WRIGHT LABORATORY
MATERIALS DIRECTORATE

WL LEGACY PROJECT CANDIDATE

Rare Earth Permanent Magnet

A Wright Laboratory Materials Directorate Development

Distribution Unlimited (ASC-97-2391)

RARE EARTH PERMANENT MAGNETS

- An excellent example of a Wright Laboratory inhouse ***revolutionary*** discovery and of an extremely successful sponsored industrial partnership for development and weapons system insertion

- Used in every Air Force and DoD aircraft, missile, satellite, submarine, torpedo, etc., typically as an ***enabling technology*** providing significant new DoD mission capability

- Significantly better, lighter, smaller, cheaper, and easier to assemble into products

RARE EARTH PERMANENT MAGNET PRESENTATION OUTLINE

- Major Air Force and Commercial Applications
- History and Significance of the Inhouse Discovery
- Milestones
- Industry Testimonials
- Little Known Facts About Permanent Magnets
- Summary of Wright Laboratory Involvement

Study Methodology

- Data Collected by Two of the Industry Founders
  - Marlin Walmer, President and Founder of Electron Energy Corp., a Manufacturer of High End Magnet Materials Used in Numerous Weapon Systems
  - Professor Emeritus Alden E. Ray of the University of Dayton, Co-Discover With Karl Strnat of Sm_2Co_{17}
- Analysis of Questionnaire Responses Received From Nearly 40 Companies and Site Visit Information Documented in Their 500 Page Report WL-TR-95-4065

PRODUCTS BASED ON SAMARIUM COBALT MAGNETS

- Satellite Communication Traveling Wave Tubes (TWTs)
  - Over 2,300 units from Hughes alone have been launched into space on 1600 launches (microwave/radar tubes)
- Missile Accelerometers, Gyros, Inertial Reference Systems
  - In 10,000 missiles and launch vehicles from Northrop alone
- Aircraft TWTs for EW Environments And Tactical Radar
  - Over 43,000 MINI-TWTs from Varian alone for hostile EW
  - F-16 radar TWTs, APG-66, APG 68, F-18 radar TWT, APG-65
- Aircraft Fly-By-Wire and More Electric Aircraft (MEA)
  - Stealth Bomber and NC-141A Electric Starlifter
- Many Commercial Spinoffs, Examples
  - Largest is TV via stationary (HEO) satellites using TWTs
  - Dental and surgical power tools
  - Hundreds of US manufacturing jobs

Reference WL-TR-95-4065

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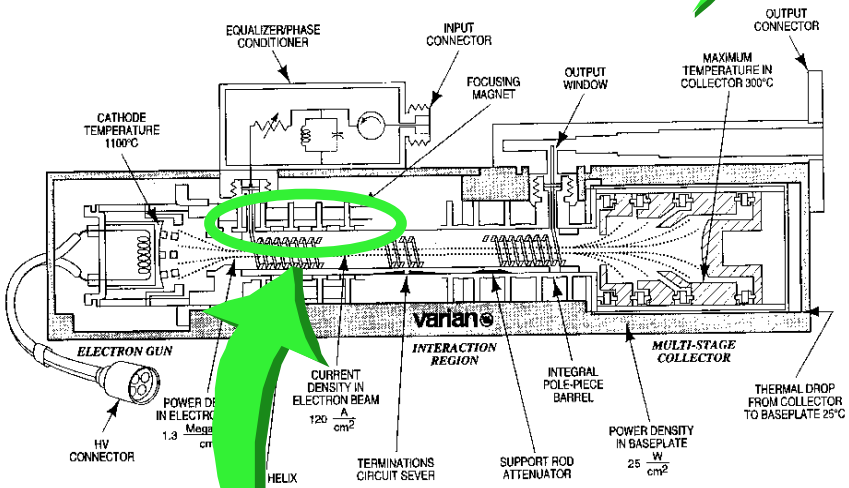
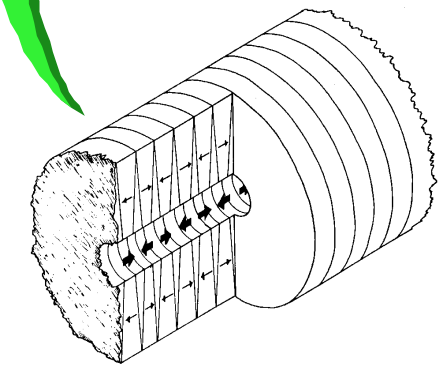
Sm Co TRAVELING WAVE TUBES (TWT) FOR SPACE COMMUNICATIONS, ECM & RADAR

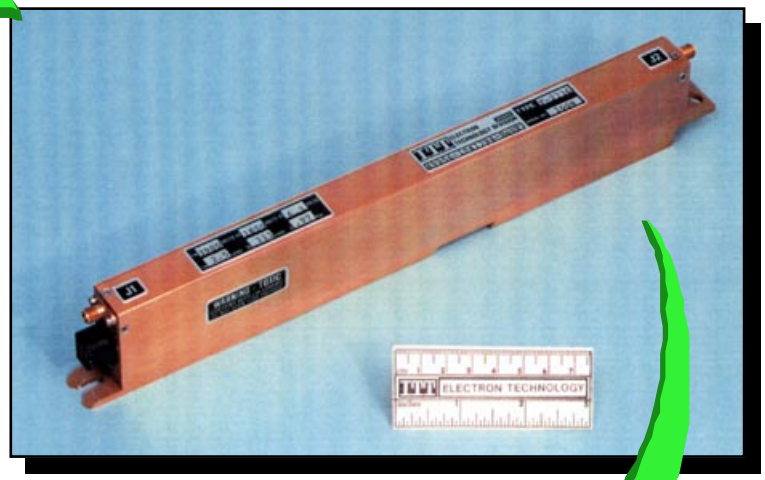
Traveling Wave Tube





Periodic Permanent Magnet (PPM) Stack

Hughes Tubes on 1600+ Space Shots



Voyager/VGER

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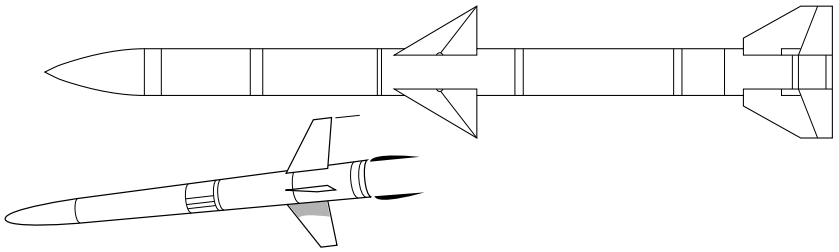
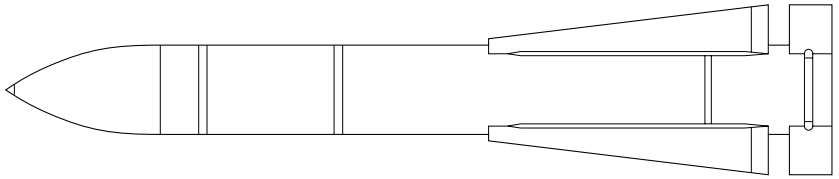
Sm Co MISSILE GUIDANCE AND LAUNCH VEHICLE APPLICATIONS

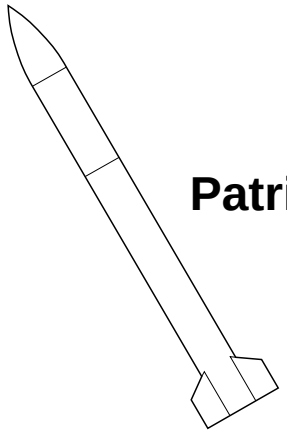
Enabling Sm Co gyros and accelerometers for more than 10,000 missiles supplied by Northrop alone (WL-TR-95-4065)



Advanced Medium Range Air-to-Air Missiles (AMRAAM)



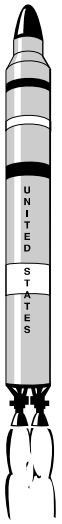
Phoenix Long Range Air-to-Air Missiles

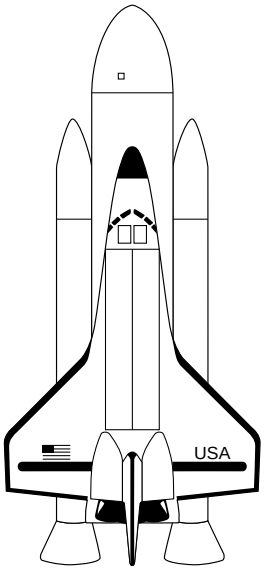


Patriot

Launch Vehicles

- **Titan**
- **Shuttle**
- **Delta**





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Sm Co FLY-BY-WIRE AND MORE ELECTRIC AIRCRAFT APPLICATIONS

Fly-by-Wire

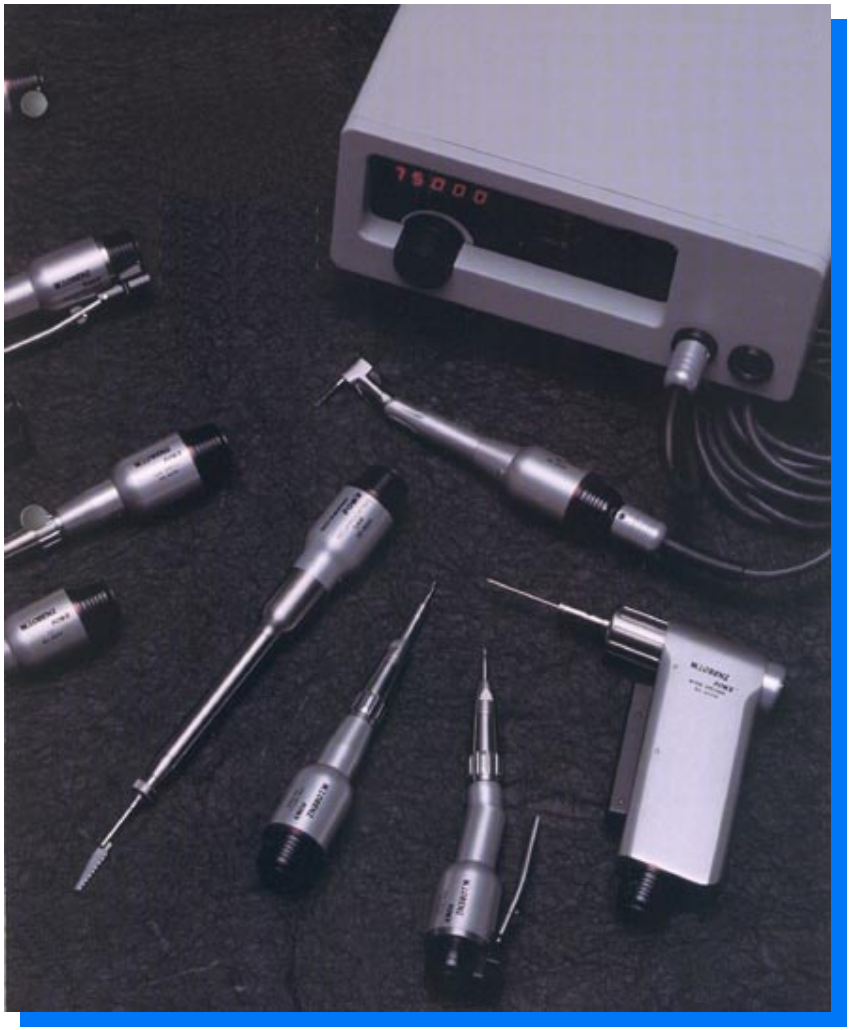
Sm Co permanent magnet generators are employed as flight critical power sources for Fly-by-Wire

More Electric Aircraft (MEA)

Sm Co based electromechanical aileron actuation demonstrated in NC-141A Electric Starlifter

Sundstrand Report WL-TR-95-4065

Sm Co MEDICAL APPLICATIONS



- **Surgical and Dental Power Tools**
  - Sm Co brushless DC motors provide high torque, high temperature stability, low mass and small size
  - Sm Co rotor magnets are the best solution for the design criteria. Arthrotek Medical Systems Report WL-TR-95-4065
- **MRI Imagers Use RE Magnets**
  - Third generation rare earth magnet, neodymium iron boron, used in tons per MRI instrument, a low temperature application. Nd Fe B discovery not a direct result of AF discovery but the search for it was motivated by the AF success

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Sm Co MAGNETS DISCOVERED IN-HOUSE AT AFMC IN 1967

Dr. Karl Strnat (1929-1992)
Working in His Laboratory
Bldg. 433, Area B, WPAFB Circa 1968

- **The Father of Rare Earth Cobalt Magnets**

Japanese Journal Cover of Issue Dedicated to Dr. Strnat

- **Symbols Translate to Explorers of Unknown Lands**

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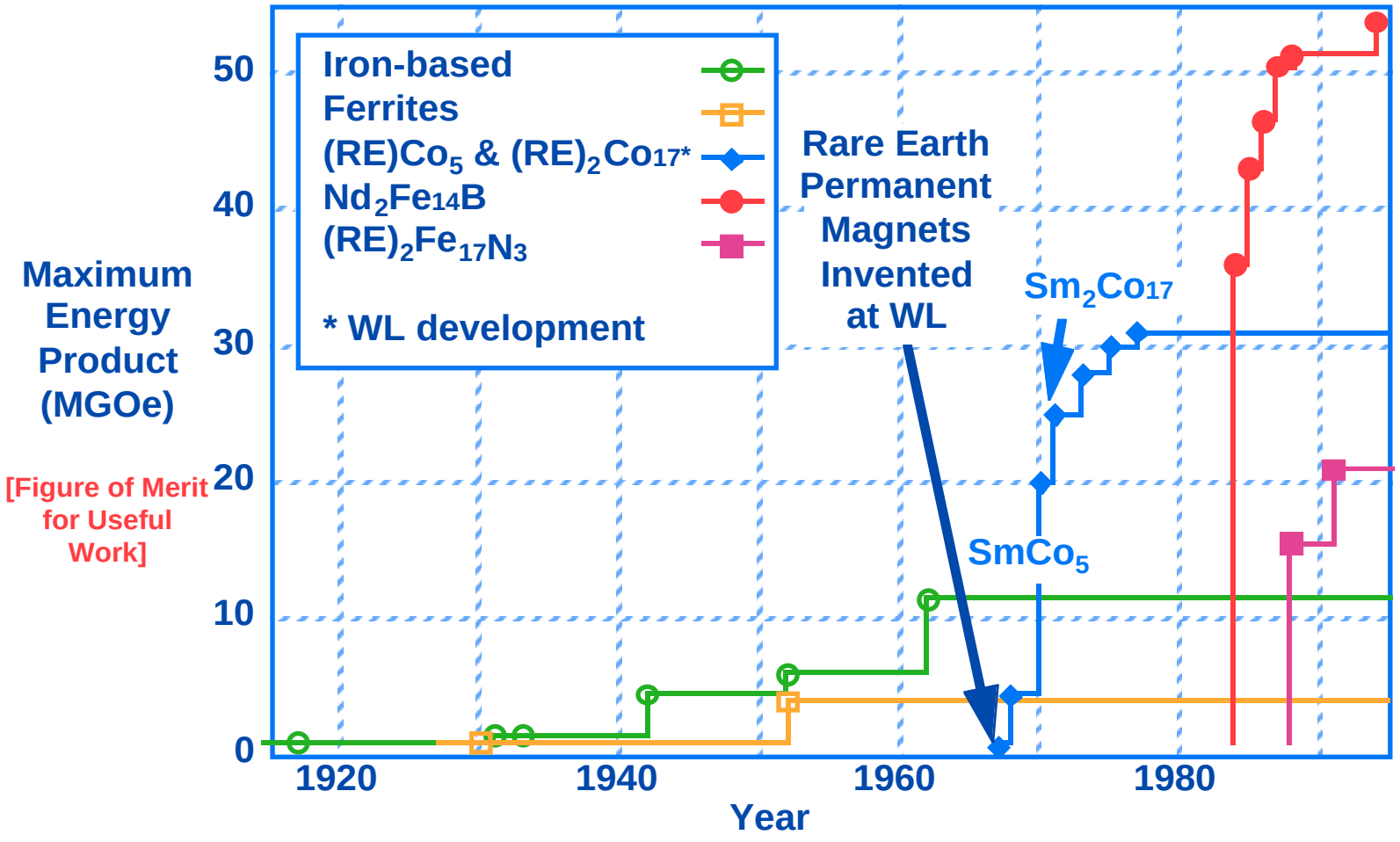
DEVELOPMENT OF PERMANENT MAGNETS



COMMERCIAL RARE EARTH MAGNETS

Type	Attributes
$SmCo_5$*	High coercivity, large magnetization, large energy product, high cost (Co), useable to ≈300˚C
Sm_2Co_{17}*	Higher magnetization, larger energy product (≈100% > $SmCo_5$), high cost (Co), useable to ≈300˚C
$(Sm_xGd_{1-x})_2(Co)_{17}$* (Gadolinium, a heavier rare earth)	Magnetic and thermal properties and cost similar to Sm_2Co_{17} but with increased property stability over temperature range of mission
$Nd_2Fe_{14}B$ (operating temperature range not adequate for many AF uses)	Very large energy product, but only useable to ≈150˚C, far below many Air Force requirements; many commercial spinoff applications

*Wright Laboratory development

RARE EARTH COBALT SUPERIORITY

- Basically - smaller, lighter, cheaper, better, easier
  - Ability to do useful work is 3X greater than Pt-Co (6x larger than Alnico) ⇒ smaller and lighter magnet
  - Significantly cheaper (no noble metals)
    - 10X Cheaper than Pt-Co
  - Better magnetic properties at high temperatures
    - Sm Co at 350°C equates to Pt-Co at room temperature
    - Only magnet choice for many DoD missions
  - Resistance to demagnetization is 2X larger
    - Easy to assemble into products
    - 20X to 50X that of Alnico

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IMPORTANT MILESTONES IN WL RARE EARTH MAGNET DEVELOPMENT

Time Period	Milestone
Contributing Factors	
Early 1940's	High purity rare earth materials separated in *Manhattan Project*
Late 1950's	*Atomic-Powered Aircraft* project brings rare earth materials to AFML for study
AFML Magnetic Materials Effort	
1961	AFML rare earth alloy research effort initiated by Dr. Karl J. Strnat to study rare earth transition metal intermetallics
1966	Strnat and Hoffer of AFML discover the hugh crystalline anisotropy in YCo_5 in inhouse research effort and predict tremendous potential of rare earth magnets; paper and Tech Report are seminal works for research around the world
1967	Strnat, Hoffer, Olson and Ostertag of AFML demonstrate first viable rare earth magnet with $SmCo_5$; patents and AFML's Cleary Award follow
1970	Commercially viable manufacture of rare earth magnets by liquid phase sintering developed under AFML contract
1971	First rare earth magnets in space in a Skylab TWT, now pervasive in all military and commercial space TWTs
1971	First application of rare earth magnets in navigation gyros, now pervasive in missile and rocket navigation
1972	First high power TWTs with revolutionary capability manufactured on ML contract, now pervasive in all military fire control and ECM systems
1972	Sm_2Co_{17} magnets developed on ML contract (≈100% higher performance and higher temperature capability and stability than $SmCo_5$)
1992	World market for rare earth permanent magnets exceeds $1B

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NOTABLE QUOTES ABOUT WL PERMANENT MAGNETS

Quote	Source
"The invention of the Sm-Co magnet by by Dr. Strnat and his associates at W-PAFB in the mid-1960's has truly played a major role in the miniaturization of the computer and the substantial improvement in electron tube devices throughout the world."	*Mr. William G. Hart, Magnet Market Analyst, Bill Hart Enterprises*
"Today an entire industry owes its state-of-the art to the invention of the rare earth magnet....It has made it possible for the U.S. military to have the best-performing radar, communication, and electronic countermeasures systems in the world today."	*Mr. Donald Gagne, Manager, Design Engineering, Teledyne Electronic Technologies*
"The invention of Sm-Co alloy magnet systems by Dr. Karl Strnat was both revolutionary and evolutionary. Prior to that event the permanent magnet industry had settled into a period of mediocre growth centered on Alnico and hard ferrite. Neither of these materials had magnetic characteristics that could satisfy the needs of the military and certain segments of the civilian market. At the present time no other permanent magnet material except Sm-Co is effective for highly sophisticated defense applications, and, based on a survey of reported R&D programs around the globe, none is on the horizon."	*Mr. Port Wheeler, Magnet Market Analyst, Wheeler Associates*
"The impact of Sm-Co in small rate integrating gyros goes beyond mere state-of-the-art performance. Sm-Co is one of several technologies, microelectronics and microprocessors being the others, which enabled a revolutionary change in navigation equipment."	*Mr. Gary E. Walker, Director Instrument Engineering, Nothrop Electronics Systems Division*
"In the high power coupled cavity arena, a number of current TWTs would not exist without Sm-Co magnets. Some examples are: The F-18, APG-65 radar TWT; the J-STARS TWT; the F-16, APG-66 and APG-68 radar TWTs....In the medium power helix TWT area, the major user of Sm-Co Magnets is the TWT in the AMRAAM missile....This tube could not be produced without the availability of Sm-Co magnets."	*Mr. Gordon Lange, Chief Engineer, Hughes Electron Dynamics Division*

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SOME LITTLE-KNOWN FACTS ABOUT PERMANENT MAGNETS

Fact	Comment
Few people are aware of how many hidden permanent magnets provide forces that operate devices that we use every day in our homes, cars, offices, and factories	Items such as motors, computer drives and printers, watch motors, anti-lock brake system, audio speakers, many forms of sensors, and communication satellite TWTs are all dependent on permanent magnet technology
Total world market for permanent magnets is over $4B annually, growing to >$10B in 10 years, with rare earth permanent magnets now about 40% of total and increasing	As countries develop, use of items which require permanent magnets, particularly rare earth magnets, will increase
Rare earth permanent magets were invented in WL in 1966	The concept of rare earth permanent magnets was first ***conceived and demonstrated*** by WL researchers
Rare earth magnets remain the highest performance magnets for a given size	Many applications require large magnetic flux with minimal magnet size; small TWTs, portable computer drives and audio headsets were enabled by rare earth permanent magnets
Rare earth magnets $SmCo_5$ and Sm_2Co_{17}-type magnets (WL developments) are the only permanent magnets useful at temperature >200˚C	Temperature stability and performance at temperature are unique to $SmCo_5$ and Sm_2Co_{17}-type magnets

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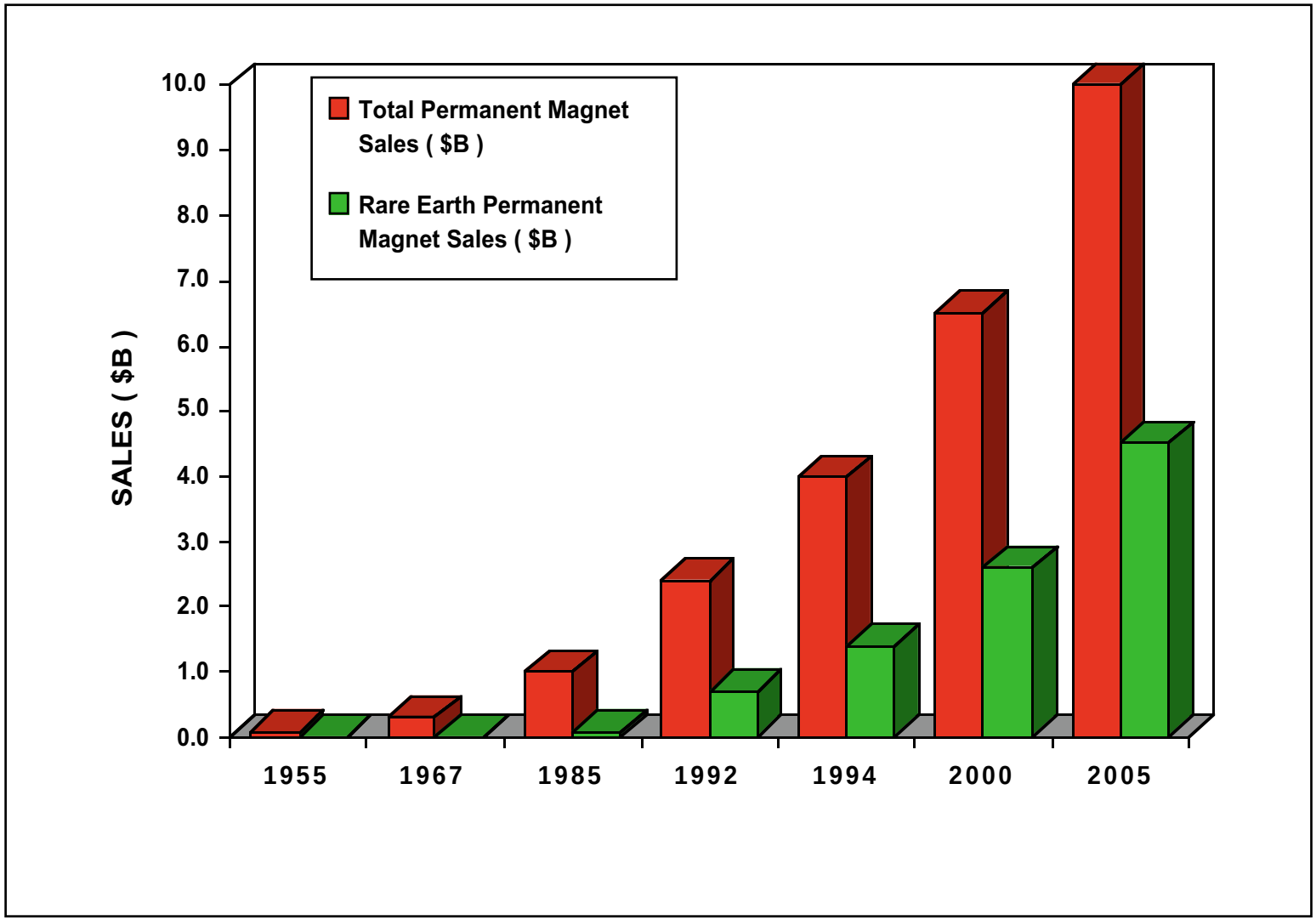
WORLDWIDE PERMANENT MAGNET MARKET



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