxide ion concentration gradient. [12]. It is important to make the Solid Oxide Fuel Cell as thin as possible. For fuel cell stability, the electrolyte must be chemically, structurally, dimensionally, and thermally stable across it.

##### *i. Zirconia Based Electrolyte: -*

Its operating temperature range is very high. The material of electrolyte must be fabricated in such a way that it's thin and strong film and there are no gas leaks. The Yttria-

stabilized zirconia is the most used electrolyte in Solid Oxide fuel cells. [12] [13] [14] Yttria-stabilized zirconia goes through a progressive phase transition that stabilizes the cubic phase at high temperature and generates vacancies for Oxygen, 1mole of dopant rate in Solid Oxide fuel cell. For the Y S Z electrolyte to avoid gas permeation from one side of the other, it must be free of porosity. [13] To minimize ohmic loss, it should be uniformly thin, with a transport number close to unity. The conductivity of ( $O^{2-}$ ) Oxygen (ion) proton should be high.

A possible electrolyte was also cerium oxide. As a result of its high ionic conductivity, it operates at low temperature is (700°C). [12] [13] [14] [15] This temperature range give many choose to select material for other cell components, which can be cheaper than before and more available material in a short time.

The chemical stability of the candidate materials under the operation conditions of the cell is a critical factor to be considered, at intermediate temperature it show high ionic conductivity and similar thermal expansion coefficients which is same as the other components ( fuel electrode and air electrode) of the fuel cell. [13] [14] [15] When operating temperature are reduced, the chemical stability is likely to be increase, which also helps in to reduce in manufacturing costs. But in case of Yttria- Stabilized Zirconia, Because of thermally activated ionic conductivity, which results is a performance at lower temperature.

### ***ii. Bismuth based electrolytes: -***

Several electrolytes were studied, and it was found that highest conductivity and stability found in Bismuth oxide- based electrolyte. [13] [15] But this electrolyte is only stable in specific temperature range 725 to 805°C. But at low oxygen pressure in this electrolyte is reduced to bismuth metal.

### ***iii. $LaGaO_3$ - based perovskite electrolyte: -***

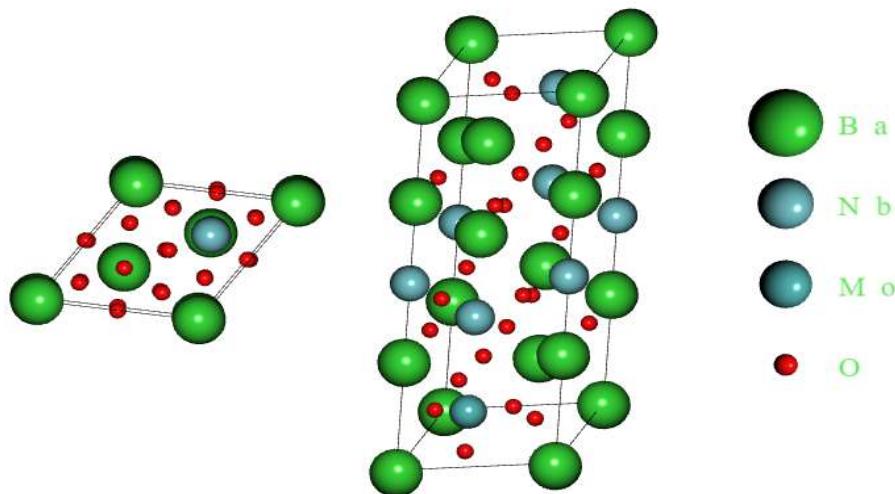
$ABX_3$  as a perovskite chemical structure.  $LaGaO_3$ - based perovskite electrolyte. A is alkaline earth metal (lanthanum) and B is transition metal Ga. [16] In Solid Oxide Fuel Cell, the wide range of perovskite cathode are there, which can exhibit electronic as well as ionic conductivity. At intermediate temperatures, some perovskites show high oxygen ion

conductivity, some of the perovskites are  $\text{La}_2\text{Mo}_2\text{O}_9$ ,  $\text{LnBO}_3$ ,  $\text{A}_2\text{B}_2\text{O}_5$ , doped  $\text{LaGaO}_3$ .<sup>[14]</sup> [16] Therefore, in Solid Oxide Fuel Cells, we can use them as a electrolyte.

In perovskite, by doping we can create many oxygen vacancies, we can use alkaline earth metals ( $\text{Ca}^{2+}$ ,  $\text{Sr}^{2+}$  and  $\text{Ba}^{2+}$ ) in A- site of  $\text{LaGaO}_3$  perovskite. In  $\text{LaGaO}_3$ ,  $\text{La}^{3+}$  can be replaced by  $\text{Sr}^{2+}$ , because  $\text{Sr}^{2+}$  have nearest ionic radius of  $\text{La}^{3+}$ .<sup>[14]</sup> Because of this replacement the oxygen vacancies increase, which will increase the ionic conductivity of the electrolyte. In this replacement or doping  $\text{La}^{3+}$  with  $\text{Sr}^{2+}$ , make some impurities in the pure perovskites comes (like  $\text{La}_4\text{SrO}_7$  and  $\text{SrGaO}_3$ ) which shows the limitation of this dop perovskite material.<sup>[14]</sup> We can also dop at B- site of the perovskite in  $\text{LaGaO}_3$  with divalent ions ( $\text{Mg}^{2+}$ ) at B, the oxygen vacancies increase, which will increase the ionic conductivity of this perovskite base electrolyte.

#### iv. Hexagonal Perovskite based electrolyte: -

In a variety of energy-related technologies, hexagonal perovskites may prove advantageous for creating new ionic conductors. Structures related to hexagonal perovskites have hexagonal  $\text{AX}_3$  layers packed close together or layers of cubic and hexagonal  $\text{AX}_3$  layers close together.<sup>[1] [2] [3] [16]</sup> There are several crystal structures associated with hexagonal perovskite oxides. It is difficult to find oxide-ion conductors with hexagonal perovskite-like structures.



**Fig.7:** - Structure of hexagonal perovskite based  $\text{Ba}_7\text{Nb}_4\text{MoO}_{20}$ <sup>[1] [2] [3]</sup>

There are many types of hexagonal perovskites were reported but, in this paper, we have synthesized  $Ba_7Nb_4MoO_{20}$  based on hexagonal perovskites by using Barium Carbonate ( $BaCO_3$ ), Niobium pentoxide ( $Nb_2O_5$ ) and Molybdenum trioxide ( $MoO_3$ ) precursors.

### 8.5. Application of Solid Oxide Fuel Cells: -

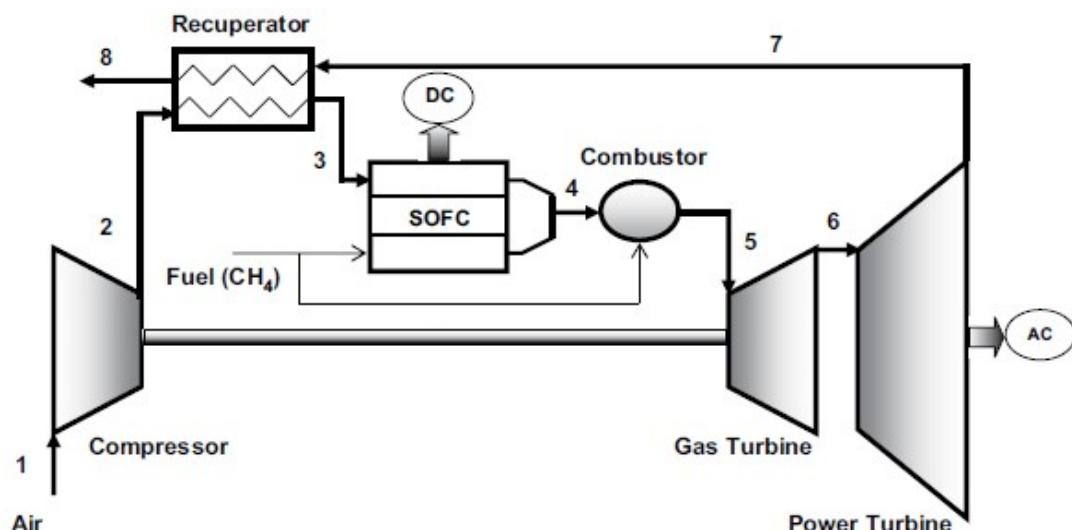
Solid Oxide Fuel Cell is one of the promising environment friendly technology which produce electricity and water, when we provide hydrogen ( or hydrogen like fuel ) at anode and oxygen or Air at cathode. In recent years, Solid Oxide Fuel Cell have received many attentions as innovative technologies. Many research works are going on, to use of Solid Oxide Fuel Cell in different field. Which can be used in many fields such as conventional electrical power plant. Solid Oxide Fuel Cell can be used in three main application such as Residential application, Combine-cycle power generation plant and Tri-generation. [\[17\]](#) [\[18\]](#) [\[19\]](#) [\[20\]](#) Till now, we cannot use Solid Oxide Fuel Cell in transportation work. Because Solid Oxide Fuel Cell are operating at very high temperature (nearly rang is 700 - 1000°C ). But now some research work is going on to reduce the operating temperature of SOFC, So that we can use this fuel cell in transportation vehicles or use as a source of power generation during traveling. [\[19\]](#) [\[20\]](#)

System using Solid Oxide Fuel Cells are also used in the transportation industry. Fuel cells which use polymer electrolyte are considered to be the best transportation applications. As a fuel for these fuel cells, hydrogen must be pure without any carbon monoxide (CO). But there is no such infrastructure present everywhere, where the pure hydrogen gas can produce. It can be possible to make such infrastructure, but it will make it more expensive and complex to complete it, and it is also not possible to eliminate entire carbon monoxide from the fuel which can further degrade the performance of fuel cell and it can permanently damage the

fuel cell. [17] [20] But in Solid Oxide Fuel Cell, the carbon monoxide and hydrogen can be used as fuel because of high operating temperature. Hydrocarbon fuel can be reformatted on cell because water is present on the anode side. Solid Oxide Fuel Cell has low cost due to there is no use of noble metal catalysts in the fuel cell. [18] [19] [20]

### **8.5.1. Solid Oxide fuel cell – gas turbine combined system: -**

The Solid Oxide fuel cell has two electrodes with Solid Oxide electrolyte is there in between both the electrodes. [21] First electrode is cathode, air flows along the cathode and second is anode, Fuel is flow along with Anode at fuel electrode or Anode. [21] When a solid oxide fuel cell is operating, a chemical reaction takes place between the fuel and the air, but there is, however, a certain percentage of fuel gas that doesn't react.

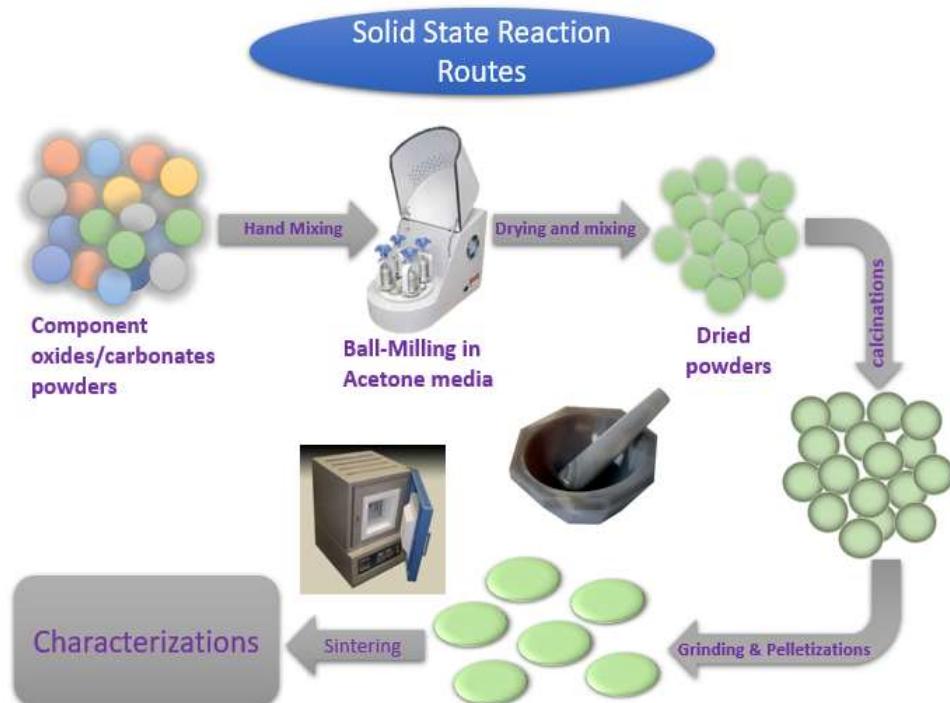


**Fig.8: - Solid Oxide fuel cell – gas turbine combined system [21]**

Fuel gas that has not been reacted in a Solid Oxide fuel cell is subjected to further reaction for maximize its usefulness in the combustion chamber. [21] The high temperature gas reacts in combustion chamber which converted into mechanical energy. That mechanical energy further converted into electrical power with the help of gas turbine (the reaction of gas generates mechanical energy which helps to rotate turbine which generates electricity). [21] Compressed air in the heat exchanger is heated by the high-temperature gas being discharged.

## 9. Synthesis Method

There are various types of perovskite material which have been synthesized by using a variety of techniques such as: - Sole- gel method, Pechini method, Co- Precipitation method and Solid- State method. Every technique has their advantages and disadvantages, but the main difference between these techniques is on the basis of phase purity, time and sintering temperature. Here our focus is on Solid- State reaction method.



*Fig.9: - Steps of Solid-State Reaction Method*

### 9.1. Solid- State Reaction Method: -

Solid state reaction method is one of the most common methods for preparation of solid oxide fuel cell's components materials. [3] Solid State reaction uses solid reagent to synthesize (or obtain) polycrystalline material. In this synthesis method, very high temperature is required for reaction. [3] The solid materials do not react together at room temperature. This method of synthesis is very easy when compared with other method. [3] By using this method large- scale production is also possible, which gives advantage to this synthesis method.

It is also necessary that the reaction occurs at a high temperature in order to occur at an acceptable rate. The range of temperature used in this method is 900 to 1500°C.<sup>[3]</sup> In this method, it is particularly important to characterize the reaction rate during solid state synthesis. There are several more conditions on which reaction rate depends such as thermodynamic properties, shape and surface area of solids, reactant structural properties and rate of diffusion as well as reaction condition.<sup>[3]</sup>

In Solid State reaction method, there are five main processes which are carried out on sample which are grinding, calcination, again grinding, palletization and sintering.



**Fig.10: - (a) Agate Mortar and (b) Ball milling**

1<sup>st</sup>, we have to select the reactant materials which depends on reaction condition and expected nature of the product. Then taking those dried reactants to weighting. It is important to ensure that the stoichiometric ratio of (reactant material) precursor powders are thoroughly mixed by using an agate mortar and pestle, for 1-2hrs and we also use ball milling for 2hrs.<sup>[3]</sup> So that our powder should be mixed very thoroughly (homogenously). After mixing the sample powder undergoes for heat treatment which will again followed by grinding of the sample.



**Fig.11:- Muffle Furnace**

2<sup>nd</sup>, the precursor (sample) powder is calcined at very high temperature (rang 900-1500°C). We have to select temperature very carefully, less than melting point of the required final product. If we did not provide sufficient heat at the time of calcination, the required product can't be form because the reaction can't take place at low temperature. [3] Due to this it become more important to give sufficient heat (or temperature) at the time of calcination.

After calcination, the calcined sample is again thoroughly mixed by using the agate mortar and pestle, for 1-2 hrs. [1][2][3] so that we can get fine samples.



**Fig.12: - Hydraulic Press for pelletizing of powder**

Next process is making pellets, The pellets are formed by using hydraulic press. The pelletizing of powders is necessary to decease the porosity of the samples and make dense samples.



*Fig.13: - Sintered pelletized powder samples*

After pelletizing of the sample, a high temperature should be used for sintering of pelletized powder samples. The temperature range of sintering will be between (1000 - 1300°C), it will also depend on the material. [3] As the particles sinter together, because of this they experience atomic diffusion, which allowing them to fuse together. We can also notice these changes just by looking at samples, after sintering the sample pellet material is shrunken.

Solid state reactions benefit from high temperatures because they induce a high diffusion rate, and the same environmental conditions are used to prepare samples of varying concentrations. [12] A purification step is not necessary after preparation of sample, nor any type solvents necessary in this method.

## **10. Characterization Methods: -**

In this paper we are going to use different characterization methods, which are Powder X-ray Diffraction (XRD) technique, Scanning Electron Microscope (SEM) spectroscopy, Fourier-Transform Infrared (FTIR) spectroscopy and UV and Raman spectroscopy and Electrical Impedance spectroscopy techniques.

### **10.1. Powder X-ray Diffraction: -**

X-Ray diffraction or XRD is most widely used characterization method. In material, it is very important to identify the properties and structure (how atoms in crystal structure are arranged), these are the most important information we need after material synthesis. Using diffraction technique, we can study the atomic arrangement in a material. [3] [23] The fundamental principle of X-ray diffraction is the constructive interference of monochromatic X-rays with a crystalline material. A cathode ray tube produces these X-rays, which are then filtered to provide monochromatic radiation. [3] [23]

When a filament is heated in a cathode ray tube, it produces electrons that emit X-rays. Voltage is applied to the electrons to accelerate them toward a target and electrons are injected into the target material to bombard it. An electron with enough energy can disrupt electrons from the target's inner shell, the X-ray spectra with distinct characteristics are created. [3] [23] There are several components to these spectra, the most prevalent of which seeming to be  $K_{\alpha}$  and  $K_{\beta}$ .  $K_{\alpha}$  is consist of two parts  $K_{\alpha 1}$  and  $K_{\alpha 2}$ .  $K_{\alpha 2}$  have slightly larger wavelength compared to  $K_{\alpha 1}$ . But  $K_{\alpha 1}$  have twice the intensity comparing with  $K_{\alpha 2}$ . [3] [23]



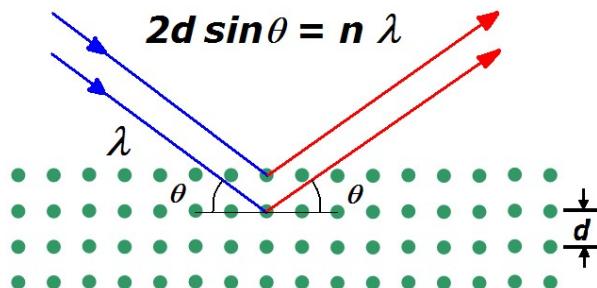
**Fig.14: - X-ray Diffraction (XRD)** [22]

Analyses of crystallographic structure are performed by using this technique. In the case of small crystals, it is possible to determine sample phase purity, crystallinity, and

composition. An x-ray beam is passed through it in this technique. The wavelength of X-ray beams is similar to the gap between atoms in the sample, so they are used to examine it. As a result, the angle of diffraction would be varied by the atom gap in the molecule. [23] Because of this, we use X-ray beams instead of employing significantly longer wavelengths. Because of longer wavelength, it would remain unchanged regardless of the spacing between atoms. [23] The X-ray beam flows through the sample material and bounce in bounce off the atoms in the molecule. Because of bouncing off the atoms, the direction of beam changes in different directions / angles (  $\theta$  ) comparing with the direction of original direction of incident beam.

### **Bragg's Law: -**

The X – ray diffraction technique follows Bragg's method. The lattice plane of crystal is incident with a collimated beam of X – rays with a spacing  $d_{hkl}$ . Let the incidence angle between the X-ray beam and the lattice plane is  $\theta$ . [3] [23] When the ray is scattered by the top and bottom surfaces of the plane, the interplanar spacing  $d_{hkl}$  produces a path difference. By geometry, we found that the  $2 d_{hkl} \sin \theta$ , is the path difference between incident X – ray beam and diffracted X – ray beam. If the wavelength is integral multiple of path difference. Then we can say that the interference is constructive between the scattered X – ray. [3] [23]



Mathematically, we can write it as:

$$2 d_{hkl} \sin \theta = n \lambda$$

Here, n is a diffraction order, and it is an integer.

The incident and scattered X – ray on the surface of specimen makes  $\theta$  angle. To record the X- ray diffraction pattern by varying the incident X-ray beam by  $\theta$  angle and the scattering angle by  $2\theta$ . The intensity of the scattered ray is recorded as the function  $2\theta$ . [23] In some cases, the sample and detector are rotating at  $\theta$  and  $2\theta$  respectively, but the source of

incident X-ray are stationary position. While in some case the source of incident X-ray and detector are rotating at  $\theta$  and  $2\theta$  respectively, and the sample is at stationary position. The diffractometers are controlled by goniometers, which enable precise rotation of their parts. [3] [23] The detector and the X-ray source are typically mounted along the sample's periphery, which rotates as the sample rotates. The peaks of the XRD spectrum are based on the Miller indices for randomly oriented planes.

After XRD data collected, we have to plot graph of that data and match it by standard phase which contains the information of diffraction angle, crystallographic information, miller indices, and relative intensities. [3] [23] According to the angle of diffraction from the incident x-ray, the  $2\theta$  positions correlate with the spacing between crystallized matter or atoms in the sample. [3] [23] Depending on how many molecules are present in that phase or how closely spaced is, the intensity of the peaks can vary significantly. If the intensity is high means that there are the more crystals or molecules with that specific spacing.

There is an inverse relationship between peak width and crystal size. A narrower peak indicates a larger crystal. A wider peak indicates the presence of a smaller crystal or sample could be amorphous in nature or there could be defect in crystal structure. [3] [23] We can also determine the unknown compound or molecule by comparing it with experimentally determined values or with literature values, by matching their peak positions, width, and thickness. [3] [23]

To determine the size of crystallites in polycrystalline samples, Scherrer equations are commonly used. The Scherrer equations can be written as:-

$$D_{hkl} = \frac{K\lambda}{\beta_{hkl} \cos \theta}$$

Where  $D_{hk}$  is the crystallite size,  $\lambda$  is the wavelength of the X-ray, " $h k l$ " is the miller indices of the planes which were under consideration, K is the crystallite shape factor, which is also known as a numerical factor,  $\beta_{hkl}$  is the full-width at half-maximum of the X-ray diffraction peak, and  $\theta$  is the Bragg's angle. [3] [23]

## **10.2. Scanning Electron Microscope (SEM) spectroscopy: -**

Scanning-Electron Microscopy (SEM) is a technique commonly used to visualize materials' microstructures and morphologies. Through the use of a focused beam of high-energy electrons, the scanning electron microscope (SEM) is able to produce wide range of signals on the surfaces of solid material. An electron-sample interaction produces signals which contain information about a sample's chemical composition, orientation, structure of crystals in the material, and external morphology. Mostly in experimental purpose, we high energy electrons are focused on a selected area of the surface of the solid material (sample). The data is used to generate 2- Dimensional image of the surface of the sample material which shows the spatial differences in these characteristics.<sup>[3]</sup> Using traditional SEM methods, areas spanning in width from about 1 cm to 5 microns may be scanned in scanning mode. As an additional function, SEMs can be used to analyse selected points on a sample. This method is particularly effective for determining quantitative as well as qualitative properties like crystalline structure, orientation, and chemical compositions of the sample.

Current is passed through a filament to produce electrons at the cathode. A high voltage is then used to accelerate the electrons towards an anode. In order to collimate the electron beam, fine apertures are made on the column and electromagnetic fields surround it. After exiting the column, the electron beam reaches to the surface of the sample material. Several physical phenomena are observed when the continuously the beam strikes on a sample.



**Fig.15: - Scanning electron microscopy (SEM) with high and low vacuum mode.** <sup>[22]</sup>

In Scanning electron microscopy (SEM), the electron has very high kinetic energy. When electron get decelerated in solid sample material, that kinetic energy gets spread as a different type of signals are generated when interaction occurs between electron and the sample material. The signal is consisted of secondary electrons (use to generate 2- D image of the surface of the sample), photons (which are used to element analysis), back- scattered electrons (this is also use to generate the SEM image of the sample), diffracted back-scattered electrons (which are used to analyse or determine the crystal structure and their orientations of the sample), Heat (heat is generated because of high kinetic energy electron strikes on the sample surface), and visible light.

The secondary electrons and back- scattered electron is most important to generate the 2- D image of the sample. For displaying morphology and topography of samples, secondary electrons are the most useful and back- scattered electrons are particularly useful for demonstrating compositional differences in multistage materials. X- ray are produce when the high energy incident electron collides inelastically with electrons of the atoms which are present on the surface of sample. When high energy (excited) electron comes to lower energy state, the energy which released in that process is X- ray. X-rays produced by electron-sample interactions do not cause any loss of volume in the sample. As a result, the same materials can be analysed several times. Because of this Scanning electron microscopy is considered as a non- destructive characterization method.

### ***10.3. Fourier Transform Infrared Spectroscopy (FTIR): -***

Fourier Transform Infrared Spectroscopy (FTIR) is very powerful optical characterization technique which measures vibrations of molecules by IR radiation at specific wavelengths. Chemical functional groups can be determined by FTIR analysis of a sample. Vibration frequencies associated with functional groups are characterized by their specific characteristics.<sup>[29]</sup> There are vibration frequency ranges that fall within the infrared frequency range (IR). As a result, when an IR signal travels through the functional groups, they vibrate at specified frequencies.<sup>[29]</sup>



**Fig.16:** - Fourier Transform Infrared Spectroscopy (FTIR) [22]

The FTIR Spectroscopy technique is based on the fact that the majority of molecules absorb light in the infrared band of the electromagnetic spectrum. Several spectral ranges are simultaneously scanned to collect data with high-resolution. [3] The frequency range is commonly recorded in wave numbers ranging from 300 to 4000  $cm^{-1}$ .[24] This provides a substantial advantage over a scattering spectrometer, which evaluates intensity across a limited spectrum of frequencies at a time.

#### **10.4. Raman Spectroscopy: -**

Molecular spectroscopic method that uses the interaction of light with sample to determine the characteristics of a substance, such as FTIR, this is known as Raman spectroscopy. By using Raman spectroscopy, we are able to collect information from light scattered by the particles in the sample, On the other hand, the IR spectroscopy is dependent on the absorption of light. The Raman spectroscopy technique can be used to obtain additional information about a reaction by revealing intramolecular and intermolecular vibrations.

Raman scattering was named in 1928 after the Indian scientist CV Raman, who observed it for the first time. By using this technique, we can get information about structural and chemical composition in the sample, and it also involves identifying substances through

the Raman 'fingerprint' of each substance. [24] These characteristics are extracted by Raman scattering from a sample using Raman spectroscopy.



**Fig.17: - Raman Spectroscopy** [22]

When light comes in contact with molecules in a solid powder sample, the majority of the photons are scattered or distributed at the same energy as the incoming photons. This is known as Rayleigh scattering and it is also known as elastic scattering. [24] [25] The small number of photons scattered in on different frequency as comparing with incident light frequency. This is known as inelastic scattering, or it is also known as Raman effect. [25] A molecule's vibrational signature can be collected using Raman technique, which helps us to understand how molecular interactions with its surroundings which is very important to identify.

### **10.5. Electrochemical Impedance Spectroscopy (EIS): -**

Electrochemical impedance spectroscopy (EIS) is a powerful and effective instrument for studying material characteristics and electrode responses. It has established itself as one of the most widely used analytical instruments in materials research. This technique is very effectively and frequently used in wide range of important areas of research and development in energy storing equipment's, fuel cell and batteries- related systems. [1] [2] [3] [26] And it is also use in analysing the properties of ionic and electronic conducting polymers. EIS is an extremely flexible, sensitive, and informative method that used to study electro-chemical kinetics at electrode interfaces and determine conduction pathways in diverse materials via mobile electronic carriers.

During the measurement, a sinusoidal voltage (V) with constant angular frequency ( $\omega=2\pi\nu$ ) is applied across the sample. The equation of voltage is given by:

$$V = V_0 e^{i\omega t}$$

As a result, the current flowing through the material which varies exactly with the applied voltage across it. Phase shift does not vary with voltage, but it vary, if angular frequency change. The equation of current is given by:

$$I = I_0 e^{i(\omega t + \varphi)}$$

Where t is the time and  $V_0$  and  $I_0$  is the maximum amplitude of voltage and current respectively. In DC, we can normally use Ohm's Law ( $V=IR$ ), But in alternative Voltage, we can't use directly  $V=IR$ . Because of phase difference between Current and voltage. [3] [12] For this we use complex quantity known as Impedance (Z).

$$Z = \frac{V}{I} = \frac{V_0 e^{i\omega t}}{I_0 e^{i(\omega t + \varphi)}} = Z_0 e^{-i\omega\varphi} = Z_0 (\cos \varphi - i \sin \varphi)$$

And  $Z_0 = \frac{V_0}{I_0}$

Resistance and reactive components both contribute to impedance. The reactive components are Inductance and Capacitance. Inductance (L) is a component which stores energy in the form of magnetic field. [3] [26] Capacitance (C) is the component which can stores charge. In impedance formula as shown above, the real part ( $\cos \varphi$ ) is related to the resistance, which is refers as  $Z^l$  (also known as real impedance) and the ( $\sin \varphi$ ) complex part is related to the Inductance and Capacitance, which is referred as  $Z^{\parallel}$  (also known as complex impedance). When phase difference  $\varphi = 0$ , then the complex impedance become 0 ( $\sin 0^\circ = 0$ ) and  $Z^l = R = Z_0$ . A sequence of impedance measurements at various frequencies may be used to calculate the resistance. [3] [26] Then we plot graph between  $Z^l$  Vs  $Z^{\parallel}$ , which is known as a Nyquist plot.

Each point on the Nyquist plot represents a different  $\omega$ . This plot makes semi-circle. A semi-circular plot cut a point at which the  $Z^{\perp}$  is crossed, which corresponds to the resistance  $R$  of the sample. In such plots more semicircles are frequently visible, each with its own value of  $R$ . The capacitance of a substance is inversely proportional to its thickness of the region. [26] The region responsible for each semicircle may thus be found by applying the relationship, as shown

$$\omega_{max}RC = 1$$

Where,  $\omega_{max}$  is the value of frequency at which  $Z^{\parallel}$  is maximum for semi-circle.  $R$  and  $C$  is resistance and capacitance respectively.

For conductivity ( $\sigma$ ), the resistance depends upon the samples dimension like length and area. [3] So, we can relate the conductivity with resistance as shown in the equation:

$$\sigma = \frac{l}{RA}$$

Where  $l$  is the thickness of the sample and  $A$  is the area of the sample. For activation energy,  $E_a$ , the conductivity is recorded as a function of Temperature.

So, 
$$E_a = -R'T \ln\left(\frac{\sigma T}{\sigma_0}\right)$$

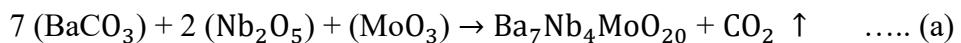
and it is also written as

$$\sigma = \frac{\sigma_0}{T} e^{-\frac{E_a}{RT}}$$

Known as Arrhenius relationship. Where,  $\sigma_0$  is pre-exponential factor.  $\sigma$  is the conductivity,  $R'$  is the gas constant and  $T$  is the temperature. As a result, we plot  $\ln(T)$  Vs  $1000/T$  known as Arrhenius plot, which shows a gradient of  $-\frac{E_a}{R}$ . Which helps us to determine the activation energy. [26]

## 11. Preparation: -

In this paper we prepared the samples of  $Ba_7Nb_{(4-x)}Mo_{(1+x)}O_{20}$  ( $x = 0, 0.1, 0.2, 0.3$ , and  $0.4$ ) by solid-state reaction method. The starting materials Barium carbonate ( $BaCO_3$ , 99.99%), Niobium pentoxide ( $Nb_2O_5$ , 99.99%), and Molybdenum trioxide ( $MoO_3$ , 99.99%) were used.<sup>[1] [2] [3]</sup> The powders of these material substances were mixed in stoichiometric quantities as described below: -



We used stoichiometric concentrations ratio of precursor components as shown in equation (a) based on their molecular weight as shown in the table as shown below: -

**Table (a): - Molecular weight of used chemical in this paper.**

Chemicals	Molecular weight (in gm/mol)
$BaCO_3$	197.35
$Nb_2O_5$	265.81
$MoO_3$	143.94

In table (b), the weight of the reactant powder which were used to synthesis of doped sample as shown below. It is important to ensure that the stoichiometric ratio of (reactant material) precursor powders are thoroughly mixed by using an agate mortar and pestle, for 1-2hrs and we also use ball milling for 2hrs. <sup>[1] [2] [3]</sup>

**Table (b):** - The quantity of the reactant powders which were used to synthesis 10gm of doped sample

Concentration (x)	$BaCO_3$ (in gm)	$Nb_2O_5$ (in gm)	$MoO_3$ (in gm)
0.0	6.71500	2.58400	0.69900
0.1	6.71221	2.51847	0.76932
0.2	6.70860	2.45260	0.83880
0.3	6.70500	2.38680	0.90820
0.4	6.70140	2.32101	0.97756

Then, the precursor (sample) powder is calcined at temperature 1050°C for 48hr in static air.<sup>[1]</sup> The calcined sample again thoroughly mixed by using the agate mortar and pestle, for 1-2 hrs. So that we can get homogenous mixture.<sup>[3]</sup> Then, that calcined sample were pelletized by using hydraulic pressure.



**Fig.18:** - The pelletized samples were sintered at 1200°C for 5hr.

The average diameter and thickness of the samples are mentioned in the table (c). The pelletized samples were sintered at 1200°C for 5hr.<sup>[1] [2] [3]</sup>

**Table (c):** - The average diameter and thickness of the  $Ba_7Nb_{(4-x)}Mo_{(1+x)}O_{20}$  ( $x = 0, 0.1, 0.2, 0.3, \text{ and } 0.4$ ) samples.

Sample	Diameter (in mm)	Thickness (in mm)
$Ba_7Nb_4MoO_{20}$	9.49	1.89
$Ba_7Nb_{3.9}Mo_{1.1}O_{20}$	9.33	1.35
$Ba_7Nb_{3.8}Mo_{1.2}O_{20}$	9.05	1.20
$Ba_7Nb_{3.7}Mo_{1.3}O_{20}$	9.11	0.92
$Ba_7Nb_{3.6}Mo_{1.4}O_{20}$	9.24	1.25

The X-ray diffraction study has been performed to evaluate phase purity and stability of the samples. And we examined the composition of the ceramic and the structure of its microstructure using scanning electron microscopy and energy-dispersive X-ray spectroscopy, as explain these in the below.

## 12. Characterization Data Analysis: -

### 12.1. XRD Analysis: -

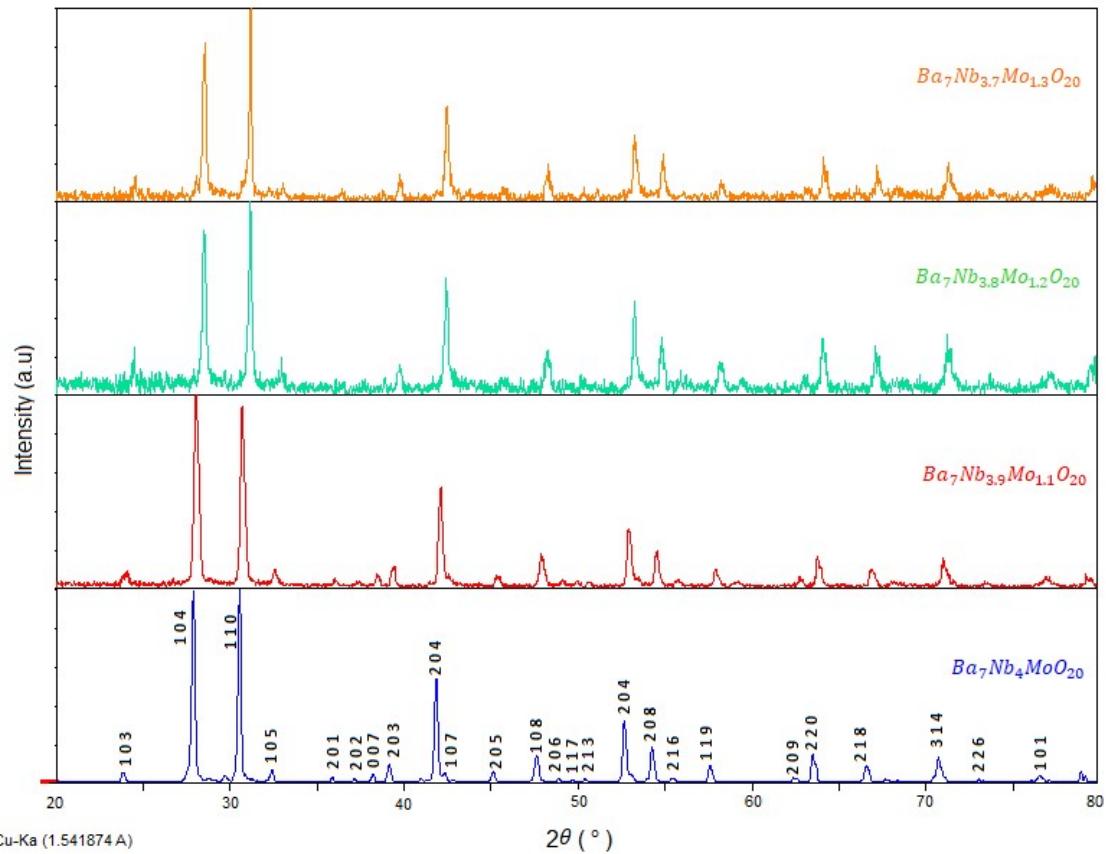
The X – ray diffraction is a physical characterization for calcined sample for all the compositions were done at room temperature and the XRD patterns were collected. The step size of  $0.02^\circ$  was used to record data over the range of  $20^\circ$  to  $80^\circ$ .<sup>[1] [2]</sup> The XRD patterns of the prepared materials indicates that the sample is in pure phase. For obtained diffractograms that compositions are identified with the space group  $P\bar{3}m1$ .<sup>[1] [2]</sup>

**Table:** The unit cell whose space group is with  $P\bar{3}m1$  crystallographic dimensions<sup>[1] [2]</sup>.

a	b	c	$\alpha$	$\beta$	$\gamma$
5.8644 Å	5.8644 Å	16.52719 Å	$90^\circ$	$90^\circ$	$120^\circ$

As we can see in the XRD pattern (  $2\theta$  Vs intensity graph ), The peaks observed are very sharp in all samples XRD pattern which suggesting that the samples prepared are highly crystalline. [23] And the intensity is also high which means that there are the more crystals or molecules with that specific spacing. The wider peaks indicate the presence of a less crystalline or amorphous in nature. [23]

The most intense peak in  $Ba_7Nb_4MoO_{20}$  are obtained at  $28.14^\circ$  and  $30.78^\circ$ , and their intensity at those points are 1393.33 and 1386.67 respectively. In  $Ba_7Nb_{3.9}Mo_{1.1}O_{20}$  obtained at  $28.20^\circ$  and  $30.68^\circ$  , and their intensity points are at 1413.3 and 1326.6 respectively. In  $Ba_7Nb_{3.8}Mo_{1.2}O_{20}$  obtained at  $28.5^\circ$  and  $31.1^\circ$  , and their intensity points are at 186.67 and 216.67 respectively. In  $Ba_7Nb_{3.7}Mo_{1.3}O_{20}$  obtained at  $28.54^\circ$  and  $31.16^\circ$  , and their intensity points are at 280 and 313.33, respectively.



**Fig.19:-** XRD pattern of as prepared  $Ba_7Nb_4MoO_{20}$ ,  $Ba_7Nb_{3.9}Mo_{1.1}O_{20}$ ,  $Ba_7Nb_{3.8}Mo_{1.2}O_{20}$ , and  $Ba_7Nb_{3.7}Mo_{1.3}O_{20}$ .

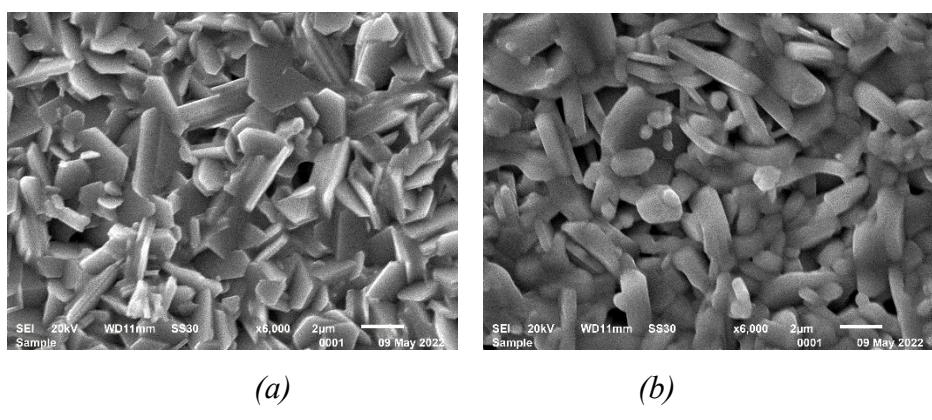
As we can see that, when the doping is increasing in the samples the XRD peaks are shifting towards right side. And when doping is increasing the 1<sup>st</sup> most intense peak

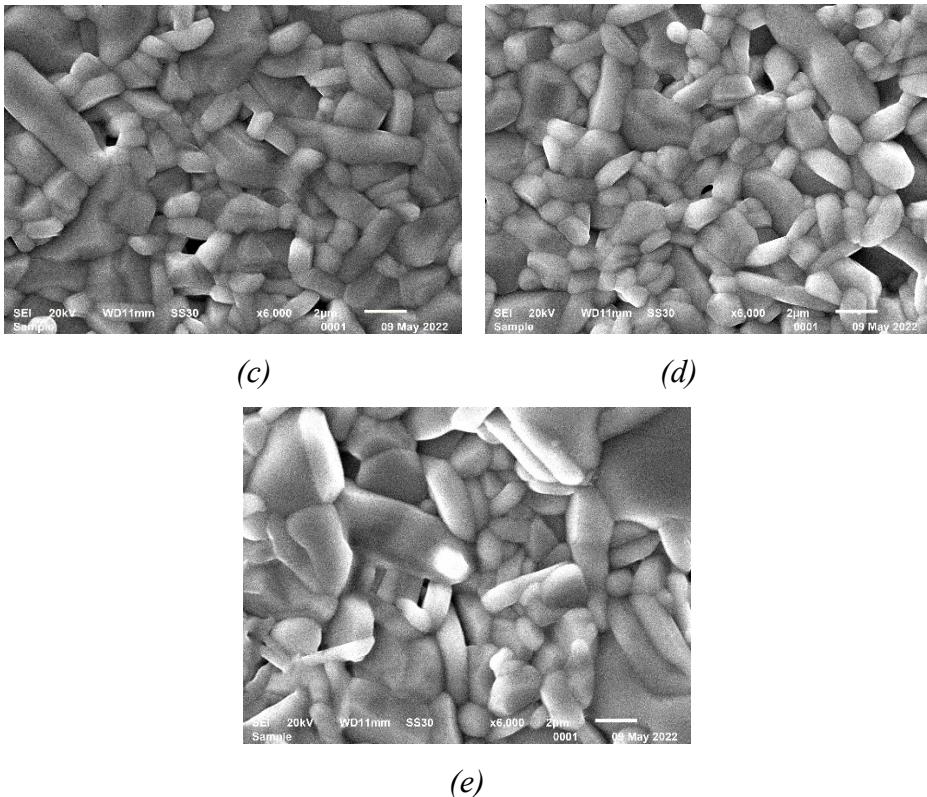
decreasing and 2<sup>nd</sup> most intense peak increasing in samples 3<sup>rd</sup> and 4<sup>th</sup> comparing 1<sup>st</sup> samples  $Ba_7Nb_4MoO_{20}$ . 2<sup>nd</sup> sample is also similar to the 1<sup>st</sup>.

By using Scherrer Formula in 1<sup>st</sup> sample  $Ba_7Nb_4MoO_{20}$ , we calculated the most intense peak 1393.33 and 45.04 nm is the value determine crystallite or grain size by using XRD graph. In 2<sup>nd</sup> sample  $Ba_7Nb_{3.9}Mo_{1.1}O_{20}$ , we calculated the most intense peak 1413.3 and 25.16 nm, Similarly, for 3<sup>rd</sup> sample  $Ba_7Nb_{3.8}Mo_{1.2}O_{20}$ , we calculated the most intense peak 216.67 and 37.64 nm and for 4<sup>th</sup> sample  $Ba_7Nb_{3.7}Mo_{1.3}O_{20}$  the most intense peak is 313.33 and 53.91 nm, were calculated using Scherrer formula, to determine crystallite or grain size by using XRD graph.

## **12.2. Scanning Electron Microscope (SEM) Analysis: -**

The Scanning Electron Microscope (SEM) micrograph were collected at room temperature for the surfaces of (a)  $Ba_7Nb_4MoO_{20}$ , (b)  $Ba_7Nb_{3.9}Mo_{1.1}O_{20}$ , (c)  $Ba_7Nb_{3.8}Mo_{1.2}O_{20}$ , (d)  $Ba_7Nb_{3.7}Mo_{1.3}O_{20}$  and (e)  $Ba_7Nb_{3.6}Mo_{1.4}O_{20}$  pellet, respectively. Before the SEM investigations the pellets were coated with gold Palladium alloy (to prevent charging of the surface and it provide uniform surface of the pellets for analysis and it also help to increase the secondary electron emission).

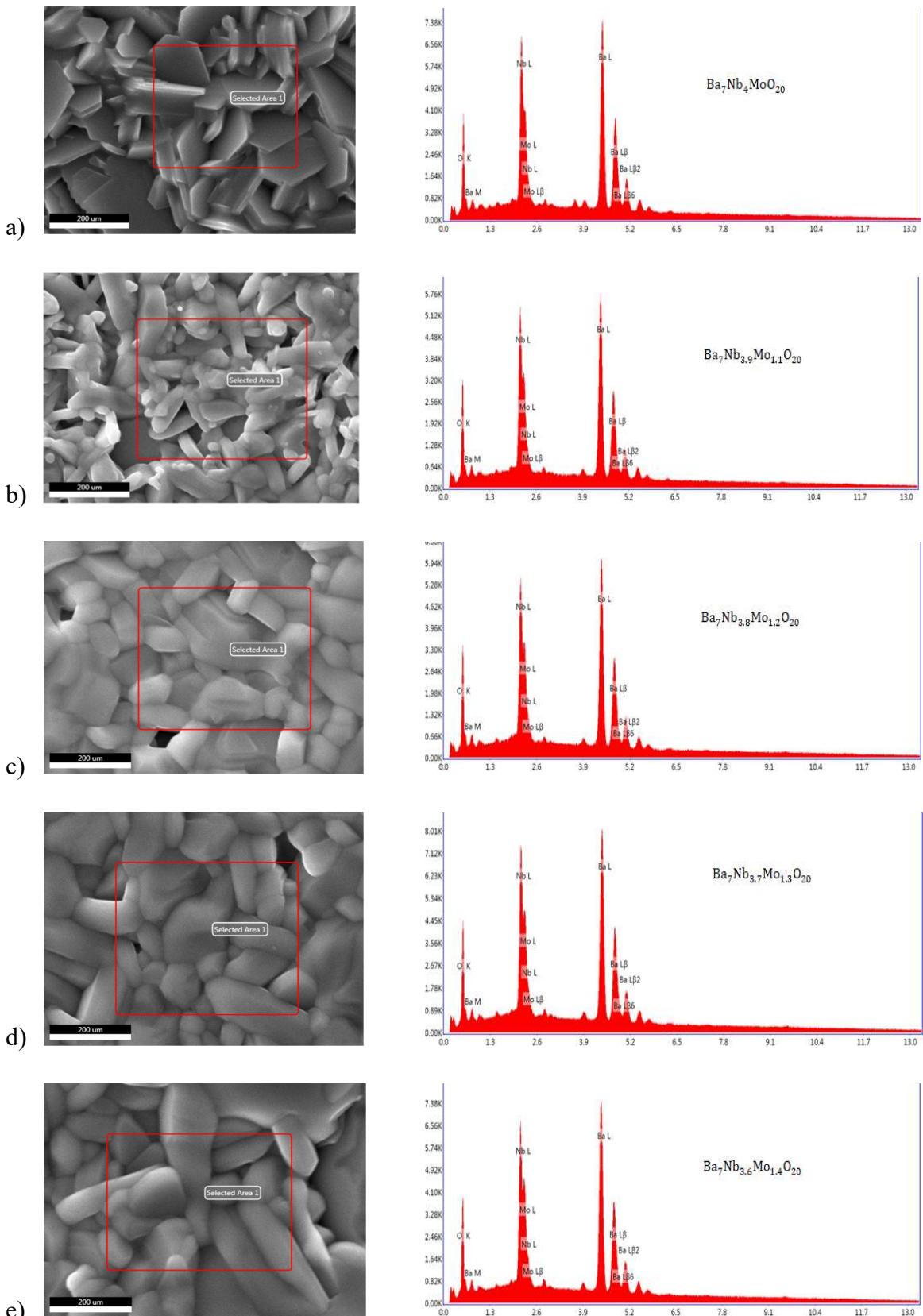




**Fig.20:-** These are the SEM micrographs of the surface of the dense sample (a)  $Ba_7Nb_4MoO_{20}$ , (b)  $Ba_7Nb_{3.9}Mo_{1.1}O_{20}$ , (c)  $Ba_7Nb_{3.8}Mo_{1.2}O_{20}$ , (d)  $Ba_7Nb_{3.7}Mo_{1.3}O_{20}$  and (e)  $Ba_7Nb_{3.6}Mo_{1.4}O_{20}$  pellet respectively, at  $2\mu m$  scale.

The grains image on the surface of pellets were generated with the help of secondary electron at room temperature. From the SEM micrographs it is observed that single phase formation has taken place. The grains for all the samples show good contact implying that the pellets are dense. On comparing the micrographs from all the samples, it is observed that the density is increasing on addition of Mo. On increasing the Mo quantity from BNMO0 to BNMO4 it is observed that there is a progressive increment in the size if grains on increasing Mo. On increasing the Mo quantity, we observed from the micrographs that some agglomeration has also taken place which increases with increase in Mo quantity.

The average grain size for all the samples have been calculated using Image J software. From the SEM micrographs the average grain size for  $Ba_7Nb_4MoO_{20}$  comes out be  $1.6 - 3.7\mu m$ , for  $Ba_7Nb_{3.9}Mo_{1.1}O_{20}$  the average size is calculated as  $1.9 - 4.8\mu m$  on further increasing the Mo quantity the average grain size for  $Ba_7Nb_{3.8}Mo_{1.2}O_{20}$  has increased to  $1.4 - 6.7\mu m$ , the average size for  $Ba_7Nb_{3.8}Mo_{1.2}O_{20}$  is  $1.5 - 7.1\mu m$  and that for  $Ba_7Nb_{3.7}Mo_{1.3}O_{20}$  is  $1.3 - 7\mu m$ . We also conducted an energy dispersive spectroscopy (EDS) for all pellets and data were collected.



**Fig.21** These are the EDX Scan of the surface of the dense sample (a)  $\text{Ba}_7\text{Nb}_4\text{MoO}_{20}$ , (b)  $\text{Ba}_7\text{Nb}_{3.9}\text{Mo}_{1.1}\text{O}_{20}$ , (c)  $\text{Ba}_7\text{Nb}_{3.8}\text{Mo}_{1.2}\text{O}_{20}$ , (d)  $\text{Ba}_7\text{Nb}_{3.7}\text{Mo}_{1.3}\text{O}_{20}$  and (e)  $\text{Ba}_7\text{Nb}_{3.6}\text{Mo}_{1.4}\text{O}_{20}$  pellet respectively, at  $200\mu\text{m}$  scale.

The EDS analysis shows that the samples of  $Ba_7Nb_{4-x}Mo_{1+x}O_{20}$  ( $x = 0.0, 0.1, 0.2, 0.3, 0.4$ ) have nearly homogeneous composition. The result EDS are shown in the table. The Theoretical atomic percentage of stoichiometric  $Ba_7Nb_4MoO_{20}$  are Ba = 21.8750%, Nb = 12.5000%, Mo = 3.1250%. [1] [2]

**Table:** - Results of the EDS data of  $Ba_7Nb_{4-x}Mo_{1+x}O_{20}$  ( $x = 0.0, 0.1, 0.2, 0.3, 0.4$ ) pellet samples. [1] [2]

Sample	Ba%	Nb%	Mo%
Theoretical	21.8750	12.5000	3.1250
$Ba_7Nb_4MoO_{20}$	28.43 ( $\pm 0.520$ )	15.34 ( $\pm 0.615$ )	4.23 ( $\pm 0.261$ )
$Ba_7Nb_{3.9}Mo_{1.1}O_{20}$	26.68 ( $\pm 0.530$ )	14.42 ( $\pm 0.610$ )	4.52 ( $\pm 0.304$ )
$Ba_7Nb_{3.8}Mo_{1.2}O_{20}$	26.7 ( $\pm 0.545$ )	14.1 ( $\pm 0.644$ )	4.58 ( $\pm 0.316$ )
$Ba_7Nb_{3.7}Mo_{1.3}O_{20}$	27.04 ( $\pm 0.533$ )	14.18 ( $\pm 0.611$ )	4.92 ( $\pm 0.327$ )
$Ba_7Nb_{3.6}Mo_{1.4}O_{20}$	27.28 ( $\pm 0.548$ )	14.09 ( $\pm 0.626$ )	5.26 ( $\pm 0.349$ )

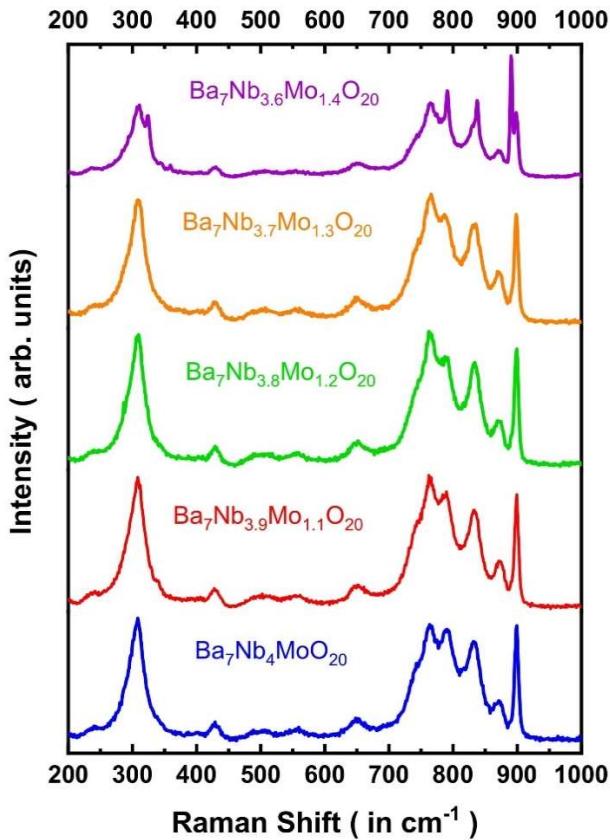
### 12.3. Raman Spectroscopy Analysis: -

The Raman scattering spectra of  $Ba_7Nb_4MoO_{20}$ ,  $Ba_7Nb_{3.9}Mo_{1.1}O_{20}$ ,  $Ba_7Nb_{3.8}Mo_{1.2}O_{20}$ ,  $Ba_7Nb_{3.7}Mo_{1.3}O_{20}$  and  $Ba_7Nb_{3.6}Mo_{1.4}O_{20}$  are shown in figure. The  $Ba_7Nb_4MoO_{20}$  and all the other doped samples are belonging to the  $D_{3d}$  crystallographic point group which have  $P\bar{3}m1$  space group. [1] [2] [25]

In the Raman spectra graph, observations indicate that the Mo shows tetrahedral  $[MoO_4]^{2-}$  mode around  $900\text{ cm}^{-1}$ . [25] The low intensity peaks between  $400\text{ cm}^{-1}$  to  $700\text{ cm}^{-1}$ , were found in the spectra which shows the evidence for octahedrally coordinated Nb or Mo sites. [25]

The modes between  $400$  to  $700\text{ cm}^{-1}$  are attributed to  $NbO_6$  or  $MoO_6$  in several different compound. [25] The two bands nearly  $300$  and  $800\text{ cm}^{-1}$  were found which correspond to  $[NbO_4]$  or  $[MoO_4]$  tetrahedral groups. [25] There are tiny changes in the spectra that may be attributed to the unique structural properties of various compounds. That could be due to the face sharing octahedra in the structure. [25]

From the spectra it is observed that the peak present at  $300\text{ cm}^{-1}$  shows a decrement in the intensity on the increment of Mo and in  $\text{Ba}_7\text{Nb}_{3.6}\text{Mo}_{1.4}\text{O}_{20}$  sample the peak has split into two. The split observed at  $300\text{ cm}^{-1}$  in  $\text{Ba}_7\text{Nb}_{3.6}\text{Mo}_{1.4}\text{O}_{20}$  sample is due to increase in the Mo quantity and decrease in Nb quantity. [25]

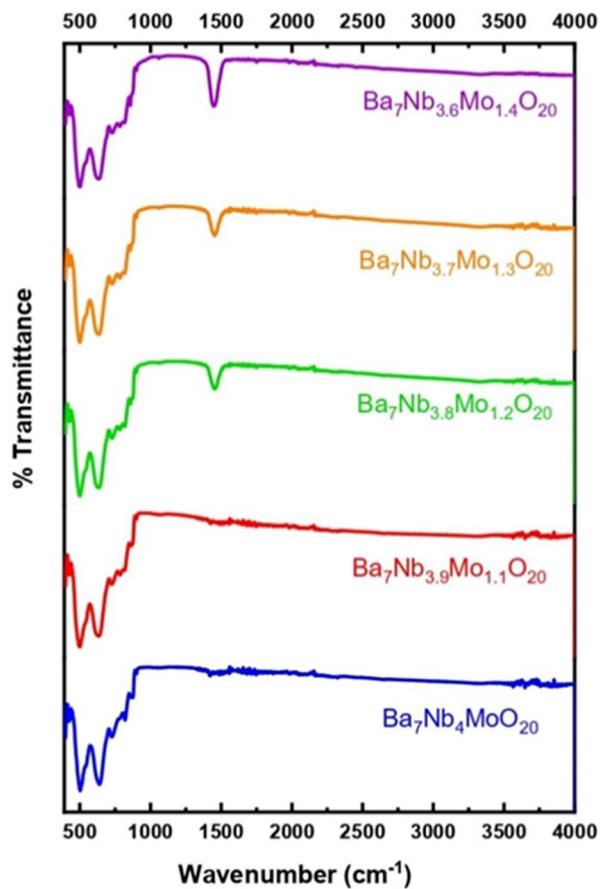


**Fig.22:** - Raman scattering spectra of (a)  $\text{Ba}_7\text{Nb}_4\text{MoO}_{20}$ , (b)  $\text{Ba}_7\text{Nb}_{3.9}\text{Mo}_{1.1}\text{O}_{20}$ , (c)  $\text{Ba}_7\text{Nb}_{3.8}\text{Mo}_{1.2}\text{O}_{20}$ , (d)  $\text{Ba}_7\text{Nb}_{3.7}\text{Mo}_{1.3}\text{O}_{20}$  and (e)  $\text{Ba}_7\text{Nb}_{3.6}\text{Mo}_{1.4}\text{O}_{20}$  samples at room temperature.

$\text{Ba}_7\text{Nb}_4\text{MoO}_{20}$  exhibited modes of octahedral symmetry, which was expected based on structural studies which indicates the presence of Palmerite structural blocks face sharing octahedra within the compound. [25] The data shows that the Raman spectroscopy can provides very important information's regarding differences in closely related structure and even for stoichiometrically identical compounds.

## 12.4. Fourier Transform-Infrared Spectroscopy (FT-IR) Analysis: -

FT-IR spectra of  $\text{Ba}_7\text{Nb}_4\text{MoO}_{20}$ ,  $\text{Ba}_7\text{Nb}_{3.9}\text{Mo}_{1.1}\text{O}_{20}$ ,  $\text{Ba}_7\text{Nb}_{3.8}\text{Mo}_{1.2}\text{O}_{20}$ ,  $\text{Ba}_7\text{Nb}_{3.7}\text{Mo}_{1.3}\text{O}_{20}$  and  $\text{Ba}_7\text{Nb}_{3.6}\text{Mo}_{1.4}\text{O}_{20}$  are obtain in the range of 400 to 4000  $\text{cm}^{-1}$  at room temperature are shown in the figure. [24] In IR plot analysis, nearly at 820  $\text{cm}^{-1}$  is attributed to M-O, the starching- vibrational mode of  $[\text{MoO}_4]^{2-}$  tetrahedron. Nearly 440  $\text{cm}^{-1}$  to 460  $\text{cm}^{-1}$  range, the weak Infrared absorption bands are observed, which could be due to the bending- vibration modes related to medium frequency region.[24]

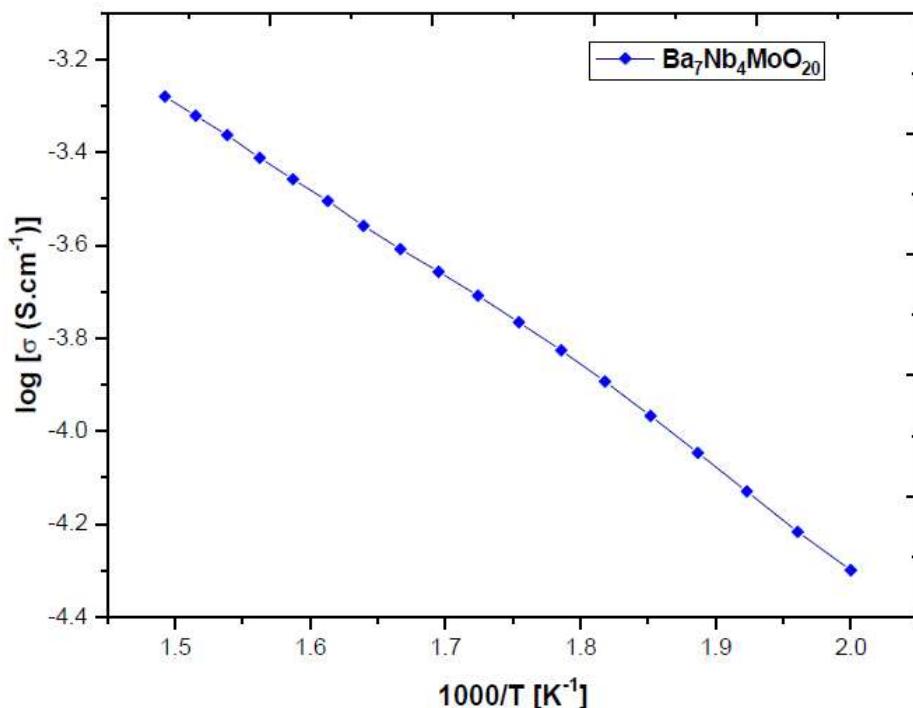


**Fig.23:** - FT-IR spectra of  $\text{Ba}_7\text{Nb}_4\text{MoO}_{20}$ ,  $\text{Ba}_7\text{Nb}_{3.9}\text{Mo}_{1.1}\text{O}_{20}$ ,  $\text{Ba}_7\text{Nb}_{3.8}\text{Mo}_{1.2}\text{O}_{20}$ ,  $\text{Ba}_7\text{Nb}_{3.7}\text{Mo}_{1.3}\text{O}_{20}$  and  $\text{Ba}_7\text{Nb}_{3.6}\text{Mo}_{1.4}\text{O}_{20}$  are obtain in the range of 400 to 4000  $\text{cm}^{-1}$  at room temperature.

The prominent bend nearly at 1450  $\text{cm}^{-1}$  were found. In literature, the FTIR spectra plot shows that when we the doping of Mo increasing and Nb decreasing in the sample. [24] The bend nearly 1450  $\text{cm}^{-1}$  increasing. It could be because of Carbon poisoning in the samples. [24]

## 12.5. Impedance Spectroscopy Analysis: -

Electrical spectroscopy for the synthesized system was carried out in temperature range of 303K – 943K using 6500 P Wayne Kerr Impedance analyser. Figure 24 shows the Arrhenius plot for the BNMO0 sample. [1] [2] [21] [26]. The conductivity values at different temperature were calculated using  $\sigma = \frac{L}{RA}$  relation where  $\sigma$  is the conductivity and R is the resistance, A is the area and L denotes the length. The resistance R is calculated using the Cole-Cole plot.



**Fig.24:- (a)** Temperature Vs Conductivity plot of  $Ba_7Nb_4MoO_{20}$  sample was shown. **(b)** Arrhenius plot of the total conductivity of  $Ba_7Nb_4MoO_{20}$  were measured by using impedance spectroscopy is shown.

From the plot (a), it is observed that the conductivity of the  $Ba_7Nb_4MoO_{20}$  sample increase with increasing the temperature which may be attributed to increase in the migration of the charge carrier. The Arrhenius graphic clearly shows that temperature has a significant impact on conductivity. The maximum conductivity for the BNMO0 sample comes of to be at 670 °C with a value of 0.00052 Scm<sup>-1</sup>.

### 13. Results: -

In this paper, we synthesized  $Ba_7Nb_{4-x}Mo_{1+x}O_{20}$  ( $x = 0, 0.1, 0.2, 0.3$ , and  $0.4$ ) hexagonal perovskite samples for SOFC electrolyte material by using Solid- State Reaction method. The starting materials Barium carbonate ( $BaCO_3$ ), Niobium pentoxide ( $Nb_2O_5$ ), and Molybdenum trioxide ( $MoO_3$ ) were used. We used XRD characterization technique to analyse the prepared sample's ( $Ba_7Nb_{4-x}Mo_{1+x}O_{20}$ ) phase purity. [1] [2] We found that the XRD patterns of the prepared materials indicates that the sample is in pure phase and obtained diffractograms that compositions are identified with the space group  $P\bar{3}m1$ . [1] [2] And we also found that when the doping is increasing in the samples the XRD peaks are shifting towards right side. And when doping is increasing the 1<sup>st</sup> most intense peak decreasing and 2<sup>nd</sup> most intense peak increasing in samples 3<sup>rd</sup> and 4<sup>th</sup> comparing 1<sup>st</sup> samples  $Ba_7Nb_4MoO_{20}$ . In 2<sup>nd</sup> sample, the 1<sup>st</sup> and 2<sup>nd</sup> most intense peak are similar to 1<sup>st</sup> sample. [1] [2]

By using Scanning Electron Microscopy (SEM) technique, it is observed that single phase formation has taken place. The grains for all the samples show good contact implying that the pellets are dense.

In Raman spectroscopy, the modes between 400 to 700  $cm^{-1}$  are attributed to  $NbO_6$  or  $MoO_6$ , The two bands nearly 300 and 800  $cm^{-1}$  were found which correspond to  $[NbO_4]$  or  $[MoO_4]$  tetrahedral groups. [25] From the spectra it is observed that the peak present at 300  $cm^{-1}$  shows a decrement in the intensity on the increment of Mo and in  $Ba_7Nb_{3.6}Mo_{1.4}O_{20}$  sample the peak has split into two which is due to increase in the Mo quantity and decrease in Nb quantity. [25]

In FT-IR spectroscopy, The FT-IR spectra of  $Ba_7Nb_4MoO_{20}$ ,  $Ba_7Nb_{3.9}Mo_{1.1}O_{20}$ ,  $Ba_7Nb_{3.8}Mo_{1.2}O_{20}$ ,  $Ba_7Nb_{3.7}Mo_{1.3}O_{20}$  and  $Ba_7Nb_{3.6}Mo_{1.4}O_{20}$  are obtain in the range of 400 to 4000  $cm^{-1}$  at room temperature. [24] The prominent bend nearly at 1450  $cm^{-1}$  were found. It could be because of Carbon poisoning in the samples. Nearly at 820  $cm^{-1}$  is attributed to M-O, the starching- vibrational mode of  $[MoO_4]^{2-}$  tetrahedron. [24]

## **14. Future Work: -**

In this paper we use solid state reaction method to synthesis hexagonal perovskite base  $Ba_7Nb_{4-x}Mo_{1+x}O_{20}$  (where x = 0, 0.1, 0.2, 0.3, and 0.4) sample material. In the samples we decreased the quantity of Niobium (Nb) and increasing Molybdenum (Mo) quantity and check how doping effect on conductivity of the material. We characterized it by XRD, FTIR, Raman, SEM, EDS, and Impedance Spectroscopy of the prepared sample. In future, we will be going to analyzing the EIS data of other four samples. We will also going to synthesize same material  $Ba_7Nb_{4+x}Mo_{1-x}O_{20}$ , but this time we will going to increase Niobium (Nb) and decreasing Molybdenum (Mo) in the material. And again, analyzing effect of that doping on the materials conductivity at different temperature. Analyzing these samples with the help of XRD, Raman, SEM, EDS, FTIR, XPS and EIS spectroscopy.

## References:

1. Sacha Fop, Kirstie S. McCombie, Eve J. Wildman, Jan M. S. Skakle, John T. S. Irvine, Paul A. Connor, Cristian Savaniu, Clemens Ritter and Abbie C. McLaughlin, “High oxide ion and proton conductivity in a disordered hexagonal perovskite”, *Nature Materials*, 19, 752–757 (2020).
2. Masatomo Yashima, Takafumi Tsujiguchi, Yuichi Sakuda, Yuta Yasui, Yu Zhou, Kotaro Fujii, Shuki Torii, Takashi Kamiyama & Stephen J. Skinner, “ High oxide-ion conductivity through the interstitial oxygen site in Ba<sub>7</sub>Nb<sub>4</sub>MoO<sub>20</sub>-based hexagonal perovskite related oxides”, *NATURE COMMUNICATIONS*, 12, Article number: 556 (2021)
3. Sacha Fop, Kirstie S. McCombie, Eve J. Wildman, Janet M. S. Skakle and Abbie C. McLaughlin, “Hexagonal perovskite derivatives: a new direction in the design of oxide ion conducting materials”, *The Royal Society of Chemistry, Chem. Commun.*, 55, 2127—2137 (2019).
4. Ahmed Sajid, Erum Pervaiz, Hatim Ali, Tayyaba Noor, Mutawara Mahmood Baig, “A perspective on development of fuel cell materials: Electrodes and electrolyte”, *John Wiley & Sons Ltd., Int J Energy Res.*, 46,6953–6988 (2022).
5. Gregor Hoogers, “FUEL CELL TECHNOLOGY HAND BOOK”, CRC, ISBN 0-8493-0877-1 (2003).
6. Ryan O'Hayre, Suk-Won Cha, Whitney Colella, Fritz B. Prinz, “Fuel Cell Fundamentals”, 3rd Edition, John Wiley & Sons, Inc., ISBN: 978-1-119-11380-5 (2016).
7. ENERGY CARRIERS AND CONVERSION SYSTEMS – Vol. II - Phosphoric Acid Fuel Cells - Hiroko Sotouchi, Akifusa Hagiwara.
8. ENERGY CARRIERS AND CONVERSION SYSTEMS – Vol. II - Alkaline Fuel Cells - Hiroko Sotouchi
9. Kai Sundmacher, Achim Kienle, Hans Josef Pesch, Joachim F. Berndt, and Gerhard Huppmann, “Molten Carbonate Fuel Cells”, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, ISBN: 978-3-527-31474-4 (2007).
10. R. Mark Ormerod, “Solid oxide fuel cells”, CSR (2002).
11. S.C. Singhal, “Advances in solid oxide fuel cell technology”, *Solid State Ionics*, 135, 305–313 (2000).

12. R. Saravanan, “Solid Oxide Fuel Cell (SOFC) Materials”, Materials Research Forum LLC, ISBN 978-1-945291-50-0 (2018).
13. John A. Kilner and M’onica Burriel, “Materials for Intermediate-Temperature Solid-Oxide Fuel Cells”, *Annu. Rev. Mater. Res.*, 44, 365-393 (2014).
14. Saddam Hussain, Li Yangping, “Review of solid oxide fuel cell materials: cathode, anode, and electrolyte”, *Energy Transitions*, 4, 113–126 (2014).
15. Chunwen Sun & Rob Hui & Justin Roller, “Cathode materials for solid oxide fuel cells: a review”, *J Solid State Electrochem*, 14, 1125–1144 (2010).
16. Stephen J. Skinner, “Recent advances in Perovskite-type materials for solid oxide fuel cell cathodes”, *International Journal of Inorganic Materials*, 3, 113–121 (2001).
17. Weiquan Li, Yang Wang, Weinan Liu, “A review of solid oxide fuel cell application”, *Earth and Environmental Science* 619 (2020) 012012.
18. Wojciech M. Budzianowski, and Jaroslaw Milewski, “Solid-Oxide Fuel Cells in Power Generation Applications: A Review”, *Recent Patents on Engineering* 2011, 5, 165-189.
19. S.Sui and G.H.Xiu, “Fuels and fuel processing in SOFC applications”, *High-Temperature Solid Oxide Fuel Cells for the 21st Century (Second Edition), Fundamentals, Design and Applications*, Pages 461-495 (2016).
20. Arnab Choudhury, H. Chandra, and A. Arora, “Application of solid oxide fuel cell technology for power generation—A review”, *Renewable and Sustainable Energy Reviews*, Volume 20, Pages 430-442 (2013).
21. R. J. BRAUN\* AND P. KAZEMPOOR, “Application of SOFCs in Combined Heat, Cooling and Power Systems”, *Solid Oxide Fuel Cells: From Materials to System Modelling* (pp.327-381), Royal Society of Chemistry, RSC Energy and Environment Series, 7, Ch: 12 (2013).
22. Images used: - [usic.du.ac.in/instruments](http://usic.du.ac.in/instruments).
23. Ashish Chauhan and Priyanka Chauhan, “Powder XRD Technique and its Applications in Science and Technology”, *Journal of Analytical & Bioanalytical Techniques*, Chauhan, and Chauhan, *J Anal Bioanal Tech* 2014.
24. Paramananda Jena, N. Nallamuthu, K. Hari Prasad, M. Venkateswarlu, N. Satyanarayana, “Structural characterization and electrical conductivity studies of BaMoO<sub>4</sub> nanofibers prepared by sol-gel and electrospinning techniques”, Springer, 72, p 480–489 (2014).

25. A. A. Brown Holden, M. Reedyk, E. Garcí'a-Gonza' lez, M. Parras, and J. M. Gonza'lez-Calbet, "Raman Scattering Study of Cation-Deficient  $Ba_n(MoNb)_n-\delta O_{3n-x}$  and Related Perovskite-like Oxides", *Chem. Mater.*, 12, 2287-2291 (2000).
26. Vadim F. Lvovich, "IMPEDANCE SPECTROSCOPY, Applications to Electrochemical and Dielectric Phenomena", A JOHN WILEY & SONS, INC., PUBLICATION, ISBN 978-0-470-62778-5 (2012).
27. Hans-Heinrich MoÈbius, "On the history of solid electrolyte fuel cells", Springer-Verlag, Journal of Solid-State Electrochemistry volume 1, pages 2–16 (1997).
28. Yang Leng, "Materials Characterization: Introduction to Microscopic and Spectroscopic Methods", 2<sup>nd</sup> Edition, Wiley-VCH Verlag GmbH & Co., ISBN: 978-3-527-33463-6 (2013).
29. Muhammad Bilal Hanif, Sajid Rauf, Martin Motola, Zaheer Ud Din Babar, Chang-Jiu Li, Cheng-Xin Li, "Recent progress of perovskite-based electrolyte materials for solid oxide fuel cells and performance optimizing strategies for energy storage applications", *Materials Research Bulletin*, V. 146, 111612 (2022).
30. Esmaeel Fatahian, Navid Tonekaboni, Hossein Fatahian, "Exergy analysis of combined cycle of gas turbine and solid oxide fuel cell in different compression ratios", *International Journal of Scientific World*, 4(2), 43 (2016).

# **WEEKLY PROGRESS REPORTS**

**Amity Institute Applied Sciences**

**WEEKLY PROGRESS REPORT (WPR)**

**For the week commencing: \_\_\_\_\_10/01/2022 to 15/01/2022\_\_\_\_\_**

**WPR: 1**

**Enrollment Number:** A4450020010

**Program:** M.Sc. Applied Physics

**Student Name:** Paras Saini

**Guide's Name:** Dr. G.N. Pandey

**Co-Guide's Name:** Dr. Raghvendra Pandey

**Project Title:** Advanced cathode materials for Intermediate Temperature Solid oxide fuel cells.

**TARGETS SET FOR THE WEEK**

- To learn – What is Fuel Cell, Different Components of Fuel Cell, Difference between battery and fuel cells. Advantages of fuel cells.
- Different types of fuel cells. What is Solid Oxide Fuel Cell (SOFC)?

**PROGRESS/ACHIEVEMENTS FOR THE WEEK**

- Basic knowledge about Fuel Cells. i.e., introduction to Solid Oxide Fuel Cell (SOFCs) were studied.

**FUTURE WORK PLANS-**

- Different Components of Solid Oxide Fuel Cells
- To read research paper related to cathode materials Solid Oxide Fuel Cells.

**Amity Institute Applied Sciences**

**WEEKLY PROGRESS REPORT (WPR)**

**For the week commencing: \_\_\_\_\_17/01/2022 to 22/01/2022\_\_\_\_\_**

**WPR: 2**

**Enrollment Number:** A4450020010

**Program:** M.Sc. Applied Physics

**Student Name:** Paras Saini

**Guide's Name:** Dr. G.N. Pandey

**Co-Guide's Name:** Dr. Raghvendra Pandey

**Project Title:** Advanced cathode materials for Intermediate Temperature Solid oxide fuel cells.

**TARGETS SET FOR THE WEEK**

- Different Components of Solid Oxide Fuel Cells
- To read research paper related to cathode materials Solid Oxide Fuel Cells

**PROGRESS/ACHIEVEMENTS FOR THE WEEK**

- Different Components of Solid Oxide Fuel Cells and materials used in cathode in SOFC were studied.

**FUTURE WORK PLANS-**

- To read research paper related to review of solid oxide fuel cell materials: Cathode, Anode and Electrolyte.
- To learn some basics of Origin software.

**Amity Institute Applied Sciences**

**WEEKLY PROGRESS REPORT (WPR)**

**For the week commencing: \_\_\_\_\_24/01/2022 to 29/01/2022\_\_\_\_\_**

**WPR: 3**

**Enrollment Number:** A4450020010

**Program:** M.Sc. Applied Physics

**Student Name:** Paras Saini

**Guide's Name:** Dr. G.N. Pandey

**Co-Guide's Name:** Dr. Raghvendra Pandey

**Project Title:** Advanced cathode materials for Intermediate Temperature Solid oxide fuel cells.

**TARGETS SET FOR THE WEEK**

- To read research paper related to review of solid oxide fuel cell materials: Cathode, Anode and Electrolyte.
- To learn some basics of Origin software.

**PROGRESS/ACHIEVEMENTS FOR THE WEEK**

- Some basics of Origin software and research paper related to review of solid oxide fuel cell materials: Cathode, Anode and Electrolyte were studied.

**FUTURE WORK PLANS-**

- To read research paper related to Synthesis and characterization of different cathodes for intermediate temperature Solid Oxide Fuel Cell (SOFC).

**Amity Institute Applied Sciences**

**WEEKLY PROGRESS REPORT (WPR)**

**For the week commencing: \_\_\_\_\_31/01/2022 to 05/02/2022\_\_\_\_\_**

**WPR: 4**

**Enrollment Number:** A4450020010

**Program:** M.Sc. Applied Physics

**Student Name:** Paras Saini

**Guide's Name:** Dr. G.N. Pandey

**Co-Guide's Name:** Dr. Raghvendra Pandey

**Project Title:** Advanced cathode materials for Intermediate Temperature Solid oxide fuel cells.

**TARGETS SET FOR THE WEEK**

- To read research paper related to Synthesis and characterization of different cathodes for intermediate temperature Solid Oxide Fuel Cell (SOFC).

**PROGRESS/ACHIEVEMENTS FOR THE WEEK**

- Research paper related to Synthesis and characterization of different cathodes for intermediate temperature Solid Oxide Fuel Cell (SOFC) were studied.

**FUTURE WORK PLANS-**

- To read about Hexagonal perovskite.
- To read research paper related to cubic-hexagonal perovskite nanocomposite as intermediate-temperature solid oxide fuel cell cathode.

**Amity Institute Applied Sciences**

**WEEKLY PROGRESS REPORT (WPR)**

**For the week commencing: \_\_\_\_\_07/02/2022 to 12/02/2022\_\_\_\_\_**

**WPR: 5**

**Enrollment Number:** A4450020010

**Program:** M.Sc. Applied Physics

**Student Name:** Paras Saini

**Guide's Name:** Dr. G.N. Pandey

**Co-Guide's Name:** Dr. Raghvendra Pandey

**Project Title:** Advanced cathode materials for Intermediate Temperature Solid oxide fuel cells.

**TARGETS SET FOR THE WEEK**

- To read about hexagonal perovskite.
- To read research paper related to cubic-hexagonal perovskite nanocomposite as intermediate-temperature solid oxide fuel cell cathode.

**PROGRESS/ACHIEVEMENTS FOR THE WEEK**

- Hexagonal perovskite and research paper related to cubic-hexagonal perovskite nanocomposite as intermediate-temperature solid oxide fuel cell cathode were studied.

**FUTURE WORK PLANS-**

- To read about Density- Functional Theory and DFT based software and programs.
- To learn basics of Quantum Espresso software.

**Amity Institute Applied Sciences**

**WEEKLY PROGRESS REPORT (WPR)**

**For the week commencing: \_\_\_\_\_ 14/02/2022 to 19/02/2022 \_\_\_\_\_**

**WPR: 6**

**Enrollment Number:** A4450020010

**Program:** M.Sc. Applied Physics

**Student Name:** Paras Saini

**Guide's Name:** Dr. G.N. Pandey

**Co- Guide's Name:** Dr. Raghvendra Pandey

**Project Title:** Advanced cathode materials for Intermediate Temperature Solid oxide fuel cells.

**TARGETS SET FOR THE WEEK**

- To read about Density- Functional Theory and DFT based software and programs.
- To learn basics of Quantum Espresso software

**PROGRESS/ACHIEVEMENTS FOR THE WEEK**

- Density- Functional Theory and DFT based software and programs were study, and basics of Quantum Espresso software were done.

**FUTURE WORK PLANS-**

- To read research paper related to  $(\text{Bi0.15La0.27Sr0.53})(\text{Co0.25Fe0.75})\text{O}_3-\delta$  perovskite: A novel cathode material for intermediate temperature solid oxide fuel cells.
- To read research paper related to High oxide-ion conductivity through the interstitial oxygen site in  $\text{Ba}_7\text{Nb}_4\text{MoO}_{20}$ -based hexagonal perovskite related oxides.

**Amity Institute Applied Sciences**

**WEEKLY PROGRESS REPORT (WPR)**

**For the week commencing: \_\_\_\_\_ 21/02/2022 to 26/02/2022 \_\_\_\_\_**

**WPR: 7**

**Enrollment Number:** A4450020010

**Program:** M.Sc. Applied Physics

**Student Name:** Paras Saini

**Guide's Name:** Dr. G.N. Pandey

**Co-Guide's Name:** Dr. Raghvendra Pandey

**Project Title:** Advanced cathode materials for Intermediate Temperature Solid oxide fuel cells.

**TARGETS SET FOR THE WEEK**

- To read research paper related to  $(\text{Bi}_{0.15}\text{La}_{0.27}\text{Sr}_{0.53}) (\text{Co}_{0.25}\text{Fe}_{0.75}) \text{O}_3\text{-}\delta$  perovskite: A novel cathode material for intermediate temperature solid oxide fuel cells.
- To read research paper related to High oxide-ion conductivity through the interstitial oxygen site in  $\text{Ba}_7\text{Nb}_4\text{MoO}_{20}$ -based hexagonal perovskite related oxides.

**PROGRESS/ACHIEVEMENTS FOR THE WEEK**

- Research paper related to  $(\text{Bi}_{0.15}\text{La}_{0.27}\text{Sr}_{0.53}) (\text{Co}_{0.25}\text{Fe}_{0.75}) \text{O}_3\text{-}\delta$  perovskite: A novel cathode material for intermediate temperature solid oxide fuel cells and High oxide-ion conductivity through the interstitial oxygen site in  $\text{Ba}_7\text{Nb}_4\text{MoO}_{20}$ -based hexagonal perovskite related oxides were studied

**FUTURE WORK PLANS-**

- To read about XRD (X-ray diffraction), use of XRD for characterization and Rietveld refinement.
- To read about Atomic Absorption Spectroscopy or AAS and Thermogravimetric for different characterization.

**Amity Institute Applied Sciences**

**WEEKLY PROGRESS REPORT (WPR)**

**For the week commencing: \_\_\_\_\_ 28/02/2022 to 05/03/2022 \_\_\_\_\_**

**WPR: 8**

**Enrollment Number:** A4450020010

**Program:** M.Sc. Applied Physics

**Student Name:** Paras Saini

**Guide's Name:** Dr. G.N. Pandey

**Co- Guide's Name:** Dr. Raghvendra Pandey

**Project Title:** Advanced cathode materials for Intermediate Temperature Solid oxide fuel cells.

**TARGETS SET FOR THE WEEK**

- To read about XRD (X-ray diffraction), use of XRD for characterization and Rietveld refinement.
- To read about Atomic Absorption Spectroscopy or AAS and Thermogravimetric for different characterization.

**PROGRESS/ACHIEVEMENTS FOR THE WEEK**

- XRD (X-ray diffraction), use of XRD for characterization and Rietveld refinement. Atomic Absorption Spectroscopy or AAS and Thermogravimetric for different characterization were done.

**FUTURE WORK PLANS-**

- To read about Raman Spectroscopy for characterization.
- Starting Sample ( $Ba_7Nb_4MoO_{20}$ ) preparation using solid state method.

**Amity Institute Applied Sciences**

**WEEKLY PROGRESS REPORT (WPR)**

**For the week commencing: \_\_\_\_\_ 07/03/2022 to 12/03/2022 \_\_\_\_\_**

**WPR: 9**

**Enrollment Number:** A4450020010

**Program:** M.Sc. Applied Physics

**Student Name:** Paras Saini

**Guide's Name:** Dr. G.N. Pandey

**Co- Guide's Name:** Dr. Raghvendra Pandey

**Project Title:** Advanced cathode materials for Intermediate Temperature Solid oxide fuel cells.

**TARGETS SET FOR THE WEEK**

- To read about Raman Spectroscopy for characterization.
- Starting Sample ( $Ba_7Nb_4MoO_{20}$ ) preparation using solid state method.

**PROGRESS/ACHIEVEMENTS FOR THE WEEK**

- Raman Spectroscopy for characterization were studied.
- I make stoichiometric ratios of the precursor powders and mixed thoroughly for 1hr by using an agate mortar and pestle and Ball-Milling for 2hr, and then calcined at 900°C for 12hr.

**FUTURE WORK PLANS-**

- Calcined sample is again mixed thoroughly for 1hr by using an agate mortar and pestle.
- Then take that sample powder and obtained were uniaxially pressed into pellets.
- Then doing sintering of pelletized sample at 1100°C for 24hr

**Amity Institute Applied Sciences**

**WEEKLY PROGRESS REPORT (WPR)**

**For the week commencing: \_\_\_\_\_ 14/03/2022 to 19/03/2022 \_\_\_\_\_**

**WPR: 10**

**Enrollment Number:** A4450020010

**Program:** M.Sc. Applied Physics

**Student Name:** Paras Saini

**Guide's Name:** Dr. G.N. Pandey

**Co- Guide's Name:** Dr. Raghvendra Pandey

**Project Title:** Advanced cathode materials for Intermediate Temperature Solid oxide fuel cells.

**TARGETS SET FOR THE WEEK**

- Calcined sample is again mixed thoroughly for 1hr by using an agate mortar and pestle.
- Then take that sample powder and obtained were uniaxially pressed into pellets.
- Then doing sintering of pelletized sample at 1100°C for 24hr

**PROGRESS/ACHIEVEMENTS FOR THE WEEK**

- First sample is ready by using Solid state reaction method.

**FUTURE WORK PLANS-**

- Sending material for XRD.
- Starting Sample ( $Ba_7Nb_{3.9}Mo_{1.1}O_{20}$ ) preparation using solid state method.

**Amity Institute Applied Sciences**

**WEEKLY PROGRESS REPORT (WPR)**

**For the week commencing: \_\_\_\_\_ 21/03/2022 to 26/03/2022 \_\_\_\_\_**

**WPR: 11**

**Enrollment Number:** A4450020010

**Program:** M.Sc. Applied Physics

**Student Name:** Paras Saini

**Guide's Name:** Dr. G.N. Pandey

**Co- Guide's Name:** Dr. Raghvendra Pandey

**Project Title:** Advanced cathode materials for Intermediate Temperature Solid oxide fuel cells.

**TARGETS SET FOR THE WEEK**

- Sending material for XRD.
- Starting Sample  $Ba_7Nb_{3.9}Mo_{1.1}O_{20}$  preparation using solid state method

**PROGRESS/ACHIEVEMENTS FOR THE WEEK**

- $Ba_7Nb_{3.9}Mo_{1.1}O_{20}$  precursor powders and mixed thoroughly for 1hr by using an agate mortar and pestle and Ball-Milling for 2hr, and then calcined at 900°C for 12hr.
- 1<sup>st</sup> Sample XRD data has been plotted.

**FUTURE WORK PLANS-**

- Starting two Samples  $Ba_7Nb_{3.8}Mo_{1.2}O_{20}$  and  $Ba_7Nb_{3.7}Mo_{1.3}O_{20}$  preparation using solid state method.
- This time we will going to calcinate samples at 1050°C for 48hr.
- Analysing the XRD plot.

**Amity Institute Applied Sciences**

**WEEKLY PROGRESS REPORT (WPR)**

**For the week commencing: \_\_\_\_\_ 28/03/2022 to 02/04/2022 \_\_\_\_\_**

**WPR: 12**

**Enrollment Number:** A4450020010

**Program:** M.Sc. Applied Physics

**Student Name:** Paras Saini

**Guide's Name:** Dr. G.N. Pandey

**Co-Guide's Name:** Dr. Raghvendra Pandey

**Project Title:** Advanced cathode materials for Intermediate Temperature Solid oxide fuel cells.

**TARGETS SET FOR THE WEEK**

- Starting two Samples  $Ba_7Nb_{3.8}Mo_{1.2}O_{20}$  and  $Ba_7Nb_{3.7}Mo_{1.3}O_{20}$  preparation using solid state method.
- This time we will going to calcinate samples at 1050°C for 48hr.
- Analysing the XRD plot.

**PROGRESS/ACHIEVEMENTS FOR THE WEEK**

- $Ba_7Nb_{3.8}Mo_{1.2}O_{20}$  and  $Ba_7Nb_{3.7}Mo_{1.3}O_{20}$  precursor powders and mixed thoroughly for 1hr by using an agate mortar and pestle and Ball-Milling for 2hr, and then calcined at 1050°C for 48hr.
- 1<sup>st</sup> Sample XRD data has been analyzed, this data is not matched with reference data. Which refers that our require sample is not form.

**FUTURE WORK PLANS-**

- Starting preparation of 5<sup>th</sup>  $Ba_7Nb_{3.6}Mo_{1.4}O_{20}$  using solid state method.
- And calcinating sample at 1050°C for 48hr.
- Again, repeating Calcination of 1<sup>st</sup> sample at 1050°C for 48hr.

**Amity Institute Applied Sciences**

**WEEKLY PROGRESS REPORT (WPR)**

**For the week commencing: \_\_\_\_\_ 04/04/2022 to 09/04/2022 \_\_\_\_\_**

**WPR: 13**

**Enrollment Number:** A4450020010

**Program:** M.Sc. Applied Physics

**Student Name:** Paras Saini

**Guide's Name:** Dr. G.N. Pandey

**Co-Guide's Name:** Dr. Raghvendra Pandey

**Project Title:** Advanced cathode materials for Intermediate Temperature Solid oxide fuel cells.

**TARGETS SET FOR THE WEEK**

- Starting preparation of 5<sup>th</sup>  $Ba_7Nb_{3.6}Mo_{1.4}O_{20}$  using solid state method.
- And calcinating sample at 1050°C for 48hr.
- Again, repeating Calcination of 1<sup>st</sup> sample at 1050°C for 48hr
- 

**PROGRESS/ACHIEVEMENTS FOR THE WEEK**

- Starting preparation of 5<sup>th</sup>  $Ba_7Nb_{3.6}Mo_{1.4}O_{20}$  using solid state method.
- And calcinating sample at 1050°C for 48hr.
- Again, repeating Calcination of 1<sup>st</sup> sample at 1050°C for 48hr.

**FUTURE WORK PLANS-**

- All five samples are calcinated at 1050°C for 48 hours. Now all samples are sent for XRD characterization.
- Sample powder uniaxially pressed into pellets.
- Then doing sintering of pelletized sample at 1200°C.

**Amity Institute Applied Sciences**

**WEEKLY PROGRESS REPORT (WPR)**

**For the week commencing: \_\_\_\_\_ 11/04/2022 to 16/04/2022 \_\_\_\_\_**

**WPR: 14**

**Enrollment Number:** A4450020010

**Program:** M.Sc. Applied Physics

**Student Name:** Paras Saini

**Guide's Name:** Dr. G.N. Pandey

**Co-Guide's Name:** Dr. Raghvendra Pandey

**Project Title:** Advanced materials for Intermediate Temperature Solid oxide fuel cells.

**TARGETS SET FOR THE WEEK**

- All five samples are calcinated at 1050°C for 48 hours. Now all samples are sent for XRD characterization.
- Sample powder uniaxially pressed into pellets.
- Then doing sintering of pelletized sample at 1200°C.

**PROGRESS/ACHIEVEMENTS FOR THE WEEK**

- Two Sample powders uniaxially pressed into pellets.
- Then done sintering of pelletized sample at 1200°C for 5 hr.

**FUTURE WORK PLANS-**

- Three Sample powder uniaxially pressed into pellets. Then doing sintering of pelletized sample at 1200°C for 5 hr.
- Learning how to calculate to Density of state, Band, and Scf file using quantum espresso.
- Reading High oxide ion and proton conductivity in a disordered hexagonal perovskite.

**Amity Institute Applied Sciences**

**WEEKLY PROGRESS REPORT (WPR)**

**For the week commencing: \_\_\_\_\_ 18/04/2022 to 23/04/2022 \_\_\_\_\_**

**WPR: 15**

**Enrollment Number:** A4450020010

**Program:** M.Sc. Applied Physics

**Student Name:** Paras Saini

**Guide's Name:** Dr. G.N. Pandey

**Co-Guide's Name:** Dr. Raghvendra Pandey

**Project Title:** Advanced materials for Intermediate Temperature Solid oxide fuel cells.

**TARGETS SET FOR THE WEEK**

- Three Sample powder uniaxially pressed into pellets. Then doing sintering of pelletized sample at 1200°C for 5 hr.
- Learning how to calculate to Density of state, Band, and Scf file using quantum espresso.
- Reading High oxide ion and proton conductivity in a disordered hexagonal perovskite.

**PROGRESS/ACHIEVEMENTS FOR THE WEEK**

- Three Sample powder uniaxially pressed into pellets. Then doing sintering of pelletized sample at 1200°C for 5 hr.
- How to calculate to Density of state, Band, and Scf file using quantum espresso learned
- High oxide ion and proton conductivity in a disordered hexagonal perovskite research paper read.

**FUTURE WORK PLANS-**

- XRD data of all Five samples are received, now we are going to plot XRD data and analyze them.
- Comparing the data collected with the standard data or reference data and doing Rietveld refinement.
- Trying to calculate Band, Density of State by using quantum espresso and Burai software.

**Amity Institute Applied Sciences**

**WEEKLY PROGRESS REPORT (WPR)**

**For the week commencing: \_\_\_\_\_ 15/04/2022 to 30/04/2022 \_\_\_\_\_**

**WPR: 16**

**Enrollment Number:** A4450020010

**Program:** M.Sc. Applied Physics

**Student Name:** Paras Saini

**Guide's Name:** Dr. G.N. Pandey

**Co-Guide's Name:** Dr. Raghvendra Pandey

**Project Title:** Advanced materials for Intermediate Temperature Solid oxide fuel cells.

**TARGETS SET FOR THE WEEK**

- XRD data of all Five samples are received, now we are going to plot XRD data and analyze them.
- Comparing the data collected with the standard data or reference data and doing Rietveld refinement.
- Trying to calculate Band, Density of State by using quantum espresso and Burai software.

**PROGRESS/ACHIEVEMENTS FOR THE WEEK**

- The five samples XRD data have been plotted using Origin Software and we compared these plots with reference data. We find out that the sample has formed which we want to make.
- The plot of Band, Density of state has been made using Burai and Quantum espresso.

**FUTURE WORK PLANS-**

- We have to do coating of platinum paste on sintered pellets samples and heating them at 1000°C for 30 minutes.
- After colling coated samples, we will check their contact with electrolyte material by using multi-meter.
- Sending the samples for FTIR, SEM characterization.

**Amity Institute Applied Sciences**

**WEEKLY PROGRESS REPORT (WPR)**

**For the week commencing: \_\_\_\_\_ 02/05/2022 to 07/05/2022 \_\_\_\_\_**

**WPR: 17**

**Enrollment Number:** A4450020010

**Program:** M.Sc. Applied Physics

**Student Name:** Paras Saini

**Guide's Name:** Dr. G.N. Pandey

**Co- Guide's Name:** Dr. Raghvendra Pandey

**Project Title:** Advanced materials for Intermediate Temperature Solid oxide fuel cells.

**TARGETS SET FOR THE WEEK**

- We have to do coating of platinum paste on sintered pellets samples and heating them at 1000°C for 30 minutes.
- After colling coated samples, we will check their contact with electrolyte material by using multi-meter.
- Sending the samples for FTIR, SEM characterization

**PROGRESS/ACHIEVEMENTS FOR THE WEEK**

- We have to do coating of platinum paste on sintered pellets samples and heating them at 1000°C for 30 minutes.
- After colling coated samples, we will check their contact with electrolyte material by using multi-meter.
- Sending the samples for FTIR, SEM characterization.

**FUTURE WORK PLANS-**

- Sending the samples for Raman characterization.
- Analyzing FTIR and SEM characterization data.
- Trying to do Rietveld refinement of 1<sup>st</sup> sample by using Fullprof software.

**Amity Institute Applied Sciences**

**WEEKLY PROGRESS REPORT (WPR)**

**For the week commencing: \_\_\_\_\_ 09/05/2022 to 14/05/2022 \_\_\_\_\_**

**WPR: 18**

**Enrollment Number:** A4450020010

**Program:** M.Sc. Applied Physics

**Student Name:** Paras Saini

**Guide's Name:** Dr. G.N. Pandey

**Co-Guide's Name:** Dr. Raghvendra Pandey

**Project Title:** Advanced Cathode materials for Intermediate Temperature Solid oxide fuel cells.

**TARGETS SET FOR THE WEEK**

- Sending the samples for Raman characterization.
- Analyzing FTIR and SEM characterization data.
- Trying to do Rietveld refinement of 1<sup>st</sup> sample by using Fullprof software.

**PROGRESS/ACHIEVEMENTS FOR THE WEEK**

- We received the samples data for Raman characterization.
- Analyzed FTIR data plot and SEM image at 2  $\mu m$  shows density is increasing on addition of Mo.
- Tried to do Rietveld refinement of 1<sup>st</sup> sample by using Fullprof software.

**FUTURE WORK PLANS-**

- Analyzing Raman characterization data and identifying the peaks in the plot.
- Also Collecting data for EDS to check atomic percentage of the sample.
- We send platinum pated pellets for Impedance spectroscopy.

**Amity Institute Applied Sciences**

**WEEKLY PROGRESS REPORT (WPR)**

**For the week commencing: \_\_\_\_\_ 16/05/2022 to 21/05/2022 \_\_\_\_\_**

**WPR: 19**

**Enrollment Number:** A4450020010

**Program:** M.Sc. Applied Physics

**Student Name:** Paras Saini

**Guide's Name:** Dr. G.N. Pandey

**Co-Guide's Name:** Dr. Raghvendra Pandey

**Project Title:** Advanced cathode materials for Intermediate Temperature Solid oxide fuel cells.

**TARGETS SET FOR THE WEEK**

- Analysing Raman characterization data and identifying the peaks in the plot.
- Also Collecting data for EDS to check atomic percentage of the sample.
- We send platinum pated pellets for Impedance spectroscopy.

**PROGRESS/ACHIEVEMENTS FOR THE WEEK**

- We Analysed Raman characterization data and identified the peaks in the plot.
- Also Collected data for EDS to check atomic percentage of the sample and we found that the difference between theoretical value and collected data value are very less.
- We received data of sample  $Ba_7Nb_{4+x}Mo_{1-x}O_{20}$ , Impedance spectroscopy data. We plotted it, calculate and analyse the Arrhenius plot.

**FUTURE WORK PLANS-**

- We will be going to synthesize same material  $Ba_7Nb_{4+x}Mo_{1-x}O_{20}$ , but this time we will going to increase Niobium (Nb) and decreasing Molybdenum (Mo) in the material.
- And again, analyzing effect of that doping on the materials conductivity at different temperature. Analyzing these samples with the help of XRD, Raman, SEM, EDS, FTIR, XPS and EIS spectroscopy.

# **PLAGIARISM REPORT**

### Submission Information

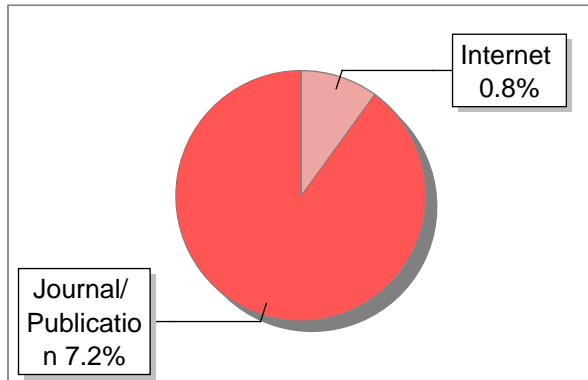
Author Name	PARAS SAINI
Title	Advanced cathode materials for Intermediate Tem..
Paper/Submission ID	520619
Submission Date	2022-05-17 10:36:17
Total Pages	41
Document type	Project Work

### Result Information

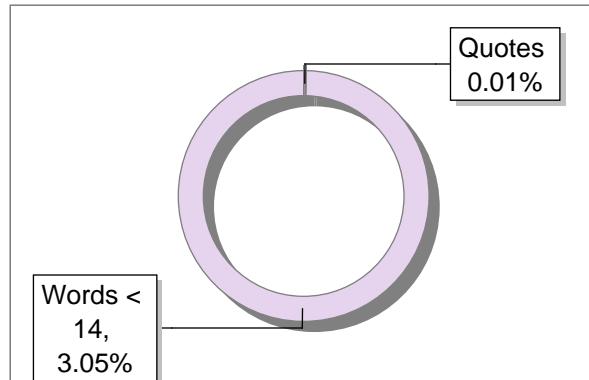
Similarity **10 %**



Sources Type



Report Content



### Exclude Information

Quotes	Not Excluded
References/Bibliography	Excluded
Sources: Less than 14 Words Similarity	Not Excluded
Excluded Source	<b>0 %</b>
Excluded Phrases	Not Excluded

A Unique QR Code use to View/Download/Share Pdf File





## DrillBit Similarity Report

**10**

SIMILARITY %

**57**

MATCHED SOURCES

**A**

GRADE

- A-Satisfactory (0-10%)**
- B-Upgrade (11-40%)**
- C-Poor (41-60%)**
- D-Unacceptable (61-100%)**

LOCATION	MATCHED DOMAIN	%	SOURCE TYPE
1	137Cs in the fungal compartment of Swedish forest soils by Mykhayl-2004	1	Publication
2	BIOCHEMICAL ENGINEERING OF Chorella sorokiniana FOR ENHANCED LIPID AC by Momocha Ngangkha-2012 , Krishikosh	1	Publication
3	Angiogenesis modulatory factors in subjects with chronic ocular complications of by Heiday-2019	<1	Publication
4	www.researchgate.net	<1	Internet Data
5	Exergoenvironmental comparison of internal reforming against external reforming by Chitsaz-2018	<1	Publication
6	Particle size effect on thermophysical properties of nanofluid and nan by Munyalo-2018	<1	Publication
7	nopr.niscain.res.in	<1	Publication
8	Eu <sub>2</sub> SrCo <sub>1.5</sub> Mn <sub>0.5</sub> O <sub>7</sub> a new promising compound as cathode in intermediate temperatur by Boulahya-2015	<1	Publication
9	Anode-supported intermediate temperature direct internal reforming solid oxide f by P-2004	<1	Publication
10	www.dx.doi.org	<1	Publication
11	www.dx.doi.org	<1	Publication

- 12** optimal allocation setting of fuel cell forloadability enhancement in a windpv integratedsystem base <1 Publication
- 
- 13** Hierarchically nanoporous La by Huang-2015 <1 Publication
- 
- 14** Fabrication and Characterization of Anode-Supported Tubular Solid-Oxide Fuel Cel by La-2009 <1 Publication
- 
- 15** docplayer.net <1 Internet Data
- 
- 16** Nalco and Ecolab to merge by -2011 <1 Publication
- 
- 17** Comparison of activation energies of laminated lithium-ion secondary cell using by Ishikawa-2011 <1 Publication
- 
- 18** A novel polymer quaternary ammonium iodide and application in quasi-solid-state by Weiyin-2005 <1 Publication
- 
- 19** Electrical and Structural Properties of Ca Substitution in High and Lo by Azhan-2016 <1 Publication
- 
- 20** Battery and solid oxide fuel cell materials by Kendrick-2013 <1 Publication
- 
- 21** Ash Deposition Trials at Three Power Stations in Denmark by Laursen-1998 <1 Publication
- 
- 22** A portable laser photostimulation and imaging microscope by Nikolenko-2010 <1 Publication
- 
- 23** www.iiste.org <1 Publication
- 
- 24** downloads.hindawi.com <1 Publication
- 
- 25** Article Published in MDPI Journal of Materials <1 Internet Data
- 
- 26** Thesis submitted to dspace.mit.edu <1 Publication
- 
- 27** The energy crisis in Pakistan A possible solution via biomass-based waste by Javed-2016 <1 Publication

28	Supplemental Binding by -1936	<1	Publication
29	Hydration and proton conduction in Nafionceramic nanocomposite membra by Amand-2009	<1	Publication
30	Effect of low-level Ca2 substitution at perovskite B site on the prop by Zhu-2019	<1	Publication
31	coek.info	<1	Internet Data
32	A novel, green cloud point extraction and separation of phenols and fl by More-2019	<1	Publication
33	researchspace.ukzn.ac.za	<1	Publication
34	businessdocbox.com	<1	Internet Data
35	One step syntheses of S incorporated ZnO nanowires for photocatalysis applicatio by Awad-2015	<1	Publication
36	Fuel cells a 21st century power system by -1998	<1	Publication
37	www.teachersource.com	<1	Publication
38	The Effects of Sr Content on the Performance of Nd <sub>1-x</sub> Sr <sub>x</sub> CoO <sub>3</sub> Air-Electrode Materi by -	<1	Publication
39	Electrochemical reduction of Cr(VI) in the decontamination process ELDECOn by Charlott-1996	<1	Publication
40	Student Thesis Published in HAL Archives	<1	Publication
41	www.researchgate.net	<1	Internet Data
42	www.ncbi.nlm.nih.gov	<1	Internet Data
43	www.mdpi.com	<1	Publication
44	www.fibre2fashion.com	<1	Internet Data

- 45** Waste or Gold Bioelectrochemical Resource Recovery in Source-Separated Urine by Nazari-2020 <1 Publication
- 46** Thesis submitted to shodhganga - shodhganga.inflibnet.ac.in <1 Publication
- 47** Thesis submitted to shodhganga - shodhganga.inflibnet.ac.in <1 Publication
- 48** Studies on Order disorder transition, Lattice expansion and Ionic conductivity by Vaisakha-2017 <1 Publication
- 49** Structural Characterization and Magneto Electrical Behavior of Sm Doped La<sub>0.7</sub>Ca<sub>0.3</sub> by S-2012 <1 Publication
- 50** Quantifying Transport, Geometrical and Morphological Parameters in Li, by Rajendra, Thushanan- 2019 <1 Publication
- 51** Preparation, Microstructure and Morphology of Electrospun Sulfonated Polystyrene by Jalal-2019 <1 Publication
- 52** Insights into the microbial degradation and catalytic mechanisms of chlorpyrifos by Huang-2021 <1 Publication
- 53** Influence of the technological parameters on the growth of a-SiH by a low press by JC-1990 <1 Publication
- 54** Harvesting of microalgae by centrifugation for biodiesel production A review by Najjar-2020 <1 Publication
- 55** A new A-site excessive strategy to improve performance of layered perovskite cat by Yang-2017 <1 Publication
- 56** www.nrel.gov <1 Publication
- 57** IEEE 2013 International Conference on Computer, Control, Informatics by <1 Publication