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Commemorative Lecture at the 44th Honda Prize
Award Ceremony on the 16th November 2023

Through the invention of Nd-Fe-B magnets
- Joy of being a researcher; the best job in the world!

Dr. Masato Sagawa

- Adviser, Daido Steel Co., Ltd.
- President, NDFEB Corporation

The Discovery of NdFeB Permanent Magnets by the Rapid Solidification Route

Dr. John J. Croat

Former President, John Croat Consulting Inc.

HONDA FOUNDATION

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■Date of Birth

August 3, 1943, Tokushima, Japan

■Education and Qualifications

1966: B. A., Department of Electrical Engineering, Kobe University

1968: M. A., Department of Electrical Engineering, Kobe University

1972: Dr. Eng., Metallurgical Materials Engineering, Graduate School of Engineering, Tohoku University

■Employment History

1972-1982: Fujitsu Ltd.

1982-1988: Sumitomo Metal Industries, Ltd. (now Proterial, Ltd.)

1988-2012: Established Intermetallics Co., Ltd., Appointed as Representative Director

2013-present: Established NDFEB Corporation, Appointed as Representative Director

2016-present: Adviser, Daido Steel Co., Ltd.

2017-2019: Adviser, Nippon Densan Co., Ltd. (now NIDEC Corporation)

2017-2019: Specially Appointed Professor, Institute of Advanced Energy, Kyoto University

2019-present: Distinguished Invited University Professor, Tohoku University

2019-present: Guest Professor, Central Iron & Steel Research Institute, China

2022-present: Senior Fellow, Research Promotion Organization for Carbon Neutrality, Meijo University

■Award

1984: Osaka Science Prize

1985: Minister of Science and Technology Agency Award

1986: International Prize for New Materials, American Physical Society (now James C. McGroddy Prize for New Materials)

1988: The Japan Institute of Metals and Materials Meritorious Award

1990: Asahi Prize

1991: Japan Magnetics Society Award

1993: Okochi Memorial Prize

1998: Acta Metallurgica J. Hollomon Award

2003: Honda-Kinen Prize

2006: Kato-Kinen Prize

2012: Japan Prize

2016: Special Award, Nagamori Award

2018: NIMS Award 2018

2020: The Japan Institute of Metals and Materials Gold Medal Award

2022: Queen Elizabeth Prize for Engineering

2022: IEEE Medal for Environmental and Safety Technologies

■Publication

- "Permanent Magnets: Materials Science and Applications", Masato Sagawa, Masaaki Hamano, Makoto Hirabayashi, AGNE Gijutsu Center Inc., ISBN 978-4-901496-38-4 (2007)

- "All About Neodymium Magnets: Protecting the Earth with Rare Earths", Masato Sagawa, AGNE Gijutsu Center Inc., ISBN 978-4-901496-58-2 (2011)

- "The Work Style of the Strongest Engineer", Shuji Nakamura, Masato Sagawa, Jitsumukyoiku-Shuppan Co., Ltd. ISBN 978-4-788911-95-6 (2016)

This report is the gist of the commemorative lecture at the 44th Honda Prize Award Ceremony at the Imperial Hotel, Tokyo on 16th November 2023.

Through the Invention of Nd-Fe-B Magnets
- Joy of being a researcher; the best job in the world!

Masato Sagawa

Through the Invention of Nd-Fe-B Magnets

- Joy of being a researcher; the best job in the world!

Honda Prize Commemorative Lecture

November 16, 2023
Masato Sagawa

■ Introduction

I feel really happy and honored to receive the Honda Prize today. This is a truly wonderful award to receive. Thank you very much.

Let me share my story with you today. The title of my talk is "Through the Invention of Nd-Fe-B Magnets - Joy of being a researcher; the best job in the world! ," and I hope that it will inspire young people to keep on engaging in research, as I did. Starting from today, I plan to deliver a number of lectures, and I will be talking about this topic there as well. Just two days after this, I will have the opportunity to talk to children about how I invented these magnets and how wonderful doing research is. Today is the start of such journey, and I hope to talk about these things to everyone from now on.

■ Research topics that had nothing to do with magnets

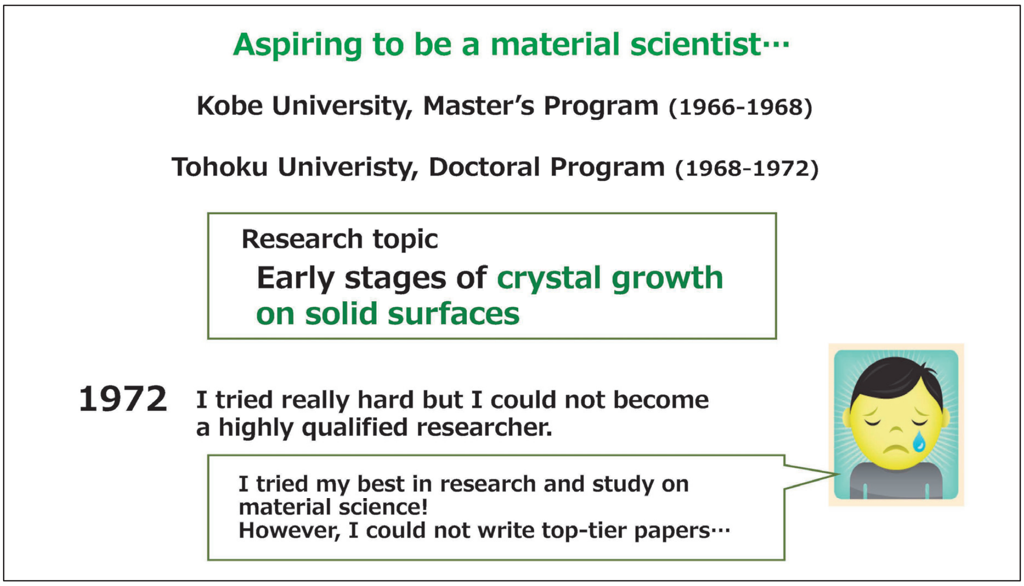


Fig. 1

〈Fig. 1〉 First, let me tell you how I invented this magnet.

Because I wanted to become a materials scientist, I studied at a master's program at Kobe University and then a doctoral program at Tohoku University. My research theme was "Early stages of crystal growth on solid surfaces." It had nothing to do with magnets. I wrote my doctoral thesis and received my Ph.D. in 1972. However, I didn't write a very good paper, and I couldn't get my paper published in any scientific journals. It made me lose my confidence.

I worked really hard as a student. I also worked very hard on my research, but I couldn't reach my goals. Here I am shedding tears in this picture, but I was really frustrated at that time when I graduated.

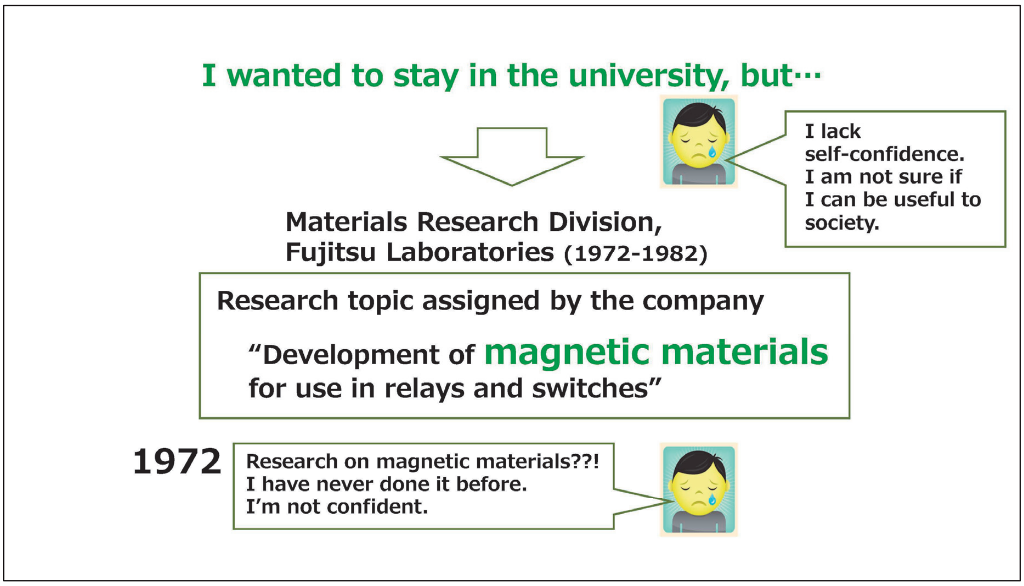


Fig. 2

〈Fig. 2〉 I wanted to stay in academia and become a professor, but I knew I would not be able to survive there. So, I decided to work somewhere else. However, I did not know what I could do at a company. I wasn't sure that I would be able to contribute anything useful for the society.

Nevertheless, I joined the Materials Research Department of Fujitsu Laboratories, as was suggested by Professor Saburo Shimodaira at Tohoku University at that time. Without asking me anything, the company assigned me to the department that was developing magnetic materials for the use in relays and switches. As I mentioned, I had never studied magnetic materials or done magnet research at all at that time even though I knew the fundamentals very well. So, I thought, "I have never done research on magnetic materials. I'm in trouble," and I cried again. I was really weak, wasn't I?

■ Discover the excitement of magnetism research

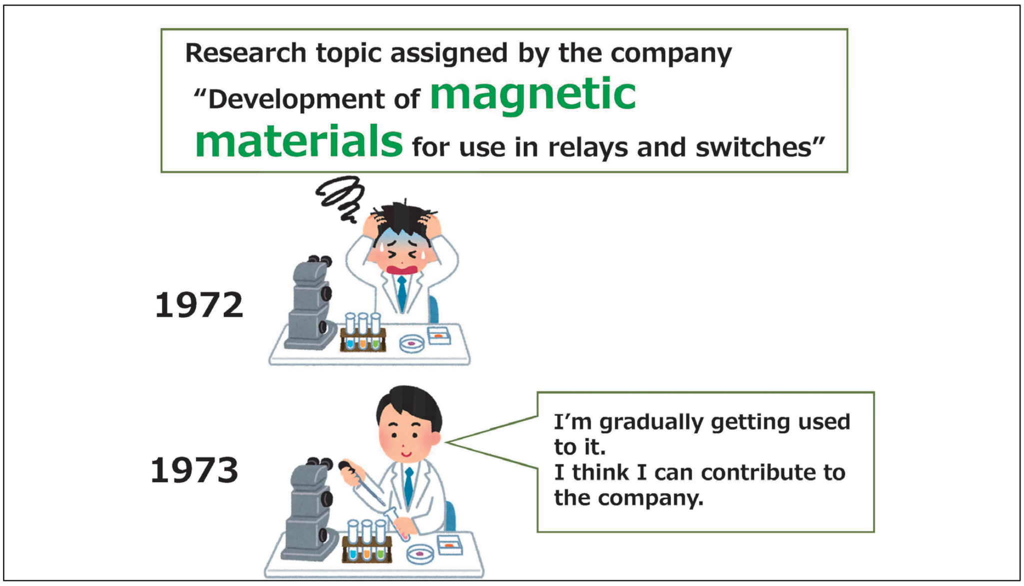


Fig. 3

〈Fig. 3〉 The research topic that the company gave me was the development of magnetic materials for the use in relays and switches. At first, I wasn't sure of myself and thought, "Oh, what am I going to do?" But I learned all about magnets by myself, from basic magnetic physics to applied research on magnetic materials. I studied continuously even when I was at home, so I could not spend enough time with my family.

After about a year, I started to get the hang of it and thought, "Maybe I can do something about this. Research on magnets is actually interesting."

■ Utilizing skills obtained during graduate school at the company.

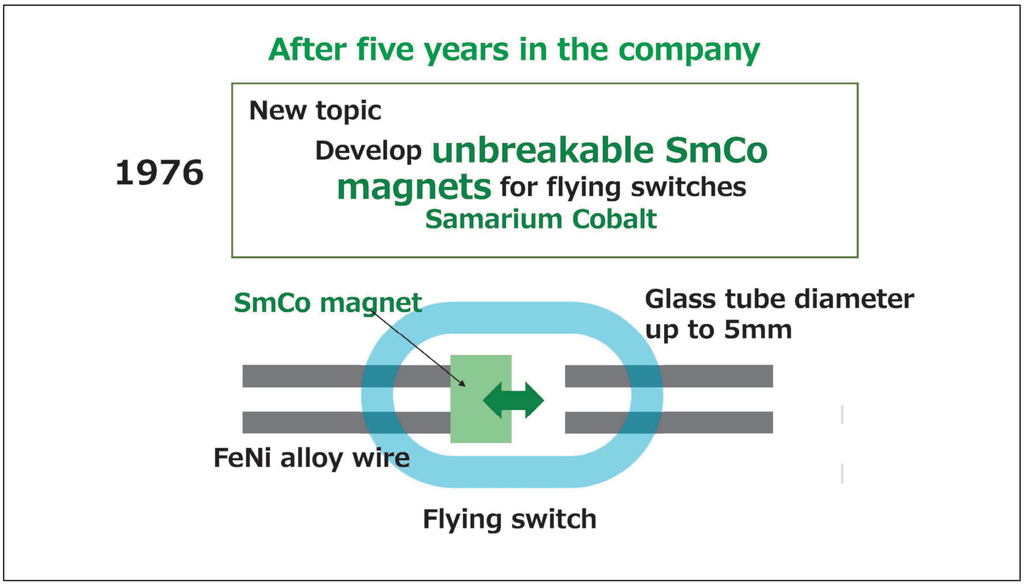


Fig. 4

〈Fig. 4〉 Research on magnetic materials is quite a diverse field. About five years after joining the company, I was given a unique research topic; to develop an unbreakable Sm-Co (samarium-cobalt) magnet for flying switches. Sm-Co was the strongest magnet at that time. As shown in the figure, two wires are hermetically sealed in a thin glass tube up to 5 mm in diameter, and a magnet is contained inside. The light green object is a Sm-Co magnet. Electricity is applied externally to create a pulsed magnetic field, and this Sm-Co magnet turns the electricity on or off by moving to the right or left. That's how it works as a switch. The people at Fujitsu Components and Materials Department were very hopeful about this product, because it allowed us to turn off and on a strong electricity current with a fairly small switch.

However, because it had to move constantly right and left, the magnet tended to break in a short while. That is why I was assigned to develop a magnet that would not break.

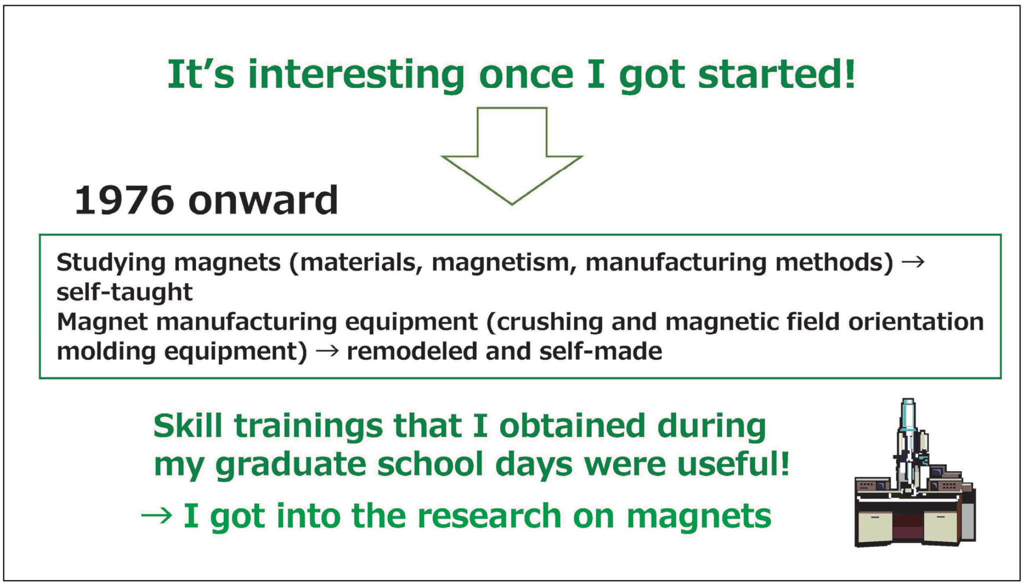


Fig. 5

〈Fig. 5〉 "All right, I'll do it," I said, and so I went researching magnets again. I studied the materials. Magnetic materials. Manufacturing methods. Magnetism means magnetic physics. I worked very hard studying magnetic physics.

We needed unique equipment to manufacture magnets. I had to be creative, modifying things at the company to make it possible to manufacture magnets. I believe that I could do that due to the skills I developed during my graduate school years. I also loved conducting experiments and building experimental tools and devices. These abilities came in handy, and things started to go well. From then, I began to get really into the research on magnets.

■ Development of unbreakable Sm-Co magnets

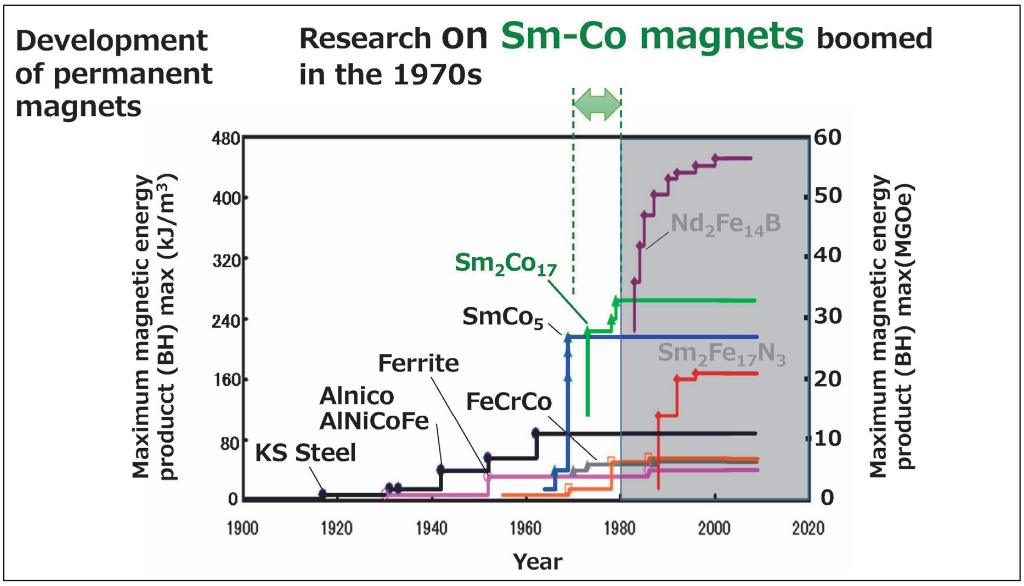


Fig. 6.

〈Fig. 6〉 This figure shows the history of the development of permanent magnets.

The horizontal axis represents the time. The vertical axis is the “maximum energy product” as a factor of magnet strength. As you can see here, the strength of magnets continually increases in a stepwise manner when new magnets are invented.

It was in the 1970s when I was asked to do research on these magnets. At that time, the magnetic properties of Sm-Co magnets were improving rapidly, and I was assigned to improve the mechanical strength of Sm-Co magnets.

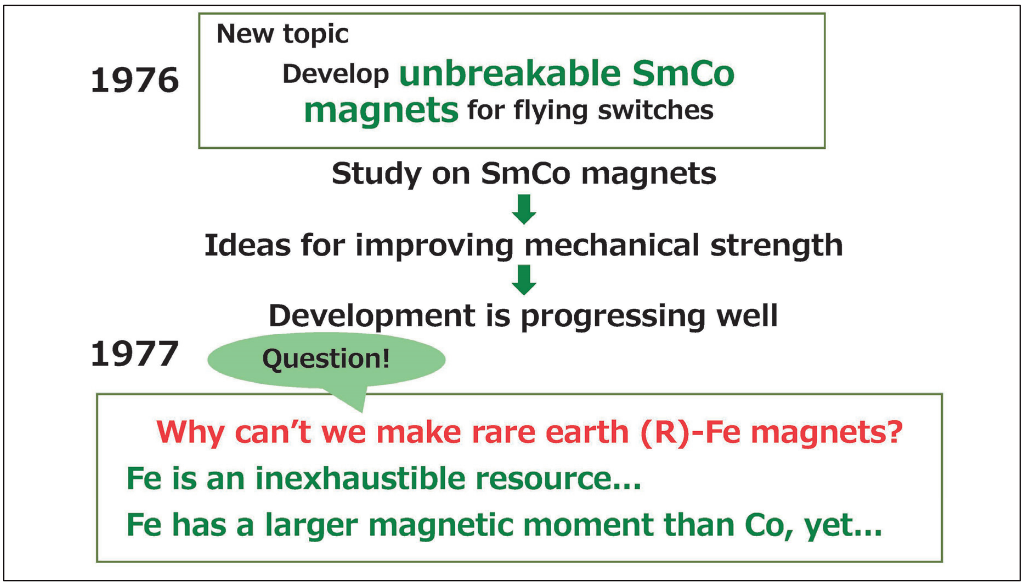


Fig. 7

〈Fig. 7〉 As I was told to “develop an unbreakable Sm-Co magnet for flying switches”, I studied Sm-Co magnets very hard. I also developed various ideas for improving the magnet’s mechanical strength, and actually made and evaluated a number of samples. I enjoyed this line of work, so I made and evaluated more and more samples (products) and came up with even more ideas. Development proceeded as expected.

However, while engaging in those development efforts, in 1977, I wondered why Sm-Fe (iron) magnets couldn’t be made. Sm-Co magnets are a combination of samarium (rare earth) and cobalt. As you know, iron is cheap and so much more abundant compared to cobalt. Also, iron is known to have a larger magnetic moment than cobalt. So, theoretically, if we could make a magnet from rare earths and iron, it would be stronger than a Sm-Co magnet. We knew it, but nobody has ever made it. This kind of thing happens sometimes, right? Well, may be the reason was because it did not work at all, but I didn’t know anyone who was doing it at that time. Then, I found out, that Dr. Croat, whom I talked about today, had tried making one, but he did not publish anything about it. Rare earths and iron magnets. I decided to do this somehow.

■ Sm-Fe magnets that has never been made before

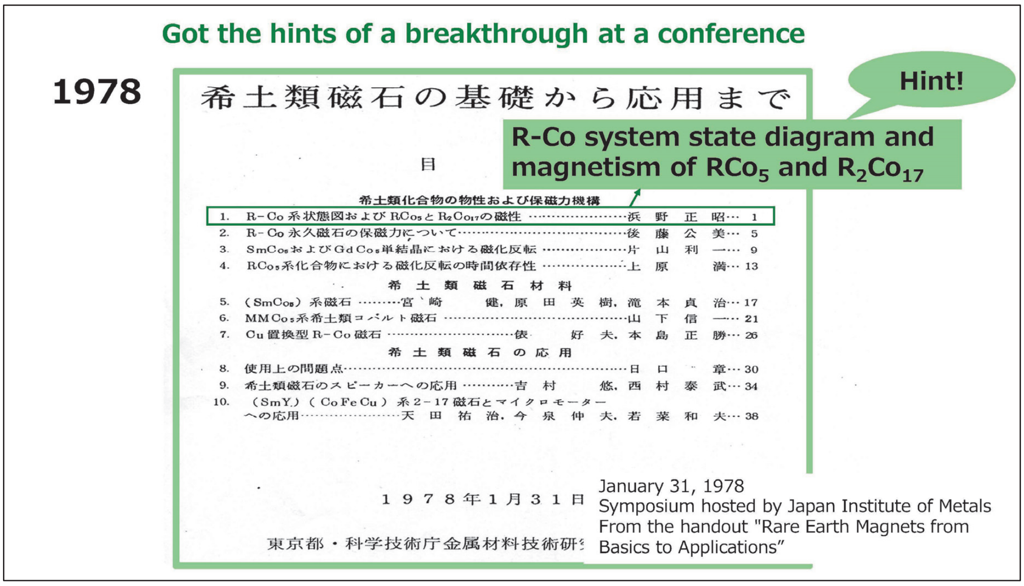


Fig. 8

〈Fig. 8〉 I did not come up with the idea of how to realize a R-Fe magnet myself, but seized a hint given by Mr. Masaaki Hamano, the first presenter during this symposium held in Japan.

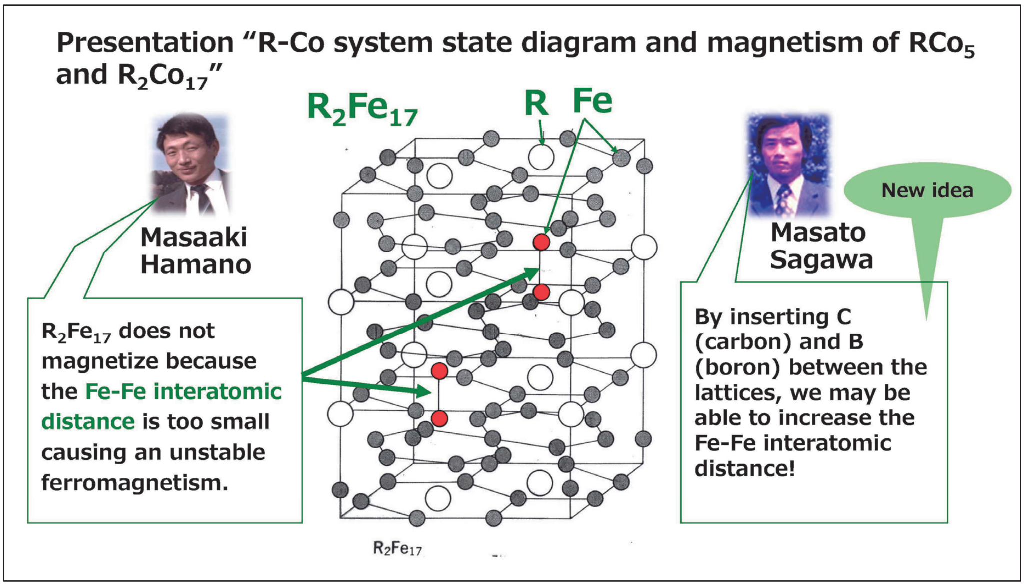


Fig. 9

〈Fig. 9〉 To explain it further, Mr. Hamano showed a typical compound of rare earths and iron and said that the iron-iron interatomic distance in the compound was too small, which caused its ferromagnetism to be unstable. That was all he said after showing the results of his basic research.

Then, I thought, "If what he said was right, I could probably expand the iron-iron interatomic distance by inserting C (carbon) or B (boron), which are known as elements with the smallest atomic radii, between the lattices. It seemed like something that anyone could think of, but nobody had actually done it. This could be called an "inspiration."

■ Did not accept the company's policy and went on to research Sm-Fe-B

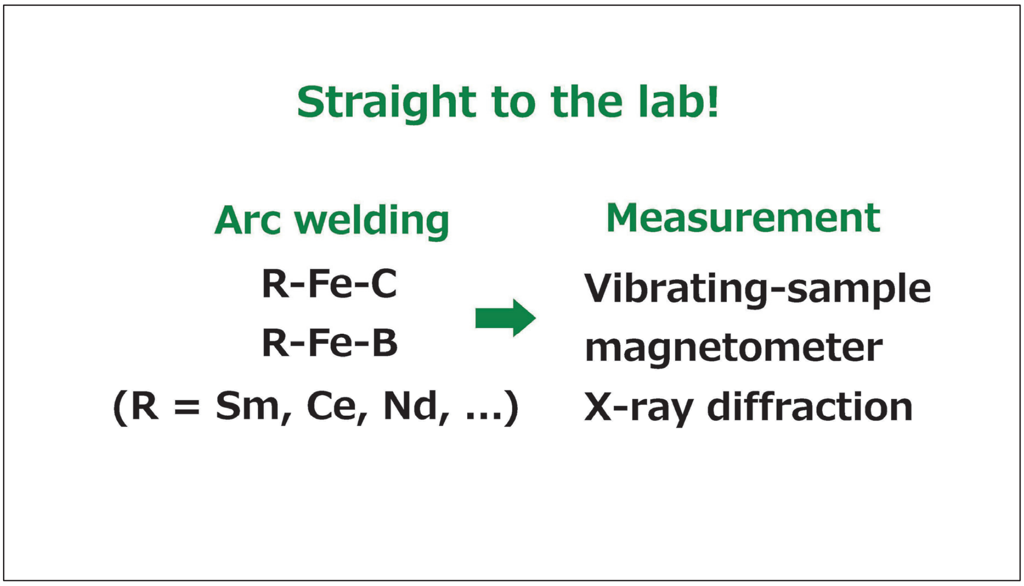


Fig. 10

〈Fig. 10〉 My important personal trait is I tend to experiment immediately. So, I immediately started making many R (rare earth)-Fe-C and R-Fe-B (boron) alloys. There are 17 kinds of R elements, and I looked for them everywhere to make alloys for my experiments. I think I was lucky that we did this quickly.

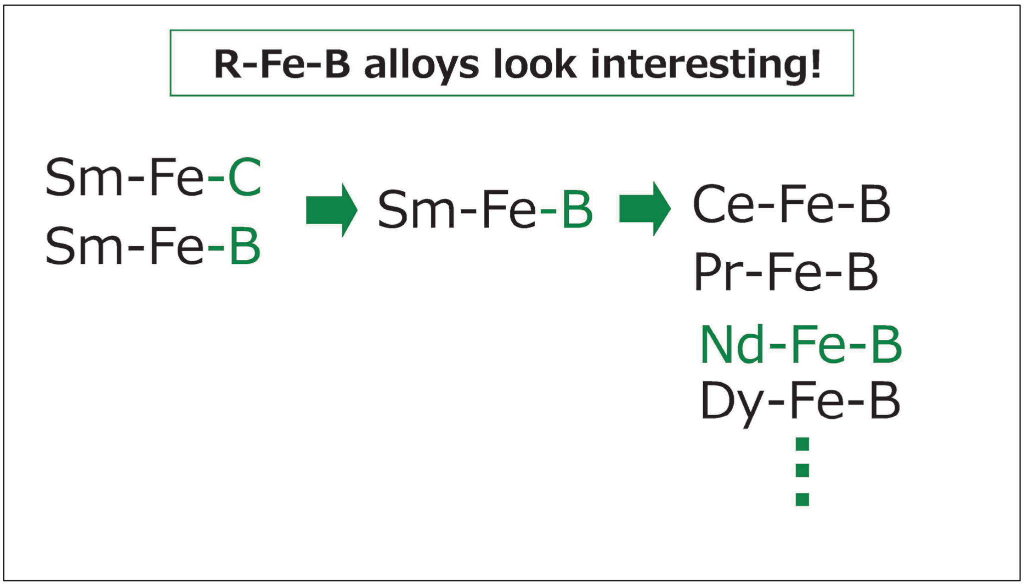


Fig. 11

〈Fig. 11〉 In this way, various Sm-Fe-C and Sm-Fe-B alloys were made, and it soon became clear that B was better than C and that Sm-Fe-B was the best one. I thought, "Sm-Fe-B has potential as a magnet candidate."

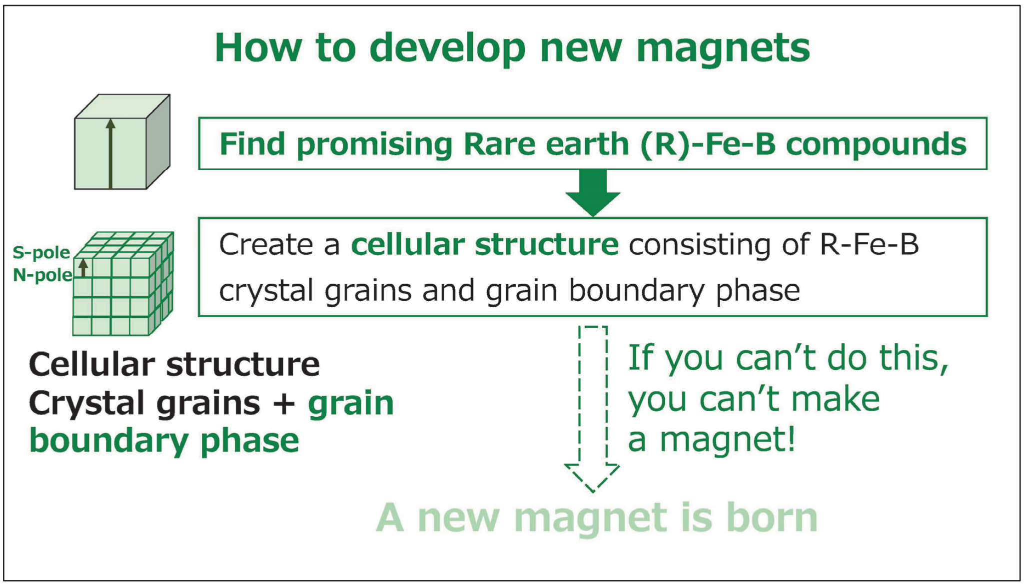


Fig. 12

〈Fig. 12〉 To develop a new magnet, not only that we must find the right compound, but we also need to create an internal structure. Does it form a cellular structure? A small single crystal substance will not become a magnet even if it is made of that compound. You must create an internal structure that can be divided into small areas; an array of small grains that are actually separated into several microns, and if you can't do that, you won't be able to make a magnet.

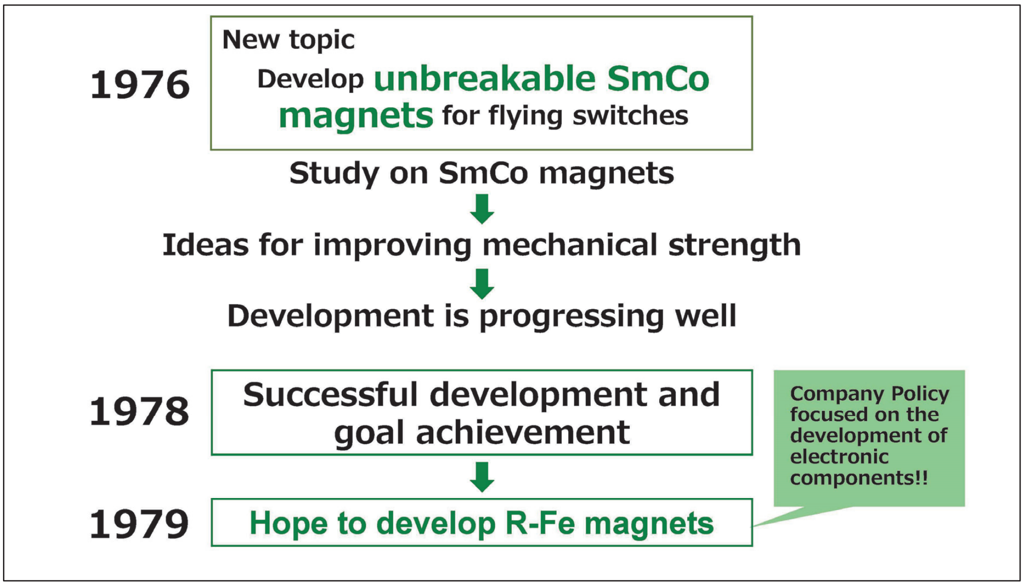


Fig. 13

〈Fig. 13〉 I still had to work on "developing an unbreakable Sm-Co magnet for flying switches". After a while, the development progressed smoothly and successfully, and we could make strong Sm-Co magnets. We also changed compositions and manufacturing methods. For example, we did a process called hot isostatic pressing, also known as HIP, in which small pores inside the magnet can be eliminated by pressurizing with argon gas from the surroundings, thus making it mechanically stronger. With this process, I obtained something much better, and the research was a success. Then, I had to think about the next research topic.

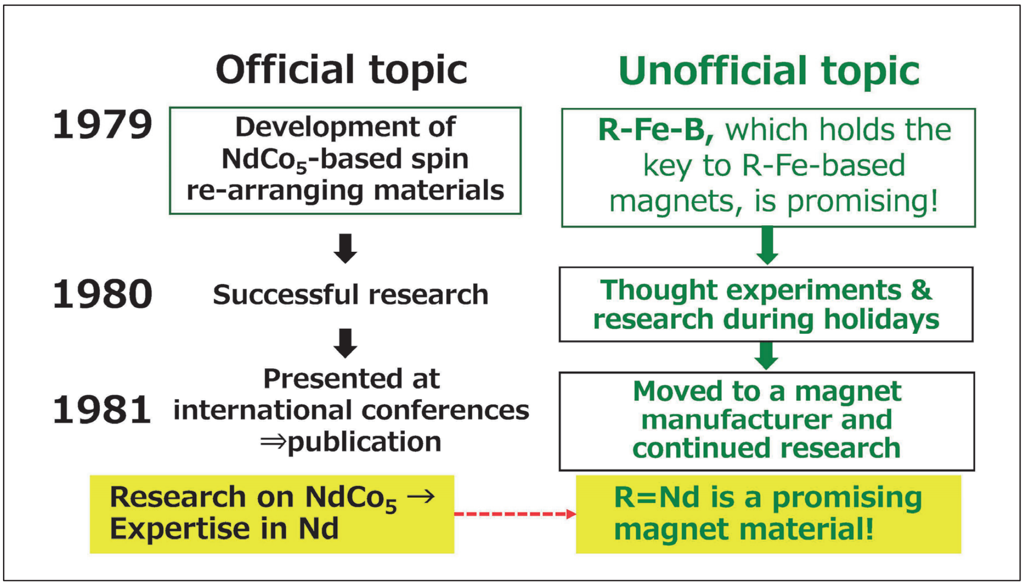


Fig. 14

〈Fig. 14〉 I found boron to be promising, so I said that I wanted to do Sm-Fe-B magnets. Then my boss said, “You can’t do that. Based on the company’s policy, you need to do research that is more directly related to electronic components and electronics.” So I had to come up with some sort of subject that would meet company’s policy.

So, I thought of a research subject, and in 1979, I proposed an official subject, “Development of NdCo5-based spin re-orientation materials.” That was the time when I started to work on neodymium for the first time.

The spin reorientation is that, for example, the N (north) and S (south) poles of a magnet change the directions to the orthogonal directions at a certain temperature range. I proposed that this would have various applications for electronics companies, and they accepted my proposal. So, I started my hard work in researching spin reorientation.

I found alloy systems that change the spin reorientation temperatures, and this happens when I put various elements into cobalt. I also modified things by adding iron. So, I got very close to Nd-Fe. I did research on spin reorientation in this way. I also proposed a more industrial method of production such as powder metallurgy, as making single crystals would not be practical. This method gradually approached the current method of producing Nd-Fe-B, but I was not aware of it at the time. In any case, this research succeeds.

The company evaluated the success of my research highly, and I was allowed to present my work at an international conference in Texas, USA. My presentation was quite well received, and our paper was published in the Journal of Applied Physics. I was able to publish a good paper and felt that I achieved quite a lot.

■ Call to the president of Sumitomo Special Metals to make a direct appeal

Through this research, I gradually became more and more familiar with neodymium. At the same time, I wanted to develop R-Fe magnets, which had always remained at the back of my mind as an unofficial subject of my research. However, I couldn't do much during company working hours, so I did a lot of thinking and research at home. Again, I didn't spend much time with my family at home. It was like that all the time.

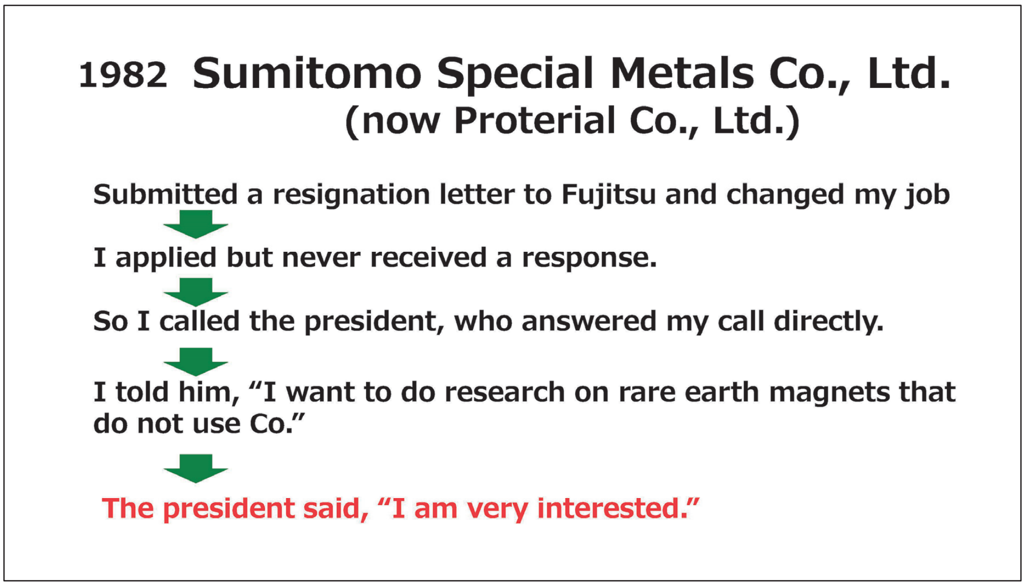


Fig. 15

〈Fig. 15〉 As I got closer and closer to Nd-Fe-B, I decided that I wanted to change jobs to work for a magnet manufacturer to continue my research. So, one day, I submitted my letter of resignation to Fujitsu. The company did not oppose it much. Fujitsu is a very respectable company. I was in a managerial position there, so I thought that they would really oppose it, but they did not.

After submitting my resignation, I was looking at various companies to work for when I found Sumitomo Special Metals and applied there. I also wrote a letter to the president, but I guess he didn't really get the message. So, I was at home after resignation, and I said to myself, "I wrote a letter to Sumitomo Special Metals, but they haven't responded at all. What should I do?" My wife said, "Why don't you call them?" So, I did it, and the president happened to answer. I told him that I wanted to do research on rare earth magnets that did not use cobalt, and he said, "I am very interested," and I had a chance to visit the company and talk with him. Then, around the beginning of 1982, I decided to go to Sumitomo Special Metals.

■ Birth of the World's Strongest Nd-Fe-B Magnet

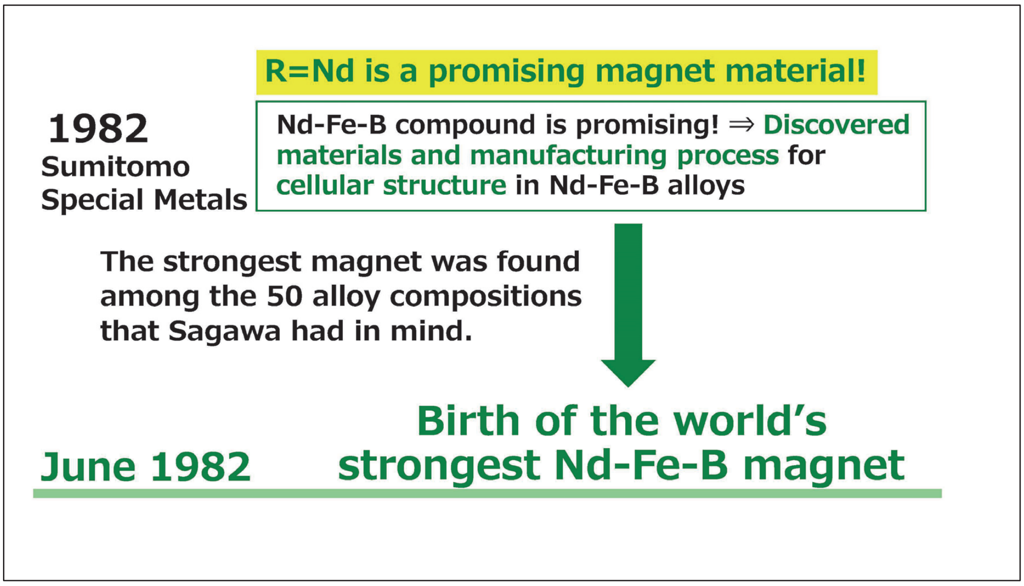


Fig. 16

〈Fig. 16〉 By that time, the idea for Nd-Fe-B had already been formed in my head. But only in my head - I had no data or anything concrete. To make a magnet, you must make a cellular structure. I hadn't done that, but I was thinking of various compositions that I wanted to make. I wrote down a list of about 50 candidate compositions that I had in mind, and then created them together with my first co-workers at Sumitomo Special Metals.

Then, among these 50 or so compositions, we found the strongest magnet in the world. "Hooray!" The Nd-Fe-B magnet was born in June 1982.

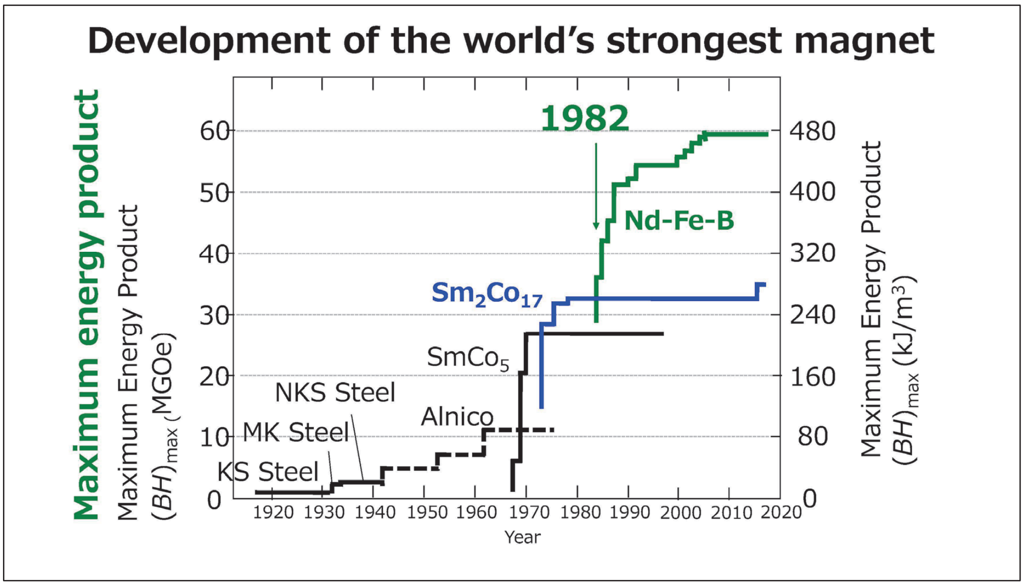


Fig. 17

〈Fig. 17〉 That was how the Nd-Fe-B magnet appeared in the graph "Development of the World's Strongest Magnets". The world's strongest magnet was born.

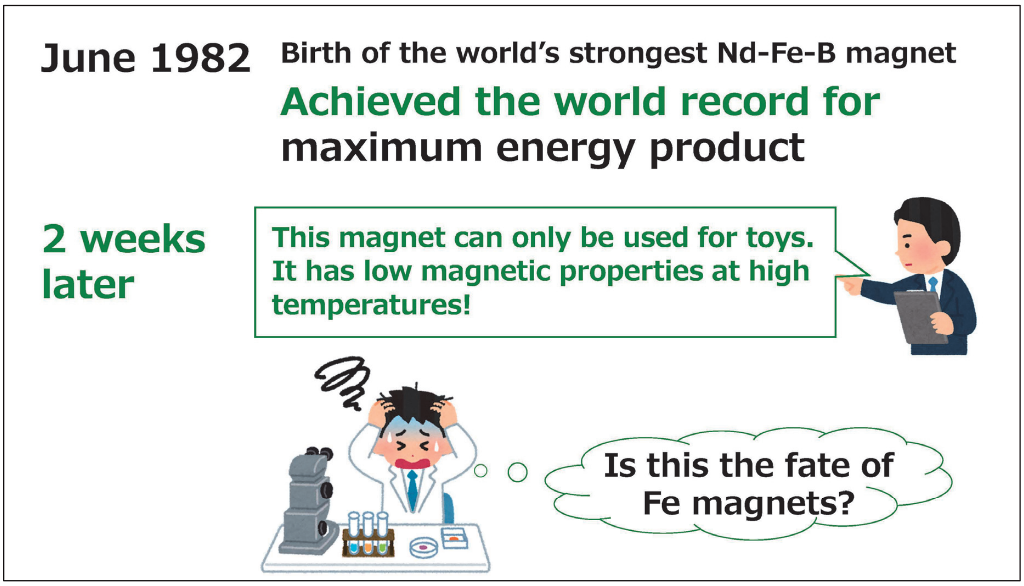


Fig. 18

〈Fig. 18〉 However, a group of people who evaluated the magnet said, "This magnet can only be used for toys. It cannot be used for motors or anything at all, because it has inferior magnetic properties. It drops its magnetism when the temperature is raised. I thought, "Oh no," and I was about to go crazy again when I thought, "It seems we have to go back to cobalt. Is cobalt really necessary for heat resistance?" I thought about it for a while, but then the team was formed, and I thought hard with my team members. We then came up with a lot of ideas and found a way to solve the problem.

Fig. 19

〈Fig. 19〉 I will explain about it on the next slide, but I worked with these people for a long time on the study of industrialization.

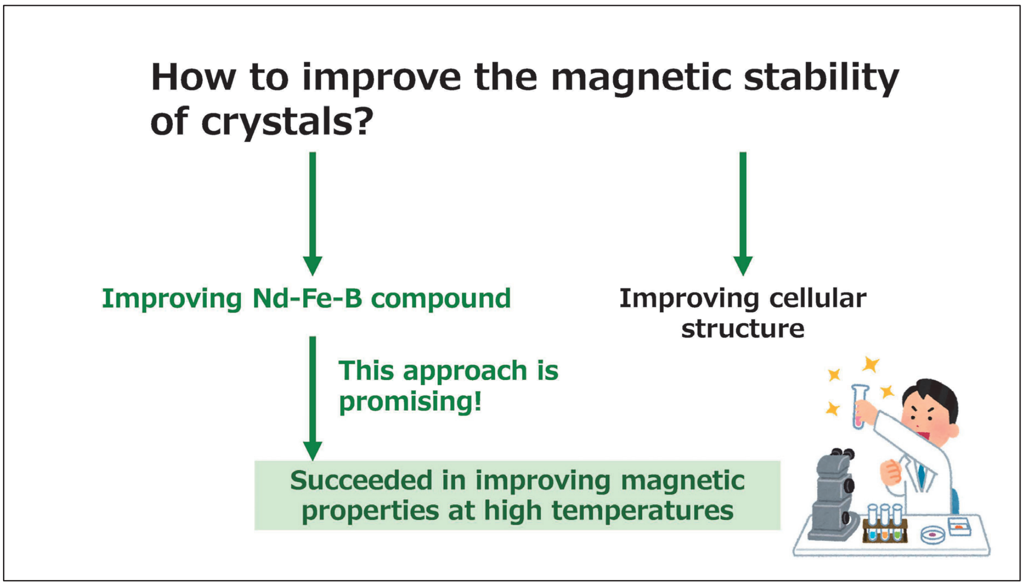


Fig. 20

〈Fig. 20〉 There are two routes to stabilize magnetic properties: improvement of the compound and improvement of the cellular structure. And the improvement of the compound worked.

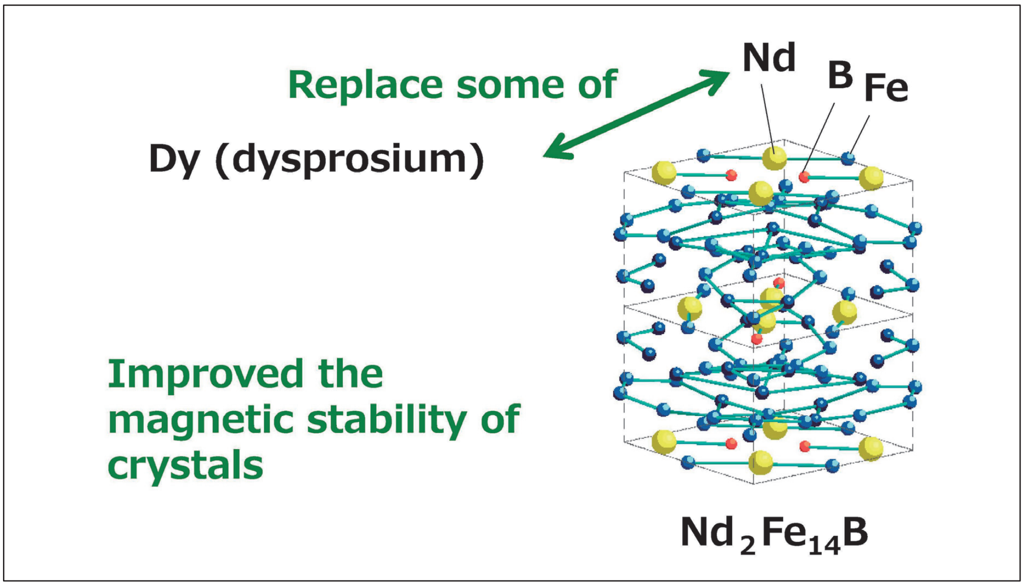


Fig. 21

〈Fig. 21〉 What I meant by improving the compound is based on the crystal structure of Nd-Fe-B magnet, which I first discovered when I developed it. The unit cell assumes a tetragonal structure, which I discovered through analysis of crystals. The lattice constants are the lengths of the a-axis, b-axis, and c-axis of each unit cell, and a and b are the same as it is a tetragonal structure. I still remember the numbers; the c-axis is 1.221 nm and the a-axis is 0.880 nm. I then thought that I could probably replace some of the neodymium atoms in that crystal with Dy (dysprosium). By doing that, I could actually stabilize the compound.

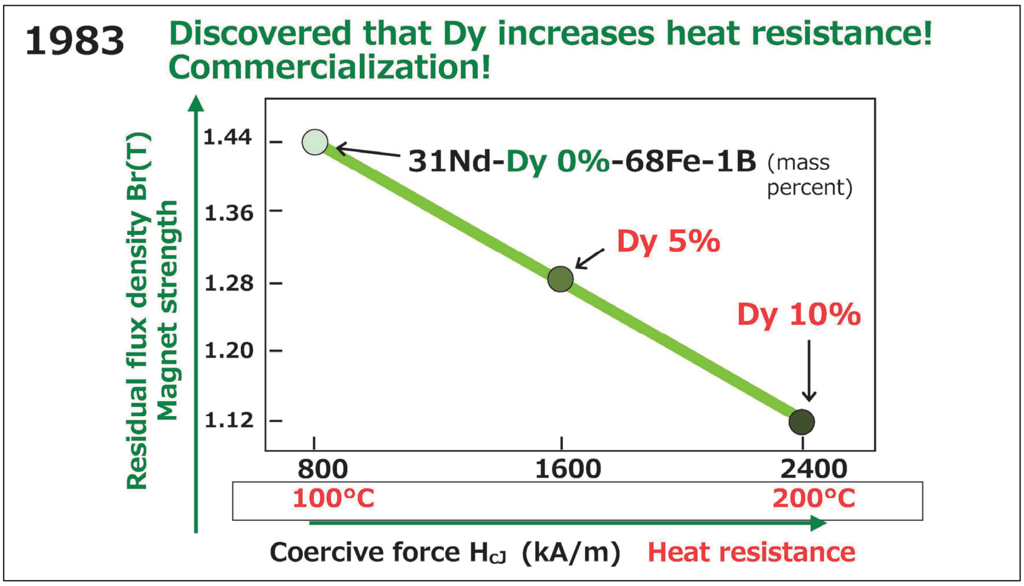


Fig. 22

〈Fig. 22〉 As shown here, we replaced some neodymium by Dy. At 0% replacement, the magnet could only withstand temperatures up to 100°C. This means that heat resistance is up to 100°C. By adding 5% Dy, the heat resistance went up to 150°C. Furthermore, by adding 10%, you get something that will last up to 300°C. However, as more Dy is added, the vertical axis which is the strength of the magnet becomes lower. However, even with 10% addition, it was still stronger than the strongest magnet of the time. So this was still well worth it. And the most important thing was that it did not use cobalt, which was a very huge advantage.

Fig. 23

〈Fig. 23〉 I presented these results on November 10, 1983, at the international conference called MMM (Magnetism and Magnetic Materials) in Pittsburgh, USA. The person beside me is Dr. Strnat, the inventor of the samarium-cobalt magnet. I was 40 years old at that time, that's quite young, isn't it?

■ Significant contributions to various fields after 3 years of mass production

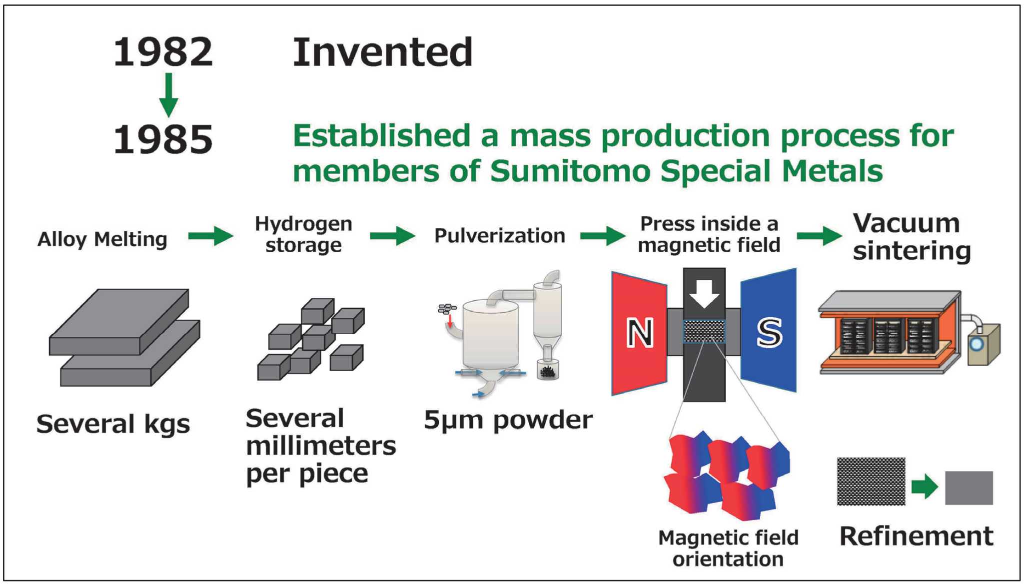


Fig. 24

〈Fig. 24〉 I invented Nd-Fe-B in 1982 and continued by working on its mass production with the Sumitomo Special Metals members. There are various process steps for mass production. We developed these and succeeded in mass production. We tried various things for each step to realize this. This was also a difficult task, but we all worked really hard for it.

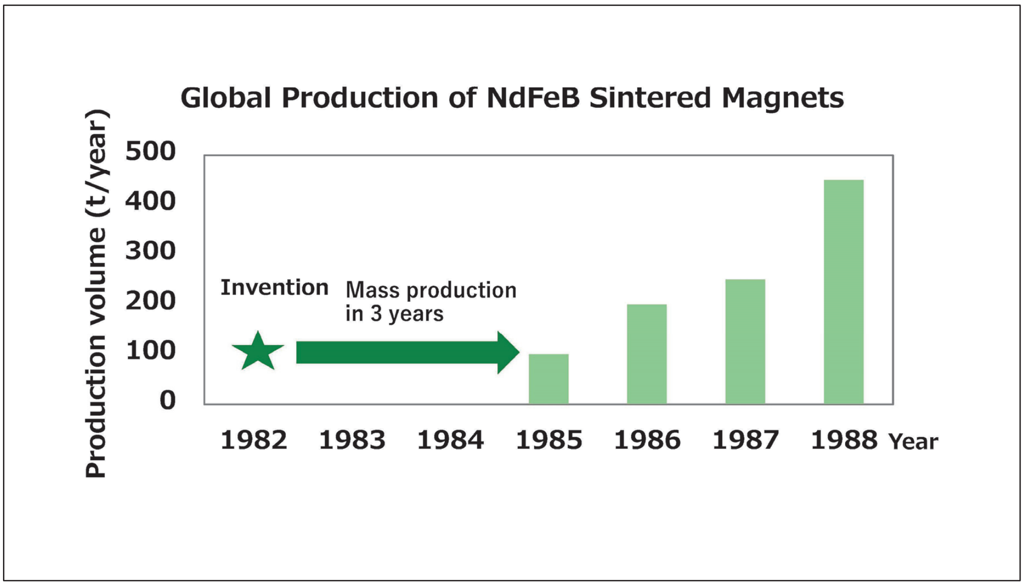


Fig. 25

〈Fig. 25〉 Looking at the production volume by year, after the invention in 1982, the production already started in 1985. Although it was very small volume, this was quite remarkable. It was very difficult for a new material to be mass-produced within three years, but we were able to do it. Our team at Sumitomo Special Metals worked very hard and could start the large-scale mass production in around 1988.

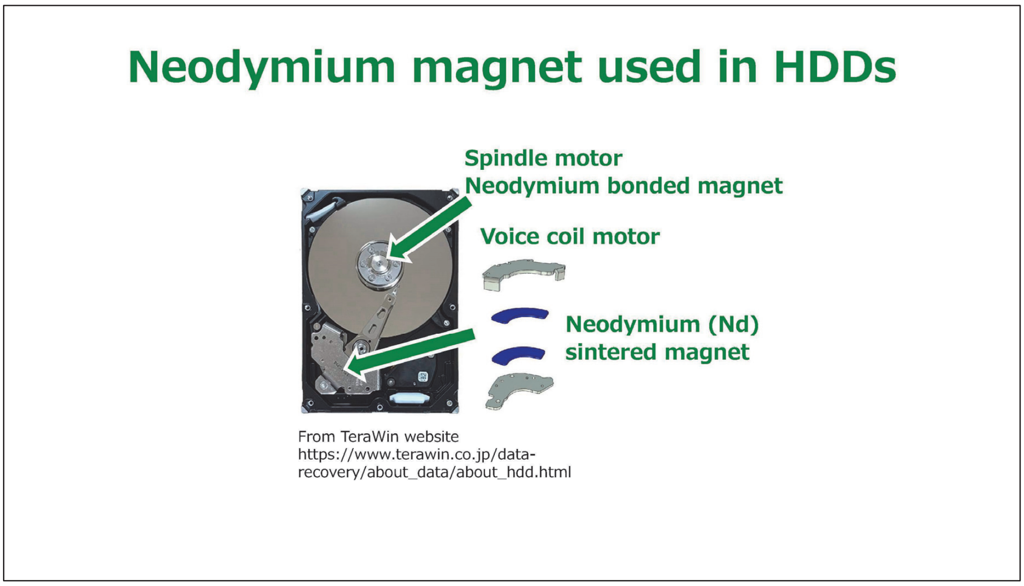


Fig. 26

〈Fig. 26〉 Neodymium magnets have many uses, but the most important one is in hard disk drives, used in personal computers. Although they are less common these days, they were very important during their era. The spindle motor that turns the disks of the hard drive uses the bonded magnet invented by Dr. Croat. The motor that drives the magnetic heads, which read and write the data by moving and stopping extremely fast, uses neodymium sintered magnets, which I invented, the discovery of which led to the tremendous development of hard drives.

Before the invention of this magnet, hard disks drives weighed 10 or 20 kg, so heavy that they could not be carried by one person. Now they can easily be held by hand.

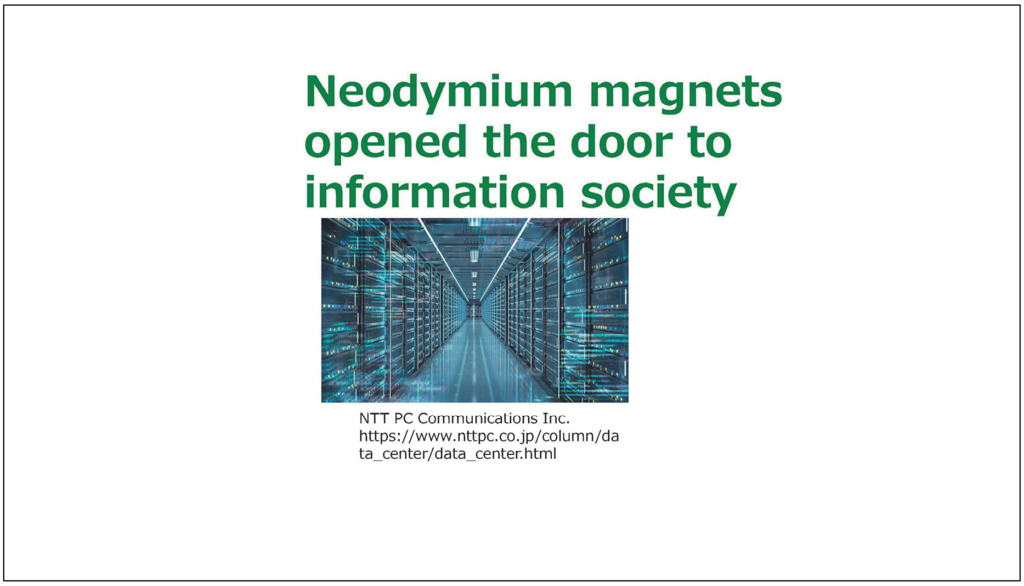


Fig. 27

〈Fig. 27〉 Because of that, it became possible to put a hard disk drive in a personal computer. This marked the beginning of today's information society. I believe that neodymium magnets made a very significant contribution to the start of the IT (Information Technology) society.

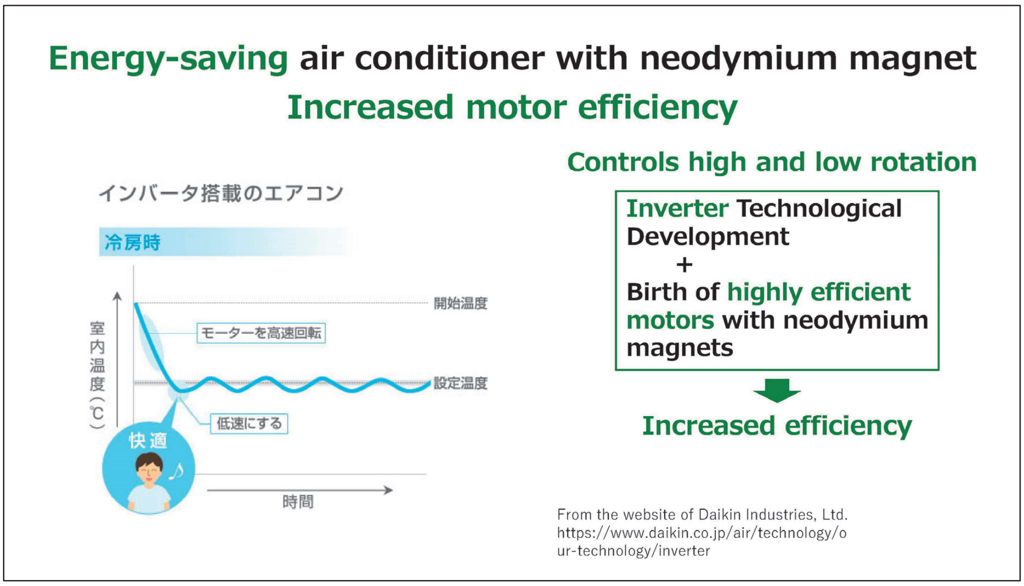


Fig. 28

〈Fig. 28〉 Neodymium magnets are also used in air conditioners. Since motors equipped with neodymium magnets became very efficient, this, in combination with the use of then developed inverters which better regulate electric power, made air conditioners extremely efficient. The efficiency was more than doubled after these devices were introduced. This is a significant improvement. So, thanks to the inverter and this magnet, air conditioners are now used very widely.

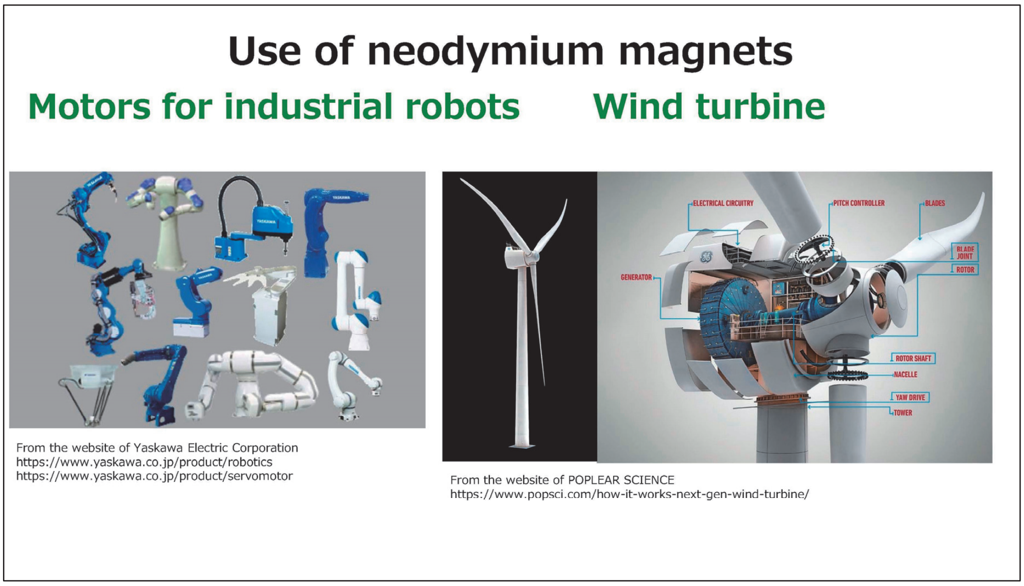


Fig. 29

〈Fig. 29〉 Then, robots. Neodymium magnets are being used in many robots. Robots are already being used today, but the use of robots will be increased in the future. I believe that there will be an era in which robots are seen not only in industrial settings but everywhere in our daily life. Neodymium magnets are also used in wind power generation to improve efficiency. In fact, they are essential for offshore wind power generation. There are so many uses of this magnet.

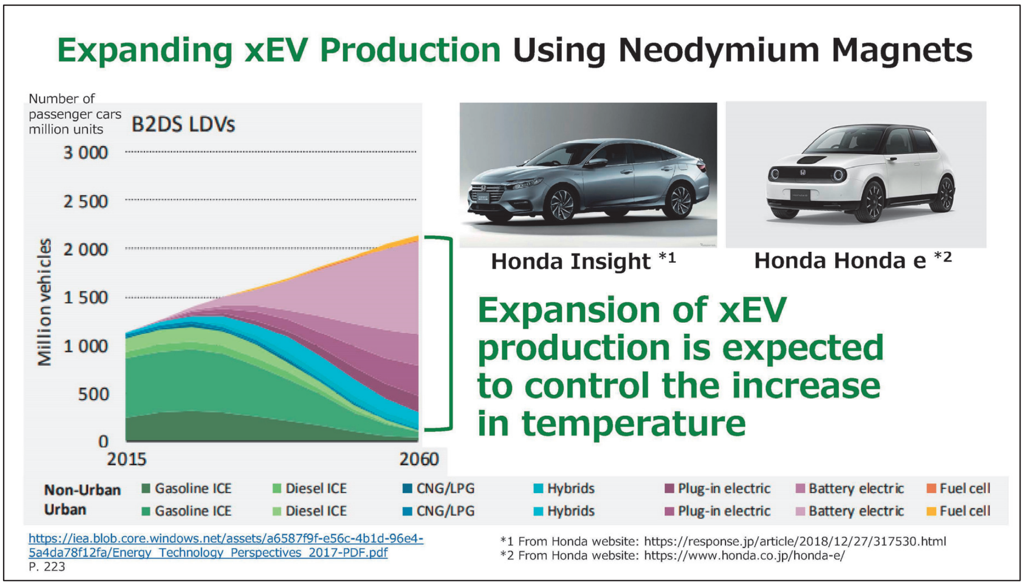


Fig. 30

〈Fig. 30〉 Next is automobiles. Many neodymium magnets are used in Honda's xEVs. This graph shows the production of hybrid vehicles in light blue and full EVs in the purple area above the light blue. Full EV production is expected to increase this much. We expect that by 2060 most will be EVs or hybrids. As I explained earlier, neodymium magnets are making a major contribution to these areas as well.

■ Scientist, such a wonderful profession!

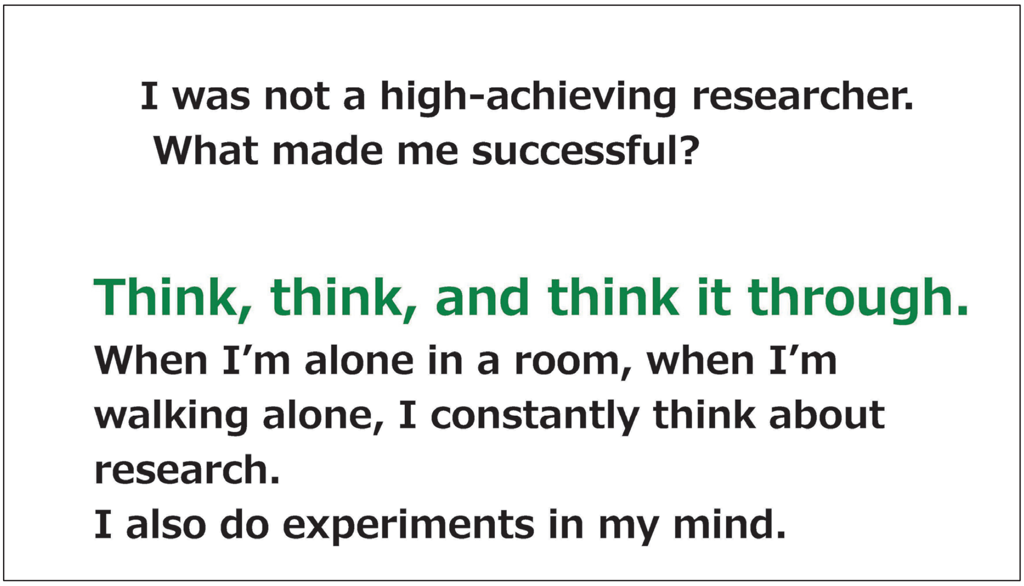


Fig. 31

〈Fig. 31〉 Despite my success in my career, as I mentioned before, I was not a high-achieving researcher. I really did not have confidence. How did I succeed in such a situation, you may ask? I believe it is because of my habit of thinking a lot. I think, think, and think it through. When I am alone in a room, when I am walking alone, I constantly think about my research. I also do experiments in my head. I am always thinking about many things and even doing experiments in my head. I have developed that kind of habit throughout my life.

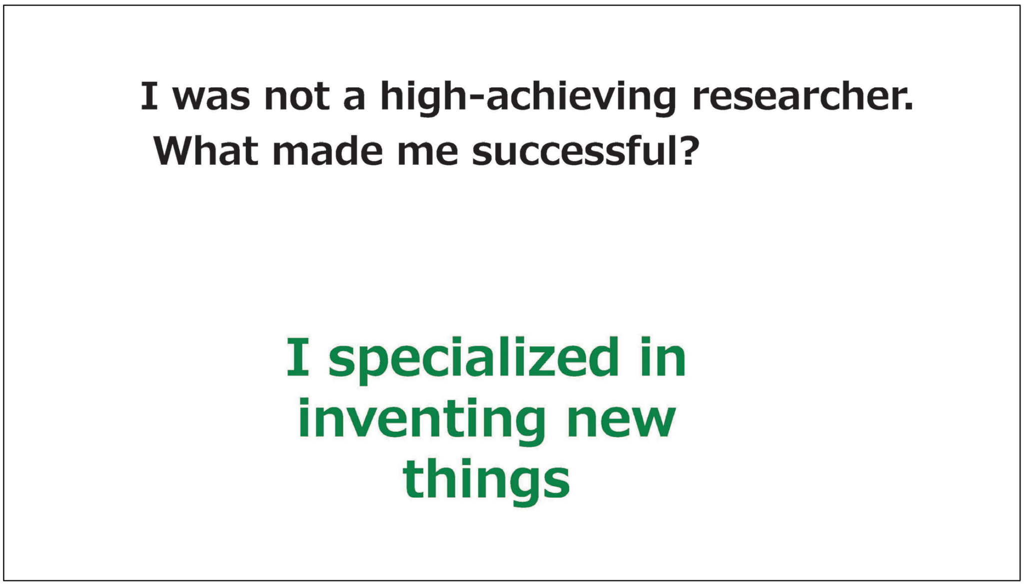


Fig. 32

〈Fig. 32〉 Also, I am good at making things. I like and am good at making experimental equipment, making samples, and mixing various alloys. I think this kind of skill is very important.

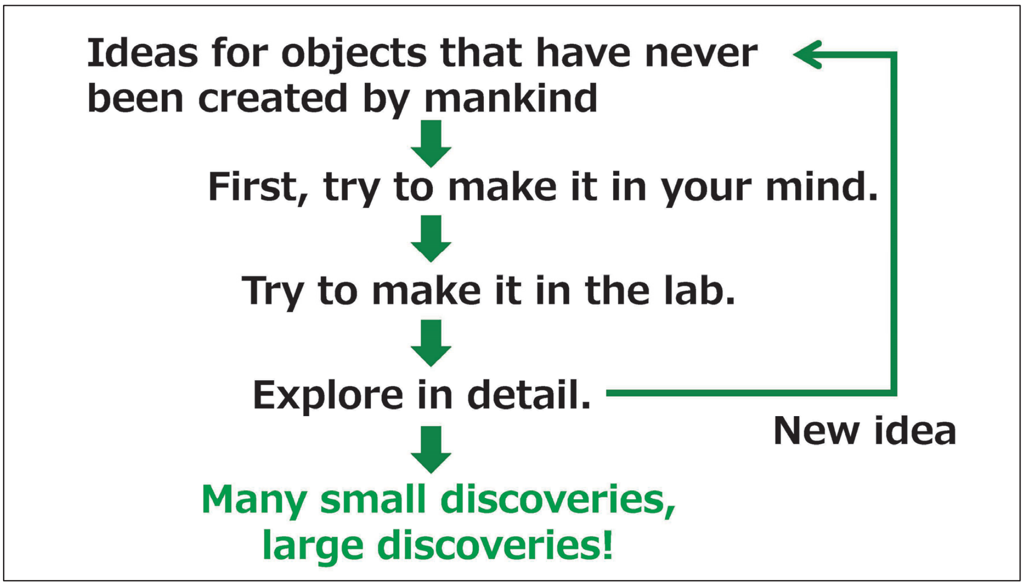


Fig. 33

〈Fig. 33〉 When you have an idea for something that has never been made before, first try to make it in your head. Then, examine it in detail. If it does not turn out to be a good idea, try again. Repeat this cycle over and over again. Great discoveries and inventions come from such a cycle.

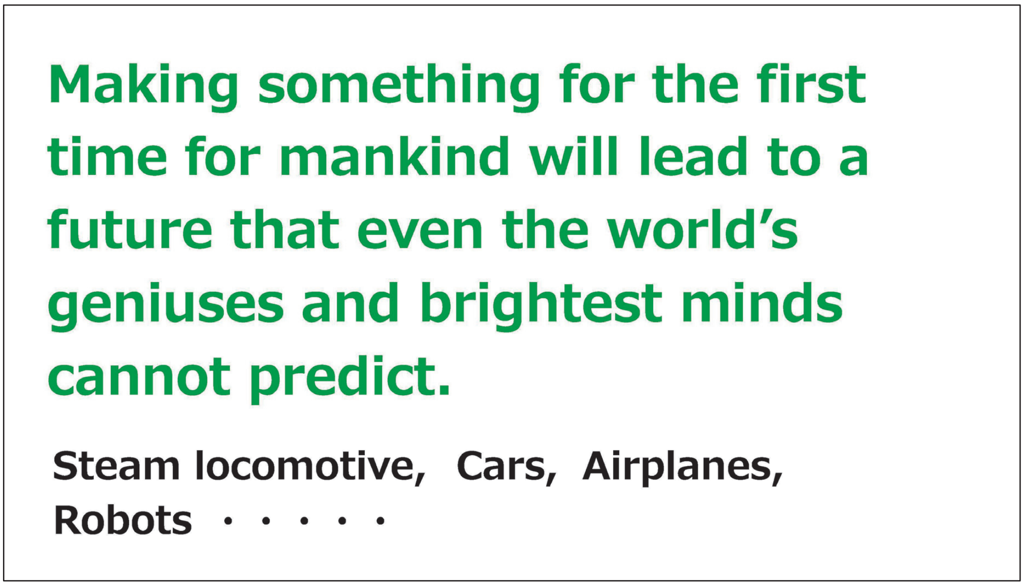


Fig. 34

〈Fig. 34〉 When you are the first human being to make something new, the future unfolds in a completely unpredictable way to the geniuses and brilliant minds in the world. I am neither a genius nor a brilliant person, but I was able to find something this big. I think I could do this through my endless endeavor in trying to make new things. This may be an exaggeration, but for example, James Watt invented the steam engine. I believe that the Industrial Revolution took place because he actually made it, and I believe that he must have been surprised. It is very important to always try making things. Even automobiles. Japanese people are particularly good at making things, and I hope that they will leverage this ability to discover new things.

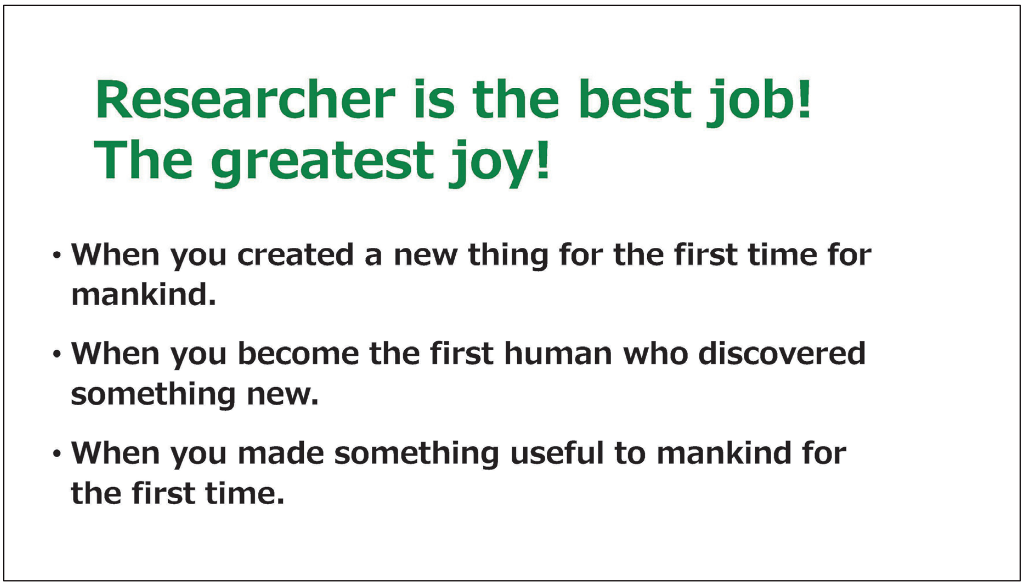
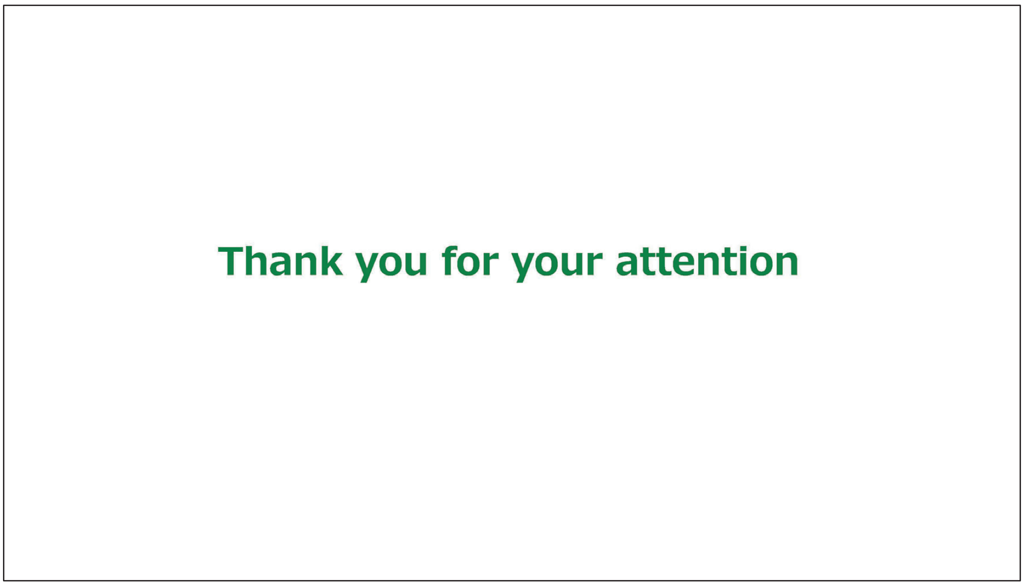


Fig. 35

〈Fig. 35〉 Being a researcher is the best job and it gives us the greatest joy. I am very happy when I become the first person to make something new. I am also thrilled when I become the first person to discover something new, or when I create something useful for the first time. There is no other such wonderful profession. I want all young people to aspire to become scientists. I don’t think there is any other profession as wonderful as a scientist.



Thank you for your attention.

Dr. John J. Croat

Former President, John Croat Consulting Inc

■Date of Birth

May 23, 1943, Iowa, U.S.A.

■Education and Qualifications

1965: BA Degree, Simpson College, Indianola, Iowa, U.S.A.

1968: MS Degree, Iowa State University, Ames, Iowa, U.S.A.

1972: PhD Degree, Iowa State University, Ames, Iowa, U.S.A.

■Employment History

1972-1980: Research Metallurgist, General Motors Research Labs., Warren Michigan (USA).

1980-1984: Senior Research Metallurgist, GM Research Labs., Warren Michigan.

1984-1986: Asst. Chief Process Engineer, Delco Remy Div. GM Corporation

1986-1990: Chief Engineer, Magnequench, Delco Remy Div., GM Corporation

1990-1996: Managing Director, Magnequench, Delco Remy Div., GM Corporation

1996-2004: President, Advanced Magnetic Materials (AMM) Korat, Thailand

2004-2017: President, John Croat Consulting Inc.

■Prize and Honors

1985: Applications of Physics Prize, American Institute of Physics

1985: Distinguished Alumni Award, Iowa State University

1986: International Prize for New Materials, American Physical Society (now James C. McGroddy Prize for New Materials)

1994: Outstanding Engineering Achievement Award, American Society of Metals

2022: IEEE Award for Environmental and Safety Technology

■Major Publications

- Books

1. Rapidly Solidified NdFeB Permanent Magnets, Elsevier Published, Published 2018.
2. Modern Permanent Magnets, Elsevier Publishing, Published 2022. Co-edited with John Ormerod.

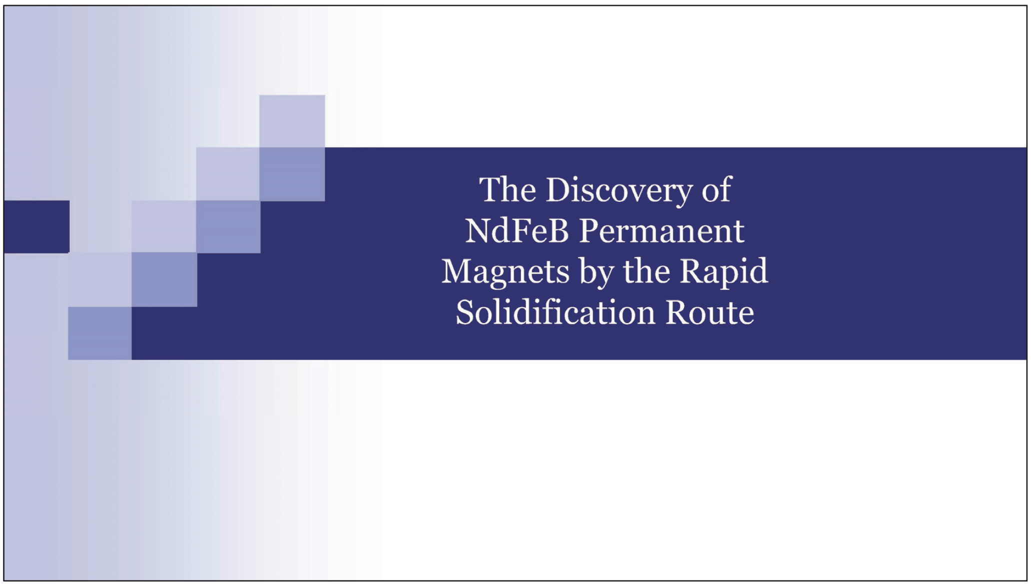
- Journal Publications

1. High Energy Product Nd-Fe-B Permanent Magnets, Appl. Phys. Lett. 44(1), 148 (1984).
2. Pr-Fe and Nd-Fe-based Materials: A New Class of High-Performance Magnets, J. Appl. Phys. 55(6), 2078 (1984).
3. Relationship Between Crystal Structure and Magnetic Properties in Nd2F214B, Phys. Rev. B, 29(7), 4126 (1984).
4. Structural and Magnetic Properties of Nd2Fe14B, J. Appl. Phys. 57(1), 4086 (1984).
5. Manufacture of Nd-Fe-B Permanent Magnets by Rapid Solidification, J. Less Common Metals, 148, 7 (1989)

This report is the gist of the commemorative lecture at the 44th Honda Prize Award Ceremony at the Imperial Hotel, Tokyo on 16th November 2023.

The Discovery of NdFeB Permanent Magnets by the Rapid Solidification Route

Dr. John J. Croat



Good afternoon. It is a pleasure to be with you today, even if it is just through this video. The title of my presentation is "The Discovery of NdFeB Permanent Magnets by the Rapid Solidification Route."

To begin, I want to thank the Honda Foundation for giving me the opportunity to present a brief overview of my research work covering the discovery of NdFeB permanent magnets. I would also like to thank them again for choosing myself and my colleague Masato Sagawa to receive this prestigious award.

Fig. 1

〈Fig. 1〉 I began my material science career when I was accepted into graduate school at the Department of Metallurgy at Iowa State University in Ames, Iowa in 1965. Located on the university campus was the Ames Laboratory, one of the several national research laboratories that had been established by the government to foster scientific research as well as train future scientists. At that time in the mid-1960s, the Ames Laboratory was the leading center in the world for research on rare earths. The first processes for separating the rare earths were developed at this laboratory in the late 1950s. At that time, it was the only place in the world where reasonably quantities of research-grade, high-purity rare earths were available. I joined a research group led by Dr. Frank Spedding, the director of the laboratory, that was involved with the preparation of high purity rare earths and measuring their magnetic and transport properties. It is though this research that I was introduced to the rare earths which became so important to my future scientific career.

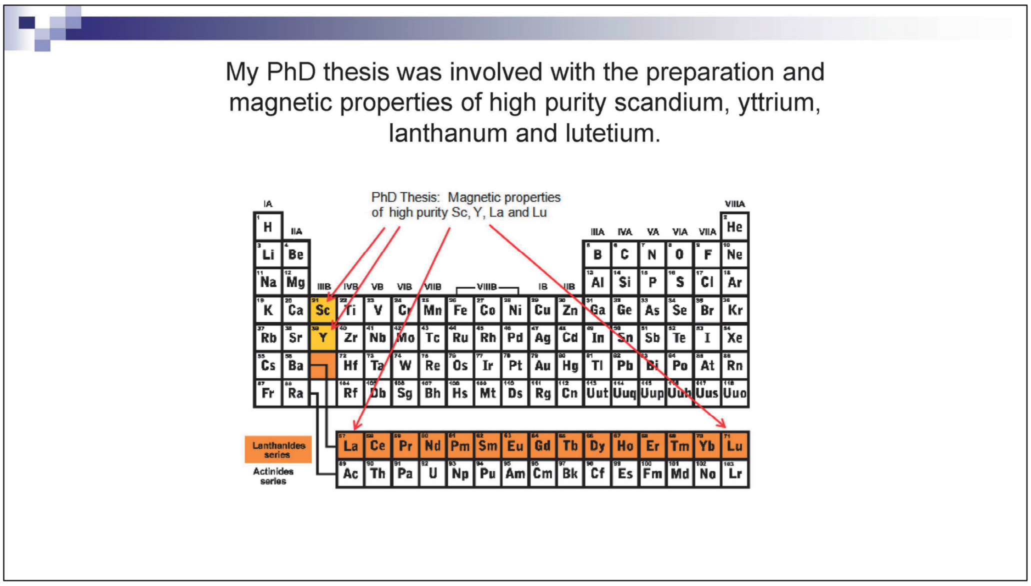


Fig. 2

〈Fig. 2〉 The rare earths or lanthanides are the next to the bottom row in the periodic table shown here. My PhD thesis involved the preparation and measuring the magnetic properties of ultra-high-purity scandium, yttrium, lanthanum, and lutetium, which I have indicated. All four of these rare earths are weakly magnetic and therefore the properties were very sensitive to impurities. For this reason, it was necessary to first prepare very high-purity specimens. Although scandium and yttrium are not part of the lanthanide series, these two elements have very similar chemical properties and are found intimately mixed with the rare earth. They are, therefore, generally considered to be one of the rare earths.

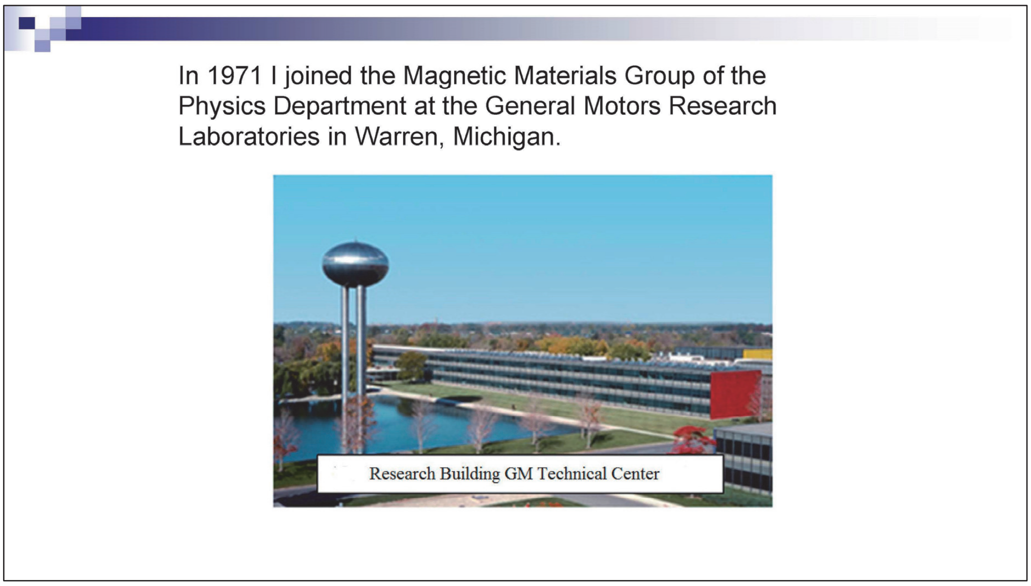


Fig. 3

〈Fig. 3〉 When I graduated with a PhD in 1972, I joined the Magnetic Materials Group of the Physics Department of the General Motors Research Laboratories in Warren, Michigan. I was the only metallurgist in the Physics Department. At that time General Motors was the world's largest auto manufacture and the world's largest user of permanent magnets, which it used in the tens of millions of motors and actuators that were used on its vehicles.

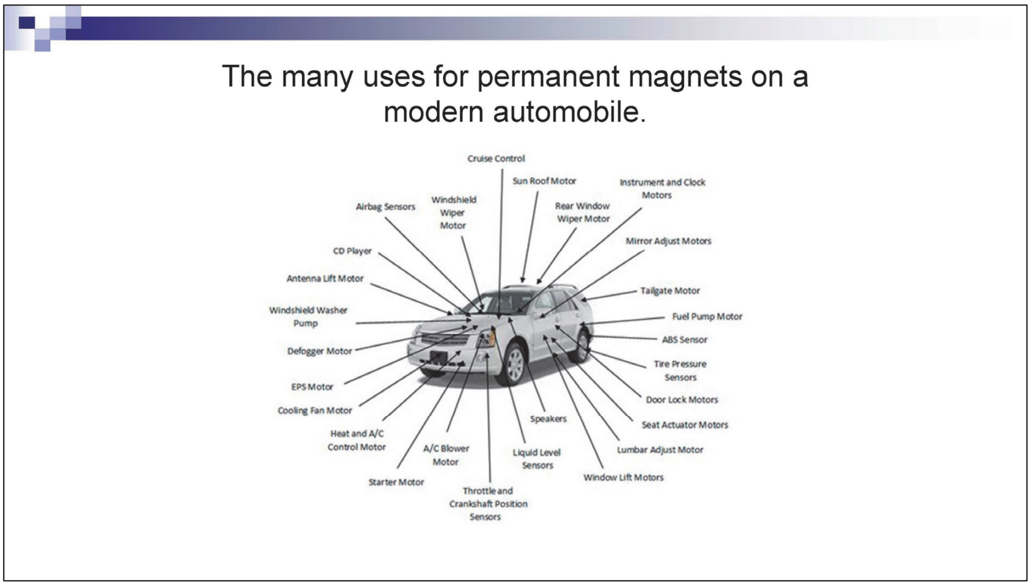


Fig. 4

〈Fig. 4〉 This slide is a somewhat outdated figure which indicates most of many different motor and actuator applications on a modern automobile that use magnets. At that time, almost all these applications used ferrite or ceramic permanent magnets, which have rather low magnetic properties. The mission of our material research group was to develop a low-cost, higher performance magnet to use in these applications that would make them smaller and lighter. The overall goal of our work was to improve the fuel economy of the automobile by reducing its weight. Just by coincidence, one year after I arrived at the GM Research Laboratory the world was confronted by the first OPEC (Organization of Petroleum Exporting Countries) oil embargo in 1973. The price of gasoline increased significantly in the US and other parts of the world and there was suddenly an even greater emphasis on increasing the fuel economy of automobiles.

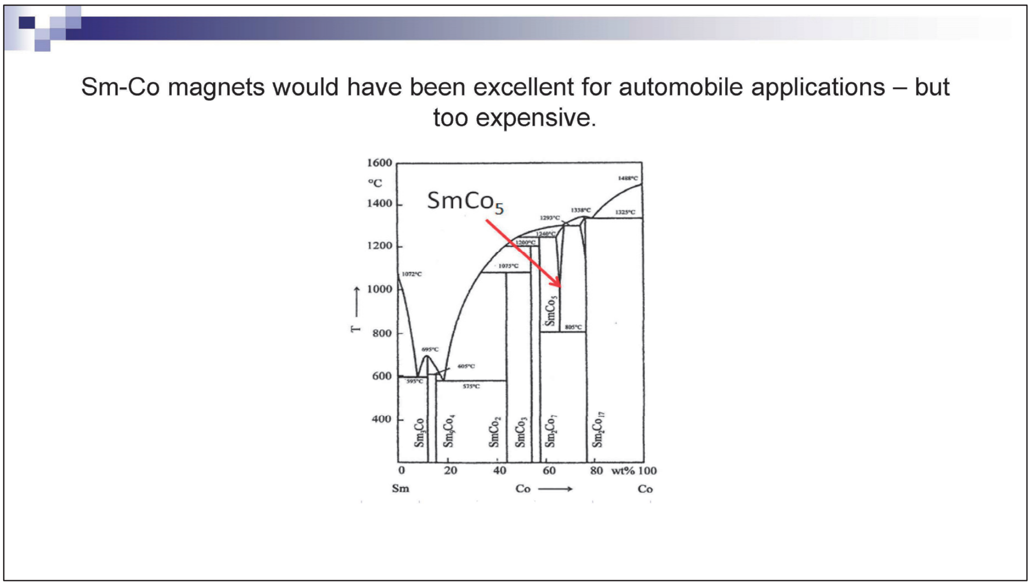


Fig. 5

〈Fig. 5〉 During the 1960s, a major development was the discovery and development of Sm-Co magnets based on the $SmCo_5$ intermetallic phase which is shown here in the Sm-Co phase diagram. As can be seen, $SmCo_5$ is just one of several intermetallic phases which form in this binary alloy system. $SmCo_5$ magnets would have worked well for automotive applications. The problem was that the magnets were too expensive for general use on automobiles because both Sm and Co are rather expensive elements. My personal goal was to invent a magnet that used one of the more abundant, lower cost rare earths combined with iron, whose cost is virtually free compared to the cost of cobalt.

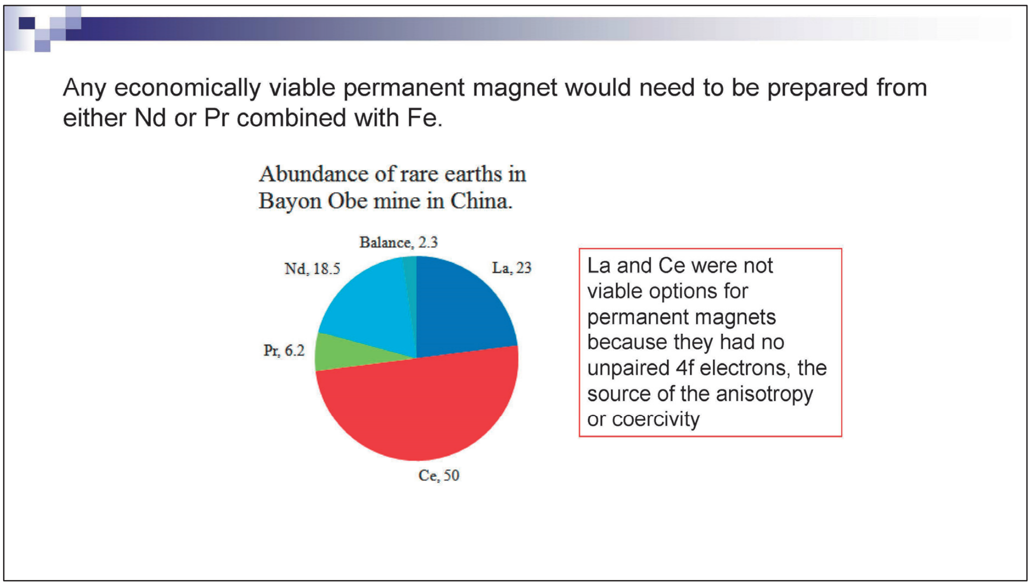


Fig. 6

〈Fig. 6〉 The only good option for producing a low-cost rare earth magnet was to use one of the rare earths Nd or Pr. The reason for this is shown in this pie chart which displays the relative abundance of the rare earths. This data happens to be from the world's major rare earth mine, the Bayon Obe mine at Baotou, China. However, the relative abundance in other mines is nearly the same. We see that the four rare earths, La, Ce, Pr and Nd, constitute over 97% of the rare earth content. All researchers in this field knew that any cost-effective RE-Fe magnet had to be produced from one of these four elements. However, we also knew that La and Ce, the two most abundant rare earth elements, would not make a good magnet because they did not possess any 4f electrons, the source of the anisotropy or coercivity in rare earth-transition metal magnets. Consequently, we knew that any economically viable magnet had to be produced from either Nd or Pr in combination with iron, the only feasible magnetic transition metal element.

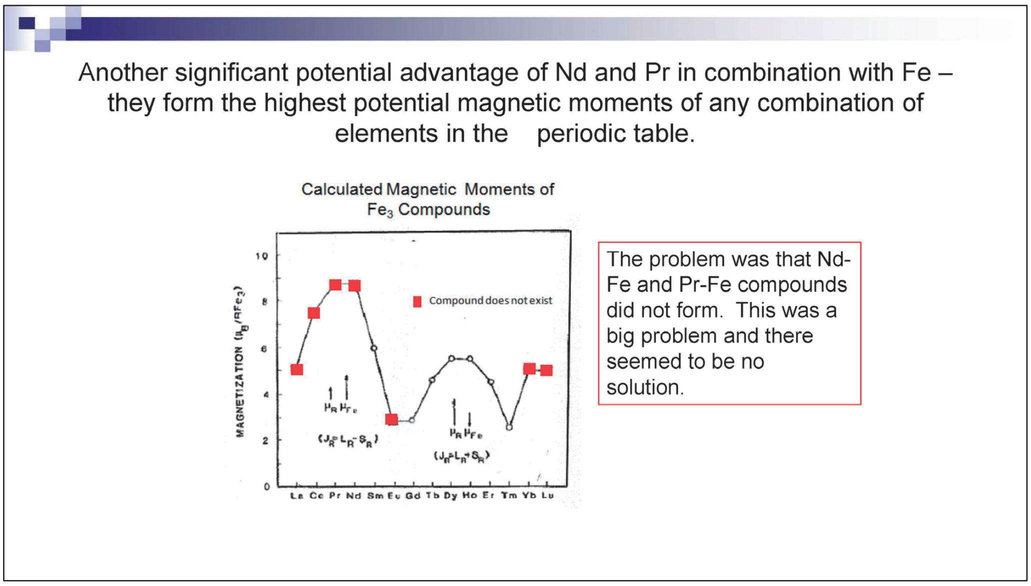


Fig. 7

〈Fig. 7〉 There was another significant potential advantage of Nd and Pr in combination with Fe. In theory, any compound or intermetallic phase would have the highest potential magnetic moments of any combination of elements in the periodic table. This is displayed here in the figure which shows the calculated magnetic moments for a series of RFe_3 compounds. The reason for the difference shown here is that the RE and Fe magnetic moments align parallel for the first half of the 4f series. what are known as the light rare earths, but anti-parallel in the second half of the 4f series, what are known as the heavy rare earths. The problem was that compounds like RFe_3 did not exist as indicated in this figure. Although some intermetallic RE-Fe phases form for some of the heavy rare earths, none existed for Nd and Pr. At this time, we knew that a suitable intermetallic phase like $SmCo_5$ was an essential and fundamental requirement for a rare earths-transition metal permanent magnet and the lack of a suitable intermetallic phase seemed like an intractable problem. There seemed like no solution.

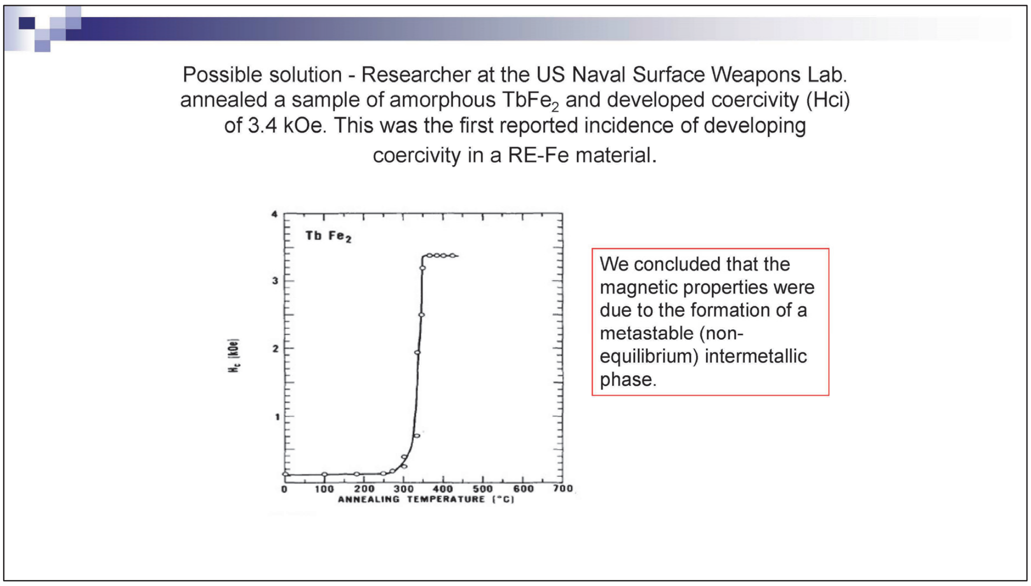


Fig. 8

〈Fig. 8〉 Although this problem of not having a suitable intermetallic phase seemed like an unsolvable problem, one day I noticed a publication that I thought might provide a solution. A researcher at the Naval Surface Weapons Laboratory was investigating amorphous RE-Fe alloys as potential acoustic detectors to locate Soviet era submarines. He found that when he annealed an amorphous $TbFe_2$ alloy that had been prepared by sputtering, the sample developed a respectable coercivity of 3.4 kOe. To my knowledge, this was the first time anyone had developed coercivity in a Re-Fe alloy. I discussed this paper with my colleagues Jan Herbst and John Keem and we all agree that the magnetic hardening was likely due to the development of a metastable or non-equilibrium phase during the annealing process of the amorphous materials.

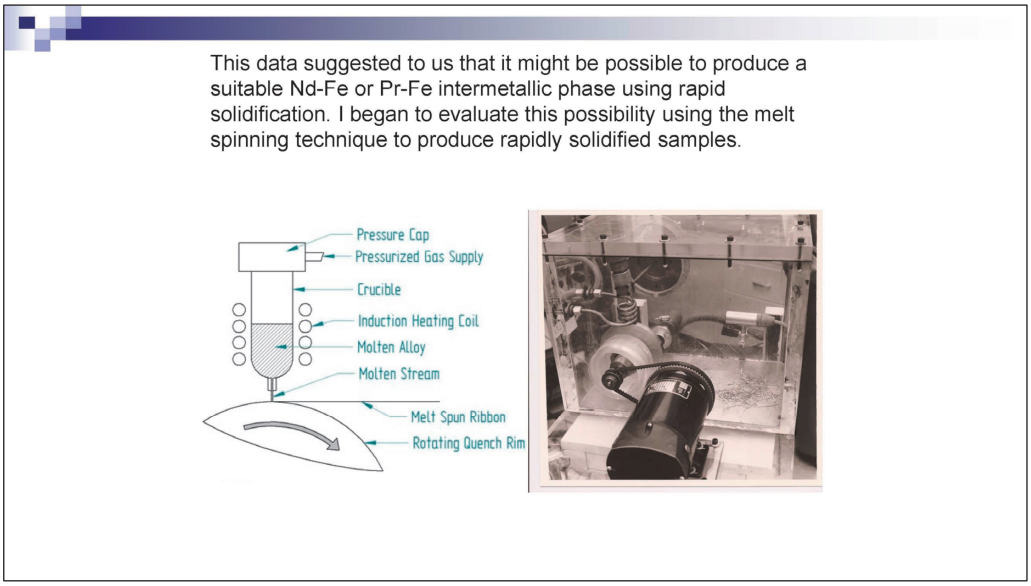


Fig. 9

〈Fig. 9〉 This publication became the genesis of my research, and I began to study the possibility of producing Nd-Fe or Pr-Fe permanent magnets by annealing rapidly solidified samples. I decided immediately that preparing rapidly solidified samples by sputtering was impractical and decided to use the melt spinning technique instead. This technique, which is shown in this slide, was somewhat new at the time and involved directing a stream of molten alloy onto the surface of a cold rotating disk. This figure also shows the first laboratory melt spinner that I built at the Research Laboratories. It had a 15 cm diameter solid copper quench wheel whose rotational speed could be precisely and easily controlled. Because of the small sample size that I used, the crucible was capped, and the molten alloy forced from the crucible with a blast of pure argon. Of course, the entire process had to be carried out in a vacuum chamber that was evacuated and back filled with high purity argon because all rare earth materials are subject to oxidation. It took me over a year to get this device built and get it to work.

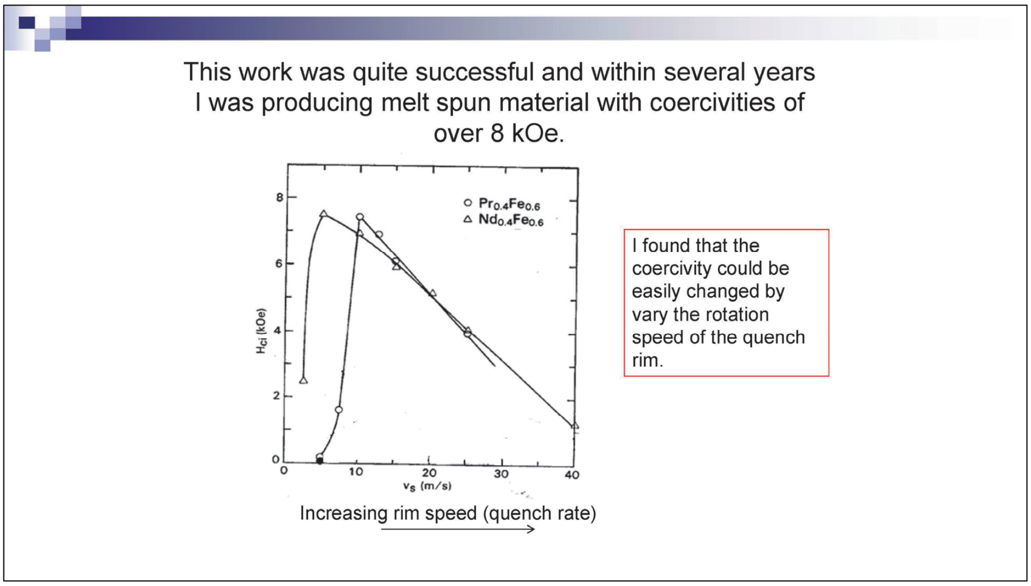


Fig. 10

〈Fig. 10〉 Once I got the melt spinner working, this work was quite successful and within several years I was producing melt spun Nd-Fe and Pr-Fe materials with coercivities over 8 kOe. I found that the coercivity could be easily changes by simply changing the rotational speed of the quench wheel. Moreover, it was determined that the magnetic properties resulted from the formation of metastable intermetallic phases as I had hoped. One problem was that these phases did not have high thermal stability and would decompose into equilibrium phases when heated above about 350^{o}C. At this point the coercivity would vanish. Like most material scientists, I began to add various elements to my materials to see if I could change their properties. One of the groups of elements that I investigated was the so called "glass forming elements" which include silicon, carbon and boron, because these elements were reported to modify the behavior of rapidly solidified alloys. Somewhat unexpectedly, one day I found that I had produced a material that exhibited unusual magnetic properties. After several weeks of study, I found that this material consisted of an unknown stable ternary Nd-Fe-B intermetallic phase. So, in the process of looking for possible metastable phases I had discovered a very important stable ternary NdFeB intermetallic phase.

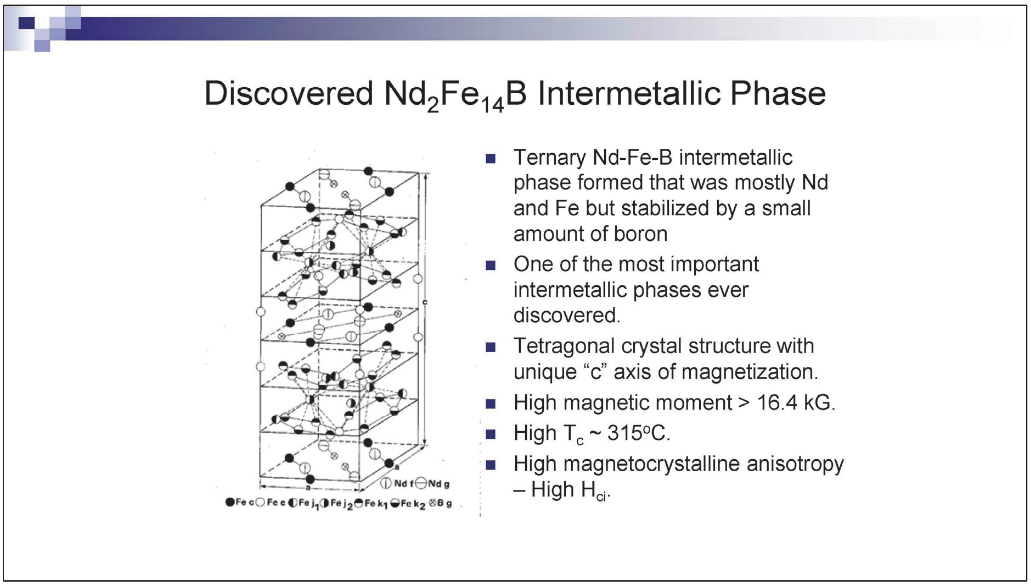


Fig. 11

〈Fig. 11〉 We eventually determined from neutron diffraction analysis that this new intermetallic phase that had a uniaxial tetragonal crystal structure that consists mostly of Nd, or Pr, and iron stabilized by a very small amount of boron. The crystal structure of this compound is shown here and has the formula $Nd_2Fe_{14}B$. It was found to have a very high magnetic moment of 16.4 kG, the highest ever found for any rare earth compound, combined with an acceptable Curie temperature of 315^{o}C and reasonably high magneto crystalline anisotropy, the property that provides the coercivity to the magnet. Therefore, this compound had all of the important properties necessary for producing a rare earth permanent magnet. Moreover, it has a low RE/Fe ratio. Since the Fe has much lower cost that the rare earth, this provided a low direct material cost. This intermetallic phase has turned out to be the most important rare earth magnetic phase discovered to date and is the basis of all families of NdFeB permanent magnets today.

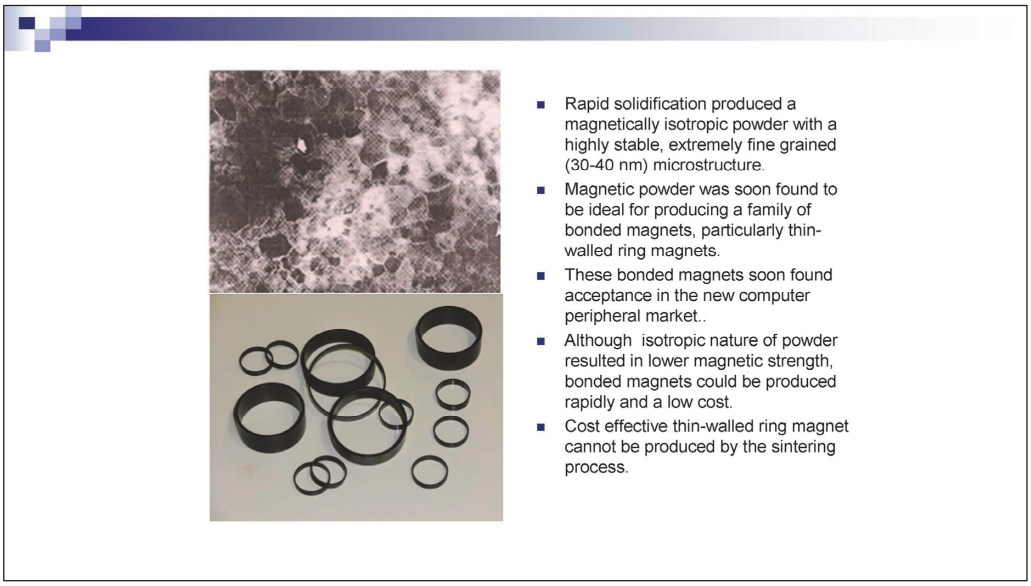


Fig. 12

〈Fig. 12〉 Early studies of the melt spun materials found that they consisted of an extremely fine grained, microstructure of magnetically isotropic $Nd_2Fe_{14}B$ grains. We soon found that this magnetic powder could be easily processed into very stable bonded magnets. In particular, we found that the thin-walled ring magnets could be produced quite easily and that these thin-walled rings were something that was being sought by small motor manufacturers. Because the magnetic powder was magnetically isotropic, the magnetic strength was lower than for anisotropic sintered NdFeB magnets. However, these thin-walled ring magnets are one of the products that are difficult to produce using the sintering process. The first companies to use this powder to produce their own magnets were Japanese small motor manufacturers.

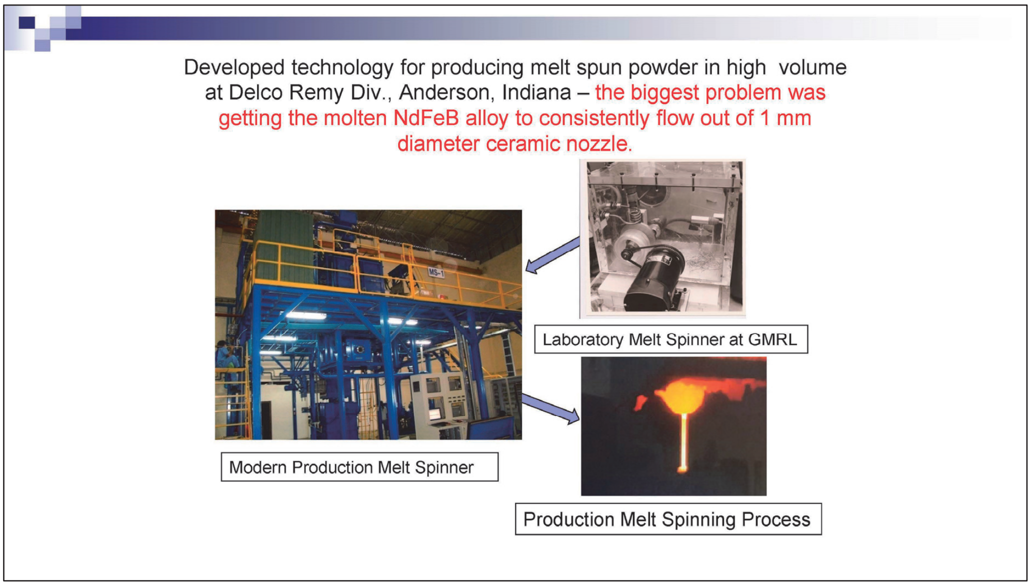


Fig. 13

〈Fig. 13〉 In 1984 I transferred to the Delco Remy Division of General Motors to help develop rapidly solidified NdFeB magnets. We found that it was quite difficult to produce melt spun NdFeB powder in high volume. The melt spinner was both difficult to start and, once started, it was difficult to keep them running. The molten alloy simply did not want to flow through the small 1 mm diameter orifice of the nozzle that we were using. However, after about two years of development we had managed to build and commission a production melt spinner that was capable of running for up to 36 hours straight and was capable of producing 2,000 kg of melt spun powder for each production run.

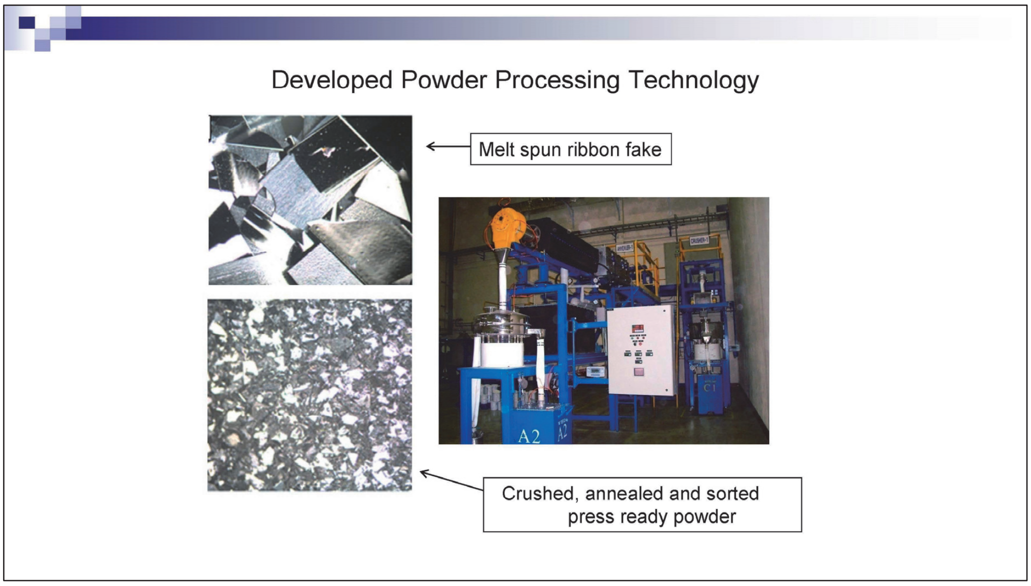


Fig. 14

〈Fig. 14〉 We also had to develop the technology needed to convert the powder, which consisted of a flake-like ribbon shown here, into a powder that could be easily used to produce bonded magnets. This powder processing system is shown here and consisted of a crusher to first crush the melt spun ribbon flake into a powder. This powder was then the annealed and sorted to produce a press ready powder which was sold to customers who wanted to make their own magnets.

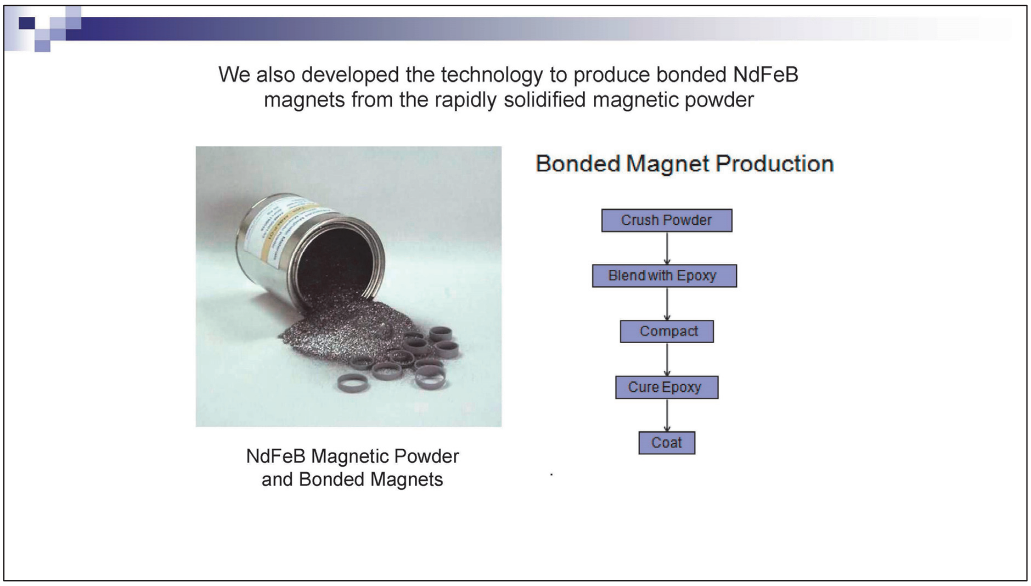


Fig. 15

〈Fig. 15〉 Finally, we also developed the technology to produce bonded magnets in high volume. Most of this development was directed at the production of ring magnets for small motors. The steps in the process were simple, consisting of blending the powder with a thermoset epoxy, compacting the part in a hydraulic or mechanical press, and then coating the magnet to prevent corrosion.

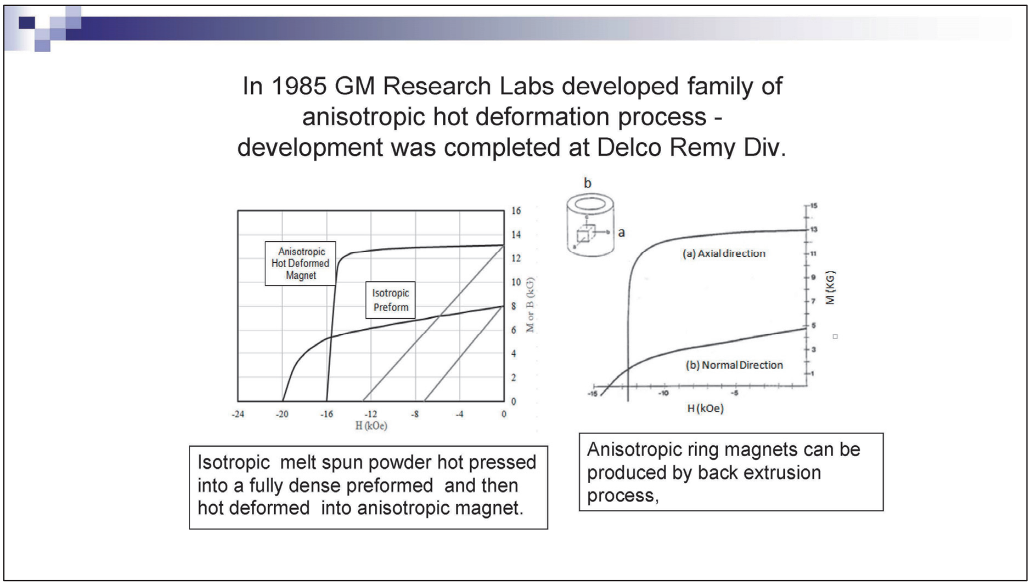


Fig. 16

〈Fig. 16〉 In 1985 the GM Research Labs had also discovered that a family of anisotropic magnets could be produced from the rapidly solidified powder by a hot deformation process. This process involved first hot-pressing the melt spun powder into a fully dense preform and then hot deforming the preform into an anisotropic magnet with properties similar to those obtained by the sintering process. The change that occurs in the magnetic properties is shown in the left-hand figure. Significantly, this hot deformation process was capable of producing radially oriented ring magnets by a back extrusion process shown here on the right. This is another product that is very difficult to produce using the sintering process. This development of these hot deformed magnets was completed at the Delco Remy Division.

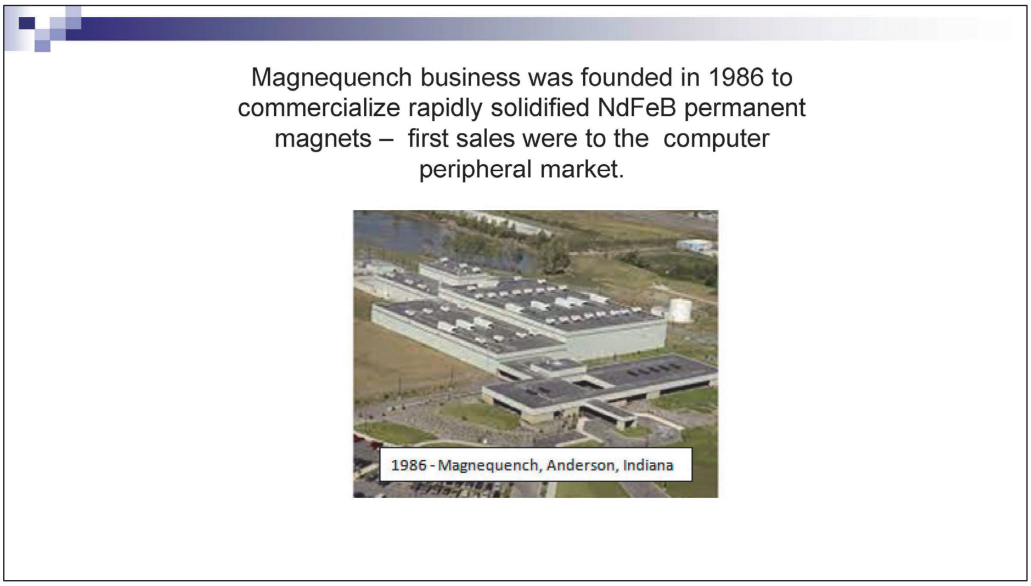


Fig. 17

〈Fig. 17〉 In 1986 General Motors founded the Magnequench business unit at Delco Remy to commercialize NdFeB permanent magnet materials. This shows a photo of the factory that was built in Anderson, Indiana. It took several years to build and commission this factory. The first sales were for the computer peripheral market.

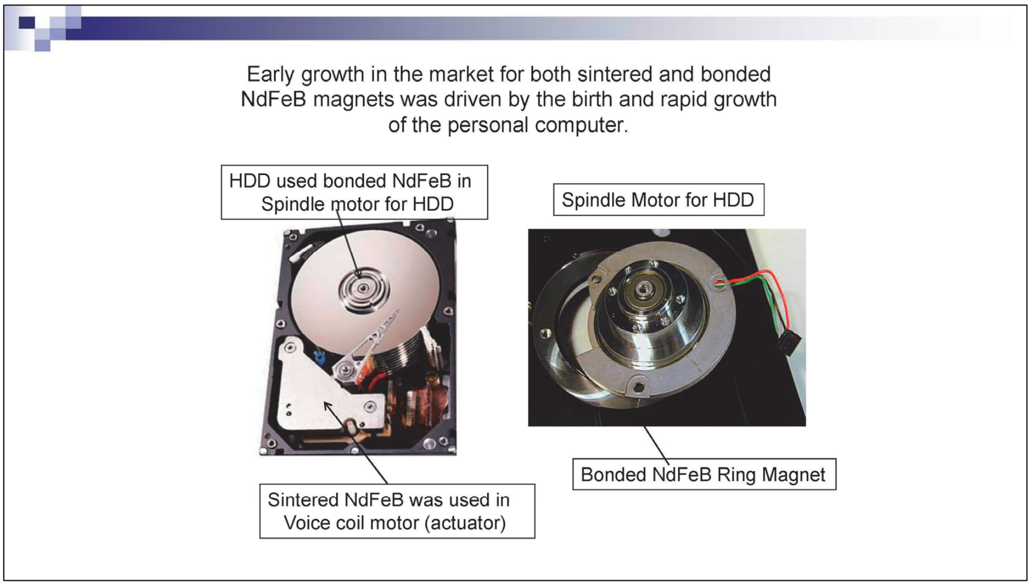


Fig. 18

〈Fig. 18〉 The first Magnequench sales occurred in the late 1980s. The market growth of both sintered and bonded NdFeB was greatly accelerated by the development and growth of the nascent personal computer market. These computers all used an HDD that used a bonded NdFeB magnet in the spindle motor which rotated the magnetic recording disks and a sintered NdFeB magnet in the voice coil motor, which is actually an actuator which moves the read/write head over the disk to record and retrieve date. Shown here on the left is a photo of a typical HDD showing the location of the spindle motor and voice coil actuator. On the right is shown a spindle motor that has been opened to observe the bonded ring magnets used in this type of motor.

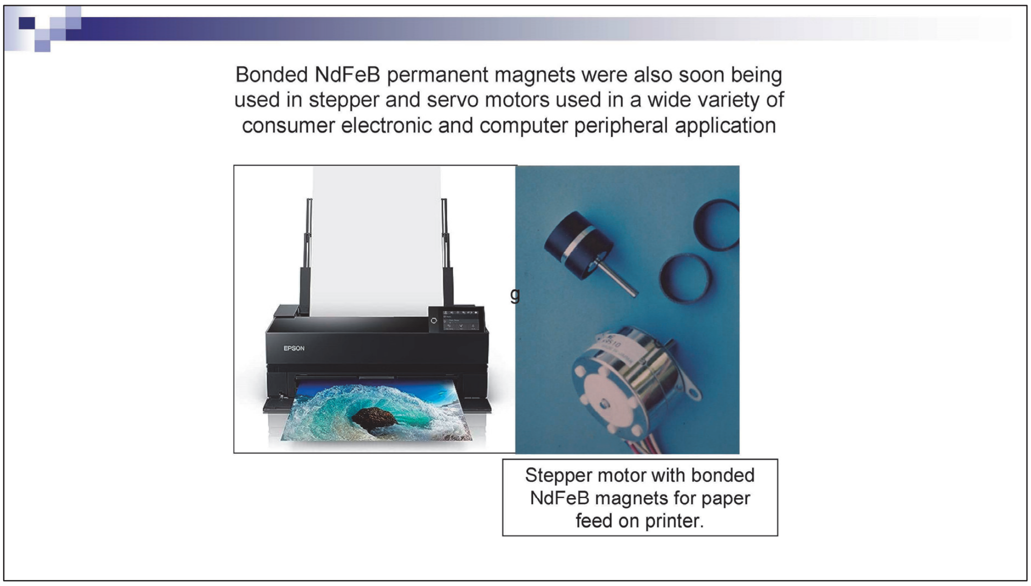


Fig. 19

〈Fig. 19〉 Bonded NdFeB permanent magnets were also soon being used in stepper motors and servo motors used in a wide variety of consumer electronic and computer peripheral applications. The example shown here is for a stepper motor used for the paper feed on a printer. Again, most of the applications involved the use of thin-walled ring magnets.

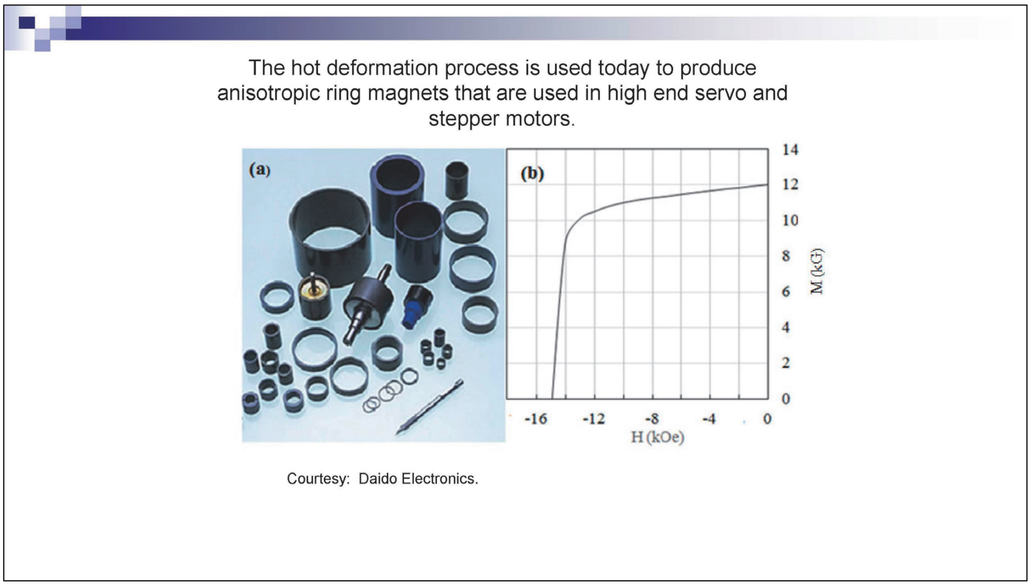


Fig. 20

〈Fig. 20〉 The hot deformation process began to be used to produce anisotropic ring magnets that are used in high-end servo and stepper motors. Shown here is a family of small radially oriented ring magnets produced by the Japanese company Daido Electronics. These magnets have been cut from tubes produced by the back extrusion process.

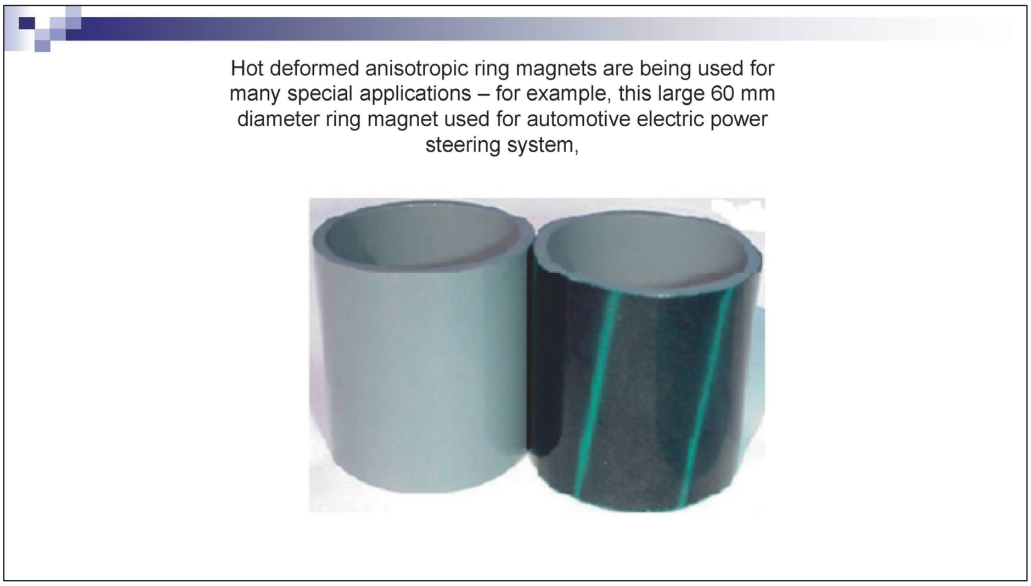


Fig. 21

〈Fig. 21〉 Although most of the hot deformed rings are targeted for smaller motors, the hot deformation process is also amenable to the production of larger ring magnets, for example, this 60 mm diameter back extruded ring magnet used for an automotive electric power steering system.

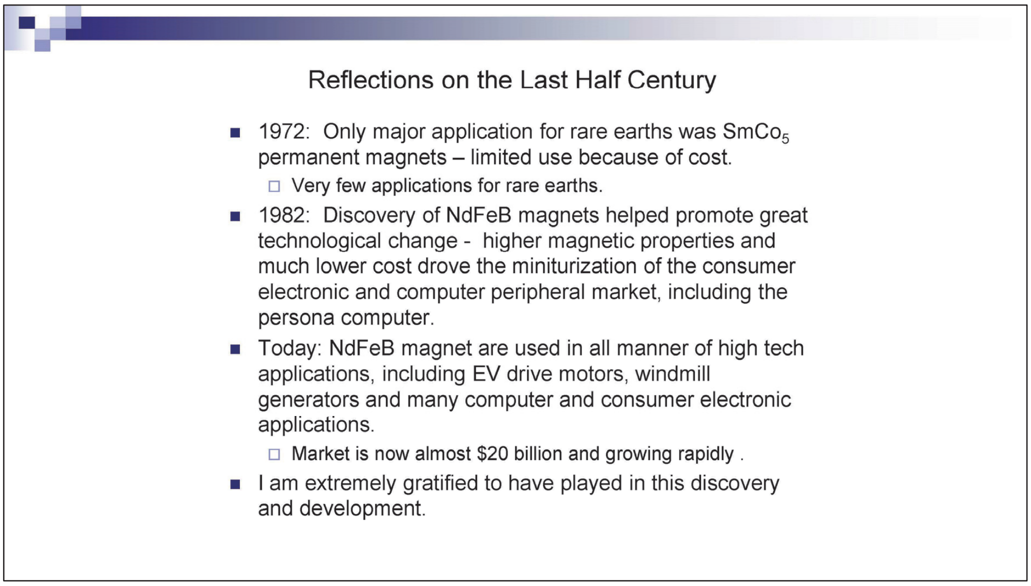


Fig. 22

〈Fig. 22〉 It has now been a half century since I completed my graduate studies in 1972. Over this period there has been an almost impossible technological change and the discovery of NdFeB magnets in 1982 almost certainly helped promote this great technological change. Their higher magnetic properties at much lower cost drove the miniaturization of the consumer electronic and computer peripheral market and were a key to the development of the personal computer. Today NdFeB magnet are used in all manner of high-tech applications, including EV drive motors, windmill generators and many computer and consumer electronic applications.

I am extremely pleased and gratified to have played in this discovery and development. Thank you.

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