



Fifty Years of Research in Helium-3 Fusion and Helium-3 Resources

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I. Introduction

The search for a clean and safe energy source to power the world in the 21st century has accelerated over the past two decades. It is widely recognized that the use of fossil fuels is detrimental to the earth's environment through the emission of greenhouse gases and acid gases. In addition, the fossil fuel supply is limited; by the middle of the 21st century it is projected that most of the economically recoverable fossil fuel supplies will have been exhausted. [1]

The use of fusion reactors is one answer to supplying the earth's increasing population with power in the future and worldwide investigative research into fusion power has been ongoing for more than 40 years. The current emphasis is on the deuterium-tritium reaction (DT), however, it may not be in the best interests of future generations. The DT reaction creates large numbers of high energy neutrons as shown in the following reaction:



These neutrons can cause extensive damage in the reactor vessel and can produce long-lived radioactive elements. To avoid this situation, the reaction between deuterium and helium-3 (D- ${}^3\text{He}$) can be used. This reaction occurs as follows:



The advantage here is that a high energy proton is produced instead of a high energy neutron. These protons can be directly converted into energy through the use of electrostatic Direct Energy Converters (DECs). A side D-D reaction occurs in D- ${}^3\text{He}$ fusion reactors which also produces neutrons, however this reaction is on the order of 1% of the energy produced in the reactor. The advantages of the D- ${}^3\text{He}$ fusion reaction has fueled much new research into the field in the past five to ten years.

Research into helium-3 (${}^3\text{He}$) fusion has increased markedly since the "rediscovery" of large quantities of ${}^3\text{He}$ on the moon by Wittenberg et al. [2] Though research into ${}^3\text{He}$ existed previous to this discovery, the number of articles published on ${}^3\text{He}$ fusion was relatively low, approximately 5 per year. From 1988-93 however, the number of articles published per year on the same topic increased to more than 30 per year. As the number of papers on ${}^3\text{He}$ fusion and resources grows, developing coherent bibliographies becomes cumbersome and time consuming. In order to facilitate and broaden ${}^3\text{He}$ research, a library of all ${}^3\text{He}$ related articles is needed. This library has to meet several criteria. First and foremost, it must be easily accessible so that finding articles is a quick and simple process

for all areas of ^3He research. Secondly, the library must be able to grow over time to accommodate the burgeoning research in the field. Lastly, the library must be as complete as possible. This paper describes the ^3He literature bibliography and library now available at the University of Wisconsin Fusion Technology Institute.

Three criteria are used in this study to determine whether or not to include an article which contains information on ^3He fusion or ^3He resources. The criteria are as follows:

- 1) The article must mention ^3He explicitly.
- 2) The article's main focus must be either ^3He fusion related research and technology, or on ^3He resources and detection.
- 3) Articles that mention ^3He as a secondary reaction or as a diagnostic tool are not included in this bibliography.

In order to identify as many articles as possible, numerous avenues of investigation were implemented to gather articles dealing with ^3He fusion and resources. The search began with the CD-ROM files available through the University of Wisconsin's library computer resources. The main CD-ROM files searched were the INSPEC database, the EI (Engineering Index), the Aerospace Index, LEXUS, and the Business and Social Science Database. These files provided a broad base of articles which could then be expanded upon. A large number of articles were provided from the personal files of the University of Wisconsin-Madison Fusion Technology Institute research staff. The remainder were found by examining bibliography entries from the previously identified papers. A large percentage of the relevant work in this field has now been assembled, however any additional articles that the reader may be aware of would be welcome additions.

Given the size of the library, accessibility and ease of finding desired articles can become difficult. Keywords were devised to breakdown ^3He research into smaller subgroups. These keywords are given and defined later. To manage this database of articles, we selected the bibliography and database manager **EndNote Plus™** for the Apple Macintosh system. This program offers easy access to particular articles, as well as the ability to sort and find articles in numerous ways. With the keywords and the EndNote Plus™ database manager, articles can be quickly and easily found for almost any desired search on ^3He research. EndNote Plus™ also allows unlimited space in which to store additional articles as they are published, another pertinent factor in its choice as the database management program.

As of April 24, 1994 the ^3He library contains 849 bibliographic entries. Figure 1 shows the distribution of articles on ^3He over time, the marked increase in the last eight

years is clearly visible. Four entries do not have years associated with them therefore, they are not included in Figure 1. Copies of 674 of these articles are currently on file at the University of Wisconsin. In addition, the bibliography contains 70 additional articles from newspapers and popular magazines for a grand total of 919 articles. The newspapers and magazines are not included in the statistical breakdowns to follow.

NOTE: The number of articles compiled for 1994 is lower than for previous years because the 1994 figures are not yet complete. This should be corrected early in 1995.

II. State of Helium-3 Research

It is interesting to look at the breakdown of articles that have been published in the ^3He field as research in this area has been conducted worldwide. Articles have been published in at least nineteen countries listed below:

- USA
- Russia
- Japan
- Austria
- Denmark
- England
- Finland
- France
- Germany
- Greece
- Hungary
- Italy
- The Netherlands
- Poland
- Switzerland
- Canada
- Australia
- Sri Lanka
- Israel

The USA accounts for 60% of the total number of articles published and is by far the largest participant in ^3He research. Japan, the European Community, and Russia are the other substantial contributors to worldwide publications.

Over the past six years, research into ^3He fusion and resources has increased dramatically. In the years 1988-1994, 467 articles have been published. This is over half the total number of articles published since the discovery of ^3He in 1939 by Louis Alvarez and Robert Cornog. [3,4] The ^3He fusion reaction has long been known to produce fewer neutrons than the standard DT fusion reaction. However, since large amounts of ^3He were unavailable to fuel a potential fusion reactor, research in the field was not encouraged. Since 1986, the renewed interest in ^3He fusion has made it a legitimate contender for a clean and safe energy source.

III. Reactor Research

There are 321 articles on ^3He reactors and many different reactor schemes that utilize ^3He in their fuel cycles. A short review is given on the articles published for the reactor types: Tokamak reactors, Field Reversed Configuration (FRC) reactors, Mirror reactors, Inertial Electrostatic Fusion (IEF) reactors, Inertial Confinement Fusion (ICF) reactors, Self Colliding reactors, and Advanced reactors.

First, it is helpful to look at the overall picture of reactor article trends. First, virtually every ^3He fusion reactor article is based on the D- ^3He fusion reaction. This reaction is promising practically, as well as for its low neutron output. The other main ^3He fusion reaction is the ^3He - ^3He reaction;



however only five articles have been written on this type of fusion reactor. This reaction produces no neutrons and is therefore radiation free. The ^3He - ^3He reaction is currently difficult to sustain but it remains a viable long term goal for a radiation free fusion reaction.

Second, we can see from Figure 2 that the total number of ^3He reactor articles has greatly increased over the past six years due to the discovery of the aforementioned ^3He source on the moon. The number of reactor articles published over the last six years (194) accounts for 64% of the total articles. The interest and research in the ^3He reactor field continues to grow because it has proven itself as a plausible design for a working reactor. All areas of ^3He fusion reactor research should be continued as they are all important to the further understanding of the practicality of ^3He fusion. The breakdown of ^3He reactor articles by reactor type is seen in Figure 3.

Tokamaks

Tokamak research has consistently been the area of largest interest throughout the fusion community and that trend continues in the field of ^3He reactors. The 138 articles

published in the ^3He tokamak reactor area is almost one half the total number of reactor articles published. Over the past five years the number of articles published per year in this field has more than tripled. The article publishing trend is seen in Figure 4, the noticeable jump in articles in the past six years is clearly visible.

FRC

Field Reversed Configuration (FRC) is the second leading article generator with 48 articles published. Fusion of ^3He ions is particularly well suited for the FRC, fueling the research trend in this area. Research into ^3He FRC reactors virtually began in 1986; coinciding with the discovery of the ^3He resource on the moon. Japan is particularly strong in FRC research as can be seen in Figure 5. Japan accounts for one third of the articles published on FRC research.

Mirror

Magnetic Mirror reactors are also well suited to ^3He fusion reactions, making this field the third most published area with 46 articles. Magnetic Mirror reactors have been studied for a long time; the first D- ^3He mirror reactor was suggested in 1962.[5] However research in the ^3He mirror field had been sporadic until a resurgence occurred in 1986. The "rediscovery" of the ^3He resource on the moon has also clearly benefited the Magnetic Mirror field. Figure 6 shows the ^3He Mirror reactor articles published over the last 30 years.

IEF

Inertial Electrostatic Fusion (IEF) was first demonstrated as a potential reactor concept in 1967 by Robert Hirsch while working for the Farnsworth Corporation.[6] Different from most fusion reactor concepts, the traditional IEF does not rely on magnets to confine a plasma. Instead it works electrostatically by attracting ions into a potential well, thereby accelerating them to high energy levels. At the center of this well, the high energy ions collide and fuse. Modern IEF designs, such as the Polywell™, use cusp type low magnetic fields to confine electrons and generate a virtual cathode. The ^3He - ^3He reaction, which requires high ion energies (several 100 keV), could conceivably run on an IEF reactor. The IEF fusion reactor using ^3He is a recent idea, only 20 articles have been written on the subject in the past seven years.

ICF

Inertial Confinement Fusion (ICF) is less suited to ^3He fusion than most other reactor designs due to the physics associated with compressing solid targets. However, the

benefits of stable reactants and a mostly aneutronic reactor have not been ignored. There have been 30 articles published in this field since 1978.

Self-Collider

A Self-Collider reactor uses high energy ion beams directed into each other in an attempt to achieve fusion collisions. The ions streams are redirected after the point of intersection into a loop so that there are at least two continuous high-energy ion beams in loops that intersect at one or more points. The MIGMA is a good example of a Self-Colliding reactor. There are 15 articles published on Self-Colliders.

Advanced

Advanced concept reactors are those that either require technology levels well above that currently available, or are so novel that there is not a substantial body of experimental work to review. There are 24 articles on advanced type reactors. Figure 7 is a combined graph showing the ^3He reactor articles published for IEF, ICF, Self-Colliders, and Advanced type reactors.

IV. He-3 Resources of the Earth and Space

Overall, there are 335 articles on ^3He resources in the current bibliography. Of these articles, 162 are concerned with terrestrial resources, 140 with lunar resources, and 54 with space (non-lunar) resources. Quick addition shows that 356 articles have been accounted for, however, since some articles contain information on terrestrial, lunar, and space resources, they are included in each category. Figure 8 shows the publishing trends for ^3He resource articles over the past 52 years. The vast majority of the articles on terrestrial resources have been written since 1969. The earlier articles dealt more with the initial discovery of the isotope than with measurable quantities. Since the '60's many articles have been written about measured quantities of ^3He on Earth as found in oceanic basalt's and crusts, volcanic gases, and natural gas wells. Unfortunately, there have not been measurements of sizable quantities of ^3He on Earth.

The use of ^3He in fusion was first suggested in 1962. The lack of this rare gas in sizable quantities had prevented a significant experimental program from being initiated. In addition, the lack of known ^3He quantities has also prevented D- ^3He fusion from gaining mainstream acceptance in the governmental and political communities.

The advantage of a D- ^3He cycle were so compelling that fusion scientists began to look beyond the earth for this rare isotope. Wittenberg et al. [2] were the first to suggest the moon as the closest source of commercial quantities of ^3He and were also the first to

make the correlation between D- ^3He fusion and ^3He on the moon. Interestingly, the presence of ^3He on the moon has been known since the 1969 Apollo 11 mission and the subsequent published results of the Lunar Sample Preliminary Examination Team later that same year. [7] The seventeen year span between the original 1969 discovery and the 1986 "rediscovery" emphasizes the need for thorough background searches before embarking on new experimental programs.

Articles on ^3He resources have been published at a high rate since 1986. Along with potential resources on the moon, it has been suggested that even greater quantities of ^3He exist on other planets such as Mars and Jupiter. It is these other sources that comprise the articles that fall under the category of Space Resources.

Terrestrial Resources

At the present time 162 sources concerning terrestrial sources of ^3He have been found and their publishing trend is shown in Figure 9. Terrestrial resources include all sources of ^3He on Earth. Articles dealing with this subject have been written since 1941 starting with R.D. Hill's article on the production of ^3He . [8] However, the vast majority of articles (153 of 161) have been written since 1969.

Lunar Resources

There are 140 references to lunar ^3He resources, 117 of which have been written since 1986 when the Wittenberg et al.[2] article was first published. Figure 10 shows the breakdown for lunar resource articles. Prior to 1986 the articles dealt with the original discovery of ^3He on the moon during the Apollo 11 mission. The first publication that mentioned the presence of ^3He on the lunar surface was written by the Lunar Sample Preliminary Examination Team in 1969. [7] Since 1986, ^3He lunar resources articles have primarily dealt with the retrieval of the isotope from the moon and the quantities that actually exist there.

Space Resources

There are 54 references to space resources of ^3He as shown in Figure 11. Space resources are those found on neither the Earth or Moon. The articles may deal with ^3He found on Mars, Jupiter and other planets, or on meteorites. More than two-thirds of the articles that deal with space resources have been published since 1986 (39 of 54).

V. He-3 Propulsion

Space propulsion via the $D-^3\text{He}$ fusion reaction has garnered much interest over the years. As evidenced by the 52 articles published over a span of 30 years, the idea behind $D-^3\text{He}$ fusion propulsion has long been known. Figure 12 displays this publishing trend for fusion propulsion articles. The first article citing $D-^3\text{He}$ as a possible fuel for fusion space propulsion appeared in 1961 by J.R. Roth. [9] Since that time, approximately one article a year appeared in scholarly journals until 1989. However, the period from 1989-1994 has seen 35 of the 52 articles on $D-^3\text{He}$ propulsion written. Now that a viable source of ^3He has been found, $D-^3\text{He}$ propulsion and exploration of our solar system have become distinct possibilities.

VI. Keywords

The following is a list of the keywords used to define the numerous different article types found in the ^3He research field. There are 29 keywords altogether.

Keyword	Definition
Code	Plasma physics or power balance computer code articles.
Cross-section	^3He cross sectional data.
D-He3	Articles on D- ^3He fusion.
DEC	Direct Energy Converter articles.
Detection	^3He detection. Includes lunar detection, detection on other planets and detection of terrestrial resources.
Economic	Economic aspects of acquiring ^3He and building ^3He fusion reactors. Economic comparisons to other power sources.
Energy	Energy resources of ^3He and the energy costs involved in acquiring those resources.
Environment	Environmental concerns dealing with ^3He .
Fueling	Reactor fueling concepts such as advanced fuels and fuel injection into plasmas. Does NOT include ^3He fuel resources.
He3-He3	Articles on ^3He - ^3He fusion.
Legal	Legal aspects of acquiring and/or using ^3He .
Lunar	Lunar resources, lunar detection, etc. Articles dealing specifically with lunar considerations only.
Mining	Lunar mining of ^3He resources.
Miscellaneous	Unknown type keyword.
Physics	Articles with emphasis on physics issues such as D- ^3He plasmas or spin polarization of ^3He nuclei.
Propulsion	Space fusion propulsion using ^3He fusion reactions.
Radiation Damage	Damage to reactor parts due to D- ^3He fusion reactions.
Radioactivity	Activation of reactor due to D- ^3He fusion reactions.
Reactor	General keyword for all reactor types, included with the following seven keywords.
Advanced	Advanced concept reactors.
FRC	Field-reversed configuration reactors.
ICF	Inertial confinement fusion reactors.
IEC	Inertial-electrostatic confinement reactors.
Mirror	Mirror reactor devices.
Self-collider	Self-colliding reactors.
Tokamak	Tokamak reactors.
Safety	Articles on ^3He reactor safety.
Space	Space applications or ^3He resources. Does NOT include lunar resources or lunar applications.
Terrestrial	Articles on terrestrial ^3He resources.

VII. Newspapers and Magazines

Newspapers

There have been 28 original newspaper articles in 17 different newspapers in 13 cities written on ^3He fusion and resources. All but one article is from the U.S., that being from Canada. It is assumed that other articles have been written about ^3He in other cities and countries, but only those that were brought to the author's attention were listed.

Popular Magazines

There are 32 articles published on ^3He in popular magazines over the period from 1982-1994. Popular press interest in ^3He started in 1986, with 31 of the 32 articles printed since that time. This coincides with the discovery of the moon as a vast ^3He resource.

VIII. Conclusions

From the discovery of ^3He in 1939 by Luis Alvarez, [3,4] to the first ^3He fusion reactor design in 1962, [5] to the discovery of large quantities of ^3He on the moon in 1986, [2] ^3He has become a major research topic in the quest for a clean and safe energy alternative for the future power needs of the world. Research into ^3He fusion and resources has spanned four continents and nineteen countries. To facilitate and expand research in this field, a comprehensive list of all the work completed in the ^3He field was needed. This concentration of all research in one location provides a vast resource to be tapped by future scientists.

Acknowledgement

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IX. References

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Articles Since 1986 Account for 63% of the Total Articles on He-3 Fusion and Resource Related Articles

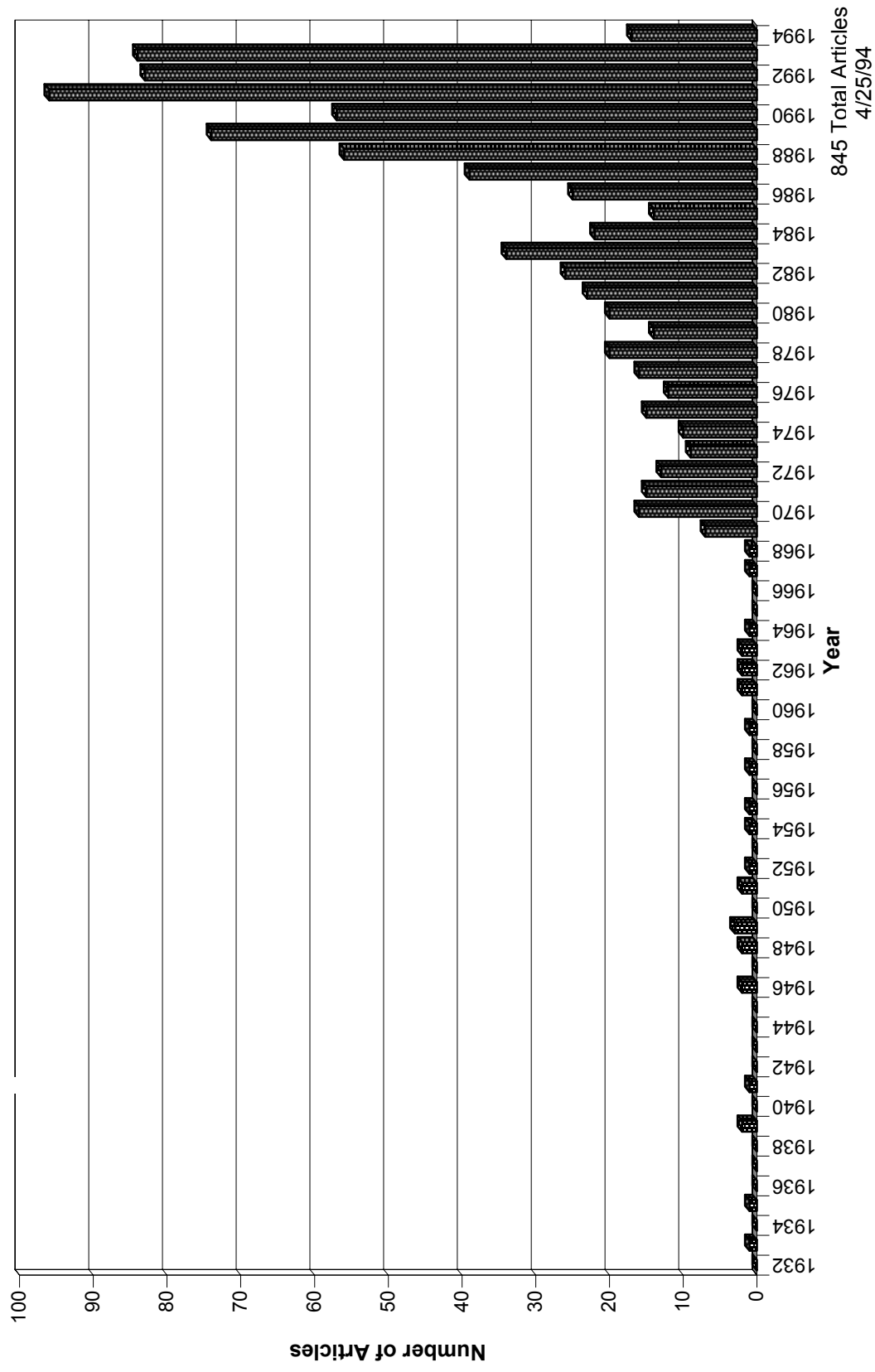


Figure 1

He-3 Fusion Has Been Investigated in Many Confinement Concepts

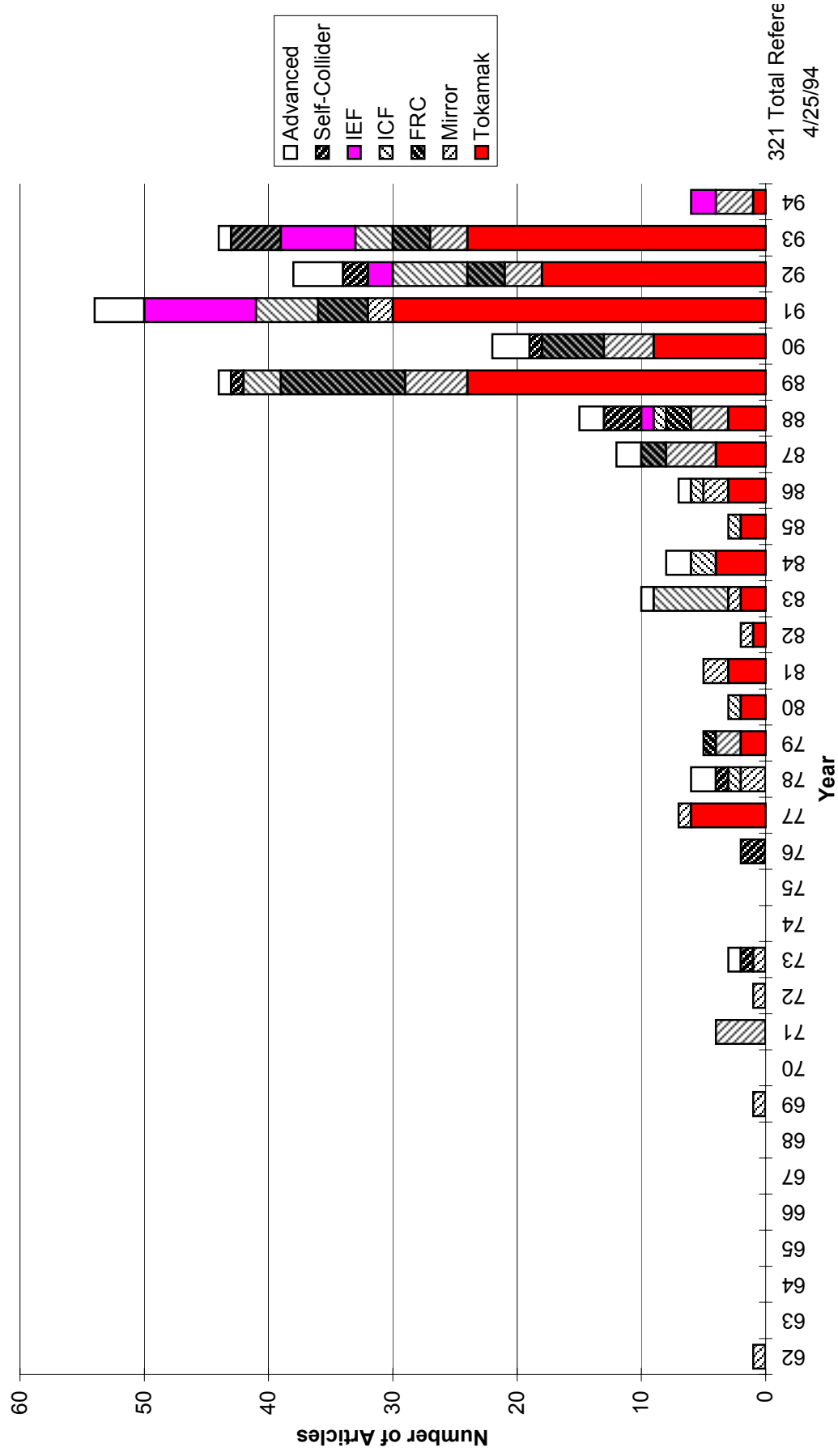


Figure 2

The D-He3 Tokamak Accounts for Approximately 43% of the Total He-3 Reactor Design Articles

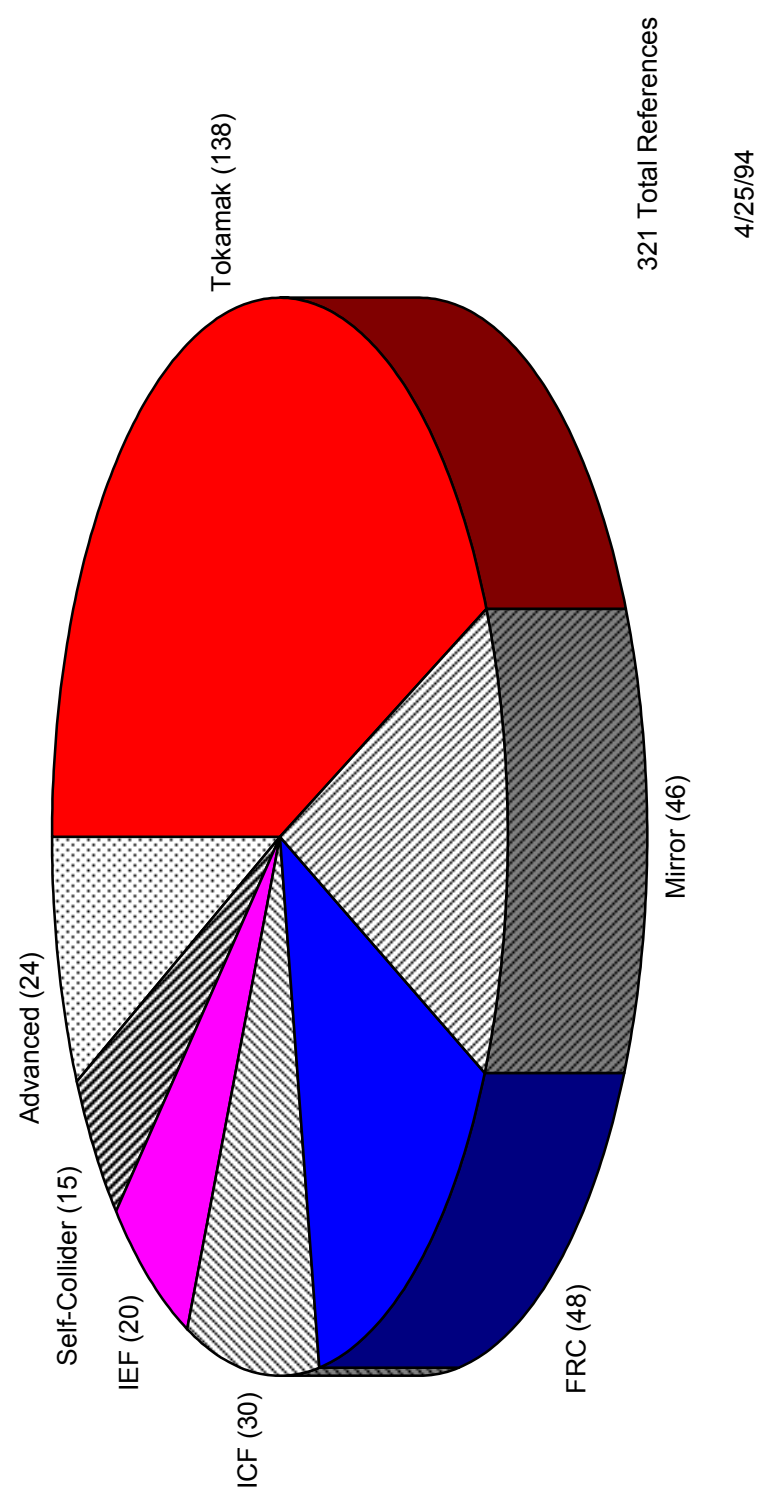


Figure 3

The Number of He-3 Tokamak Articles Has Dramatically Increased Since 1988

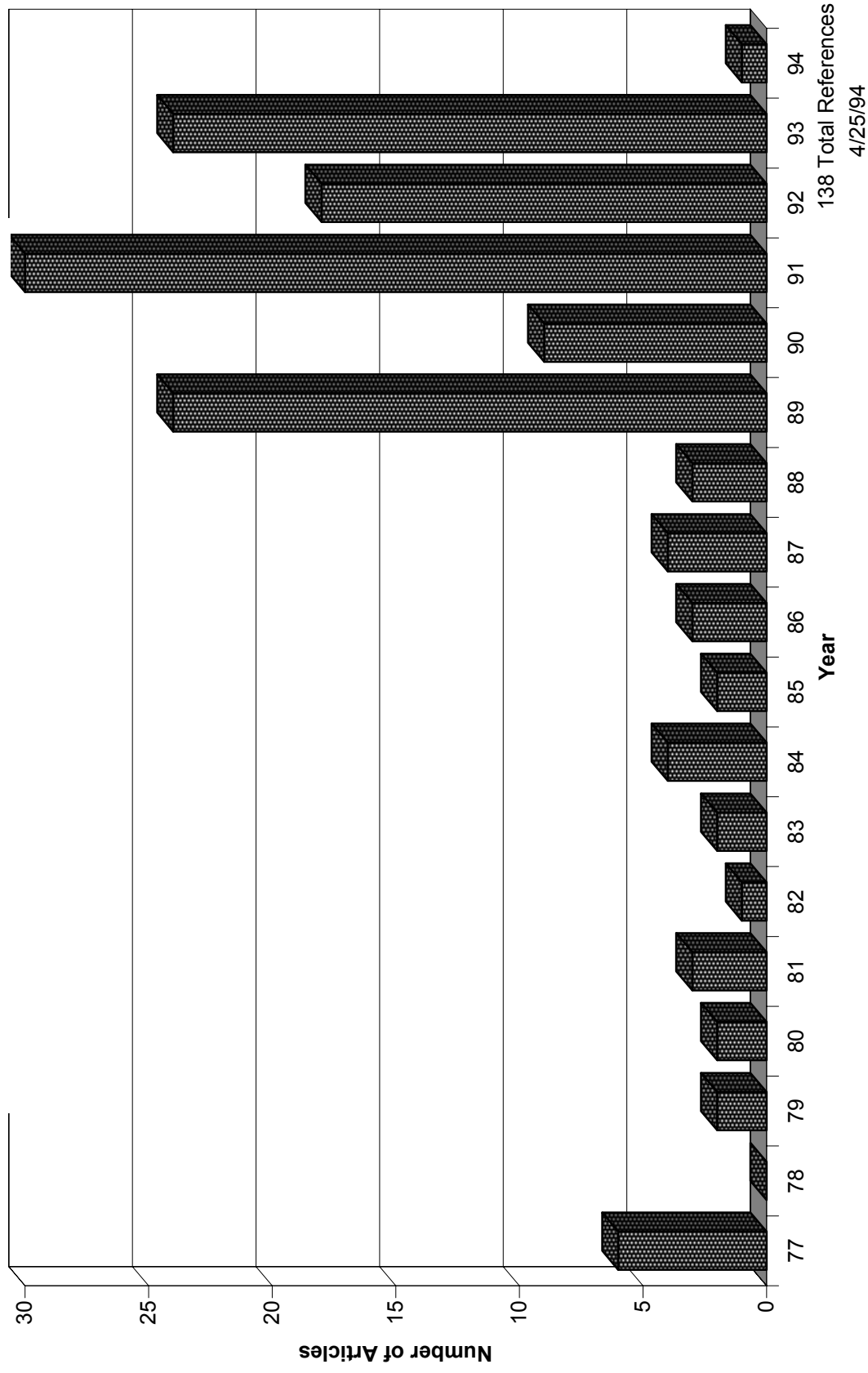


Figure 4

The Interest in D-He3 Fuels in a Field Reversed Mirror Configuration is Second Only to D-He3 Tokamak Studies

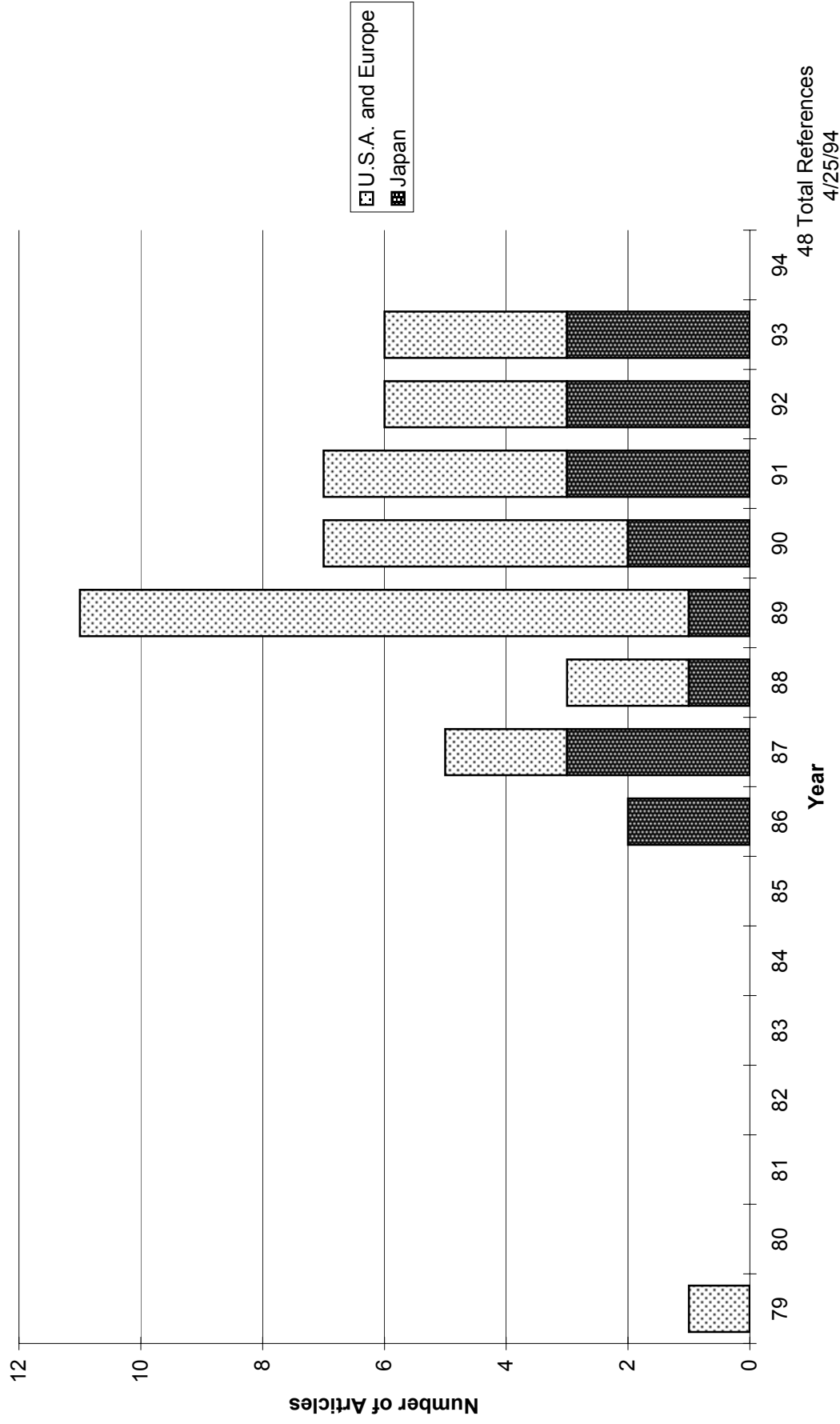
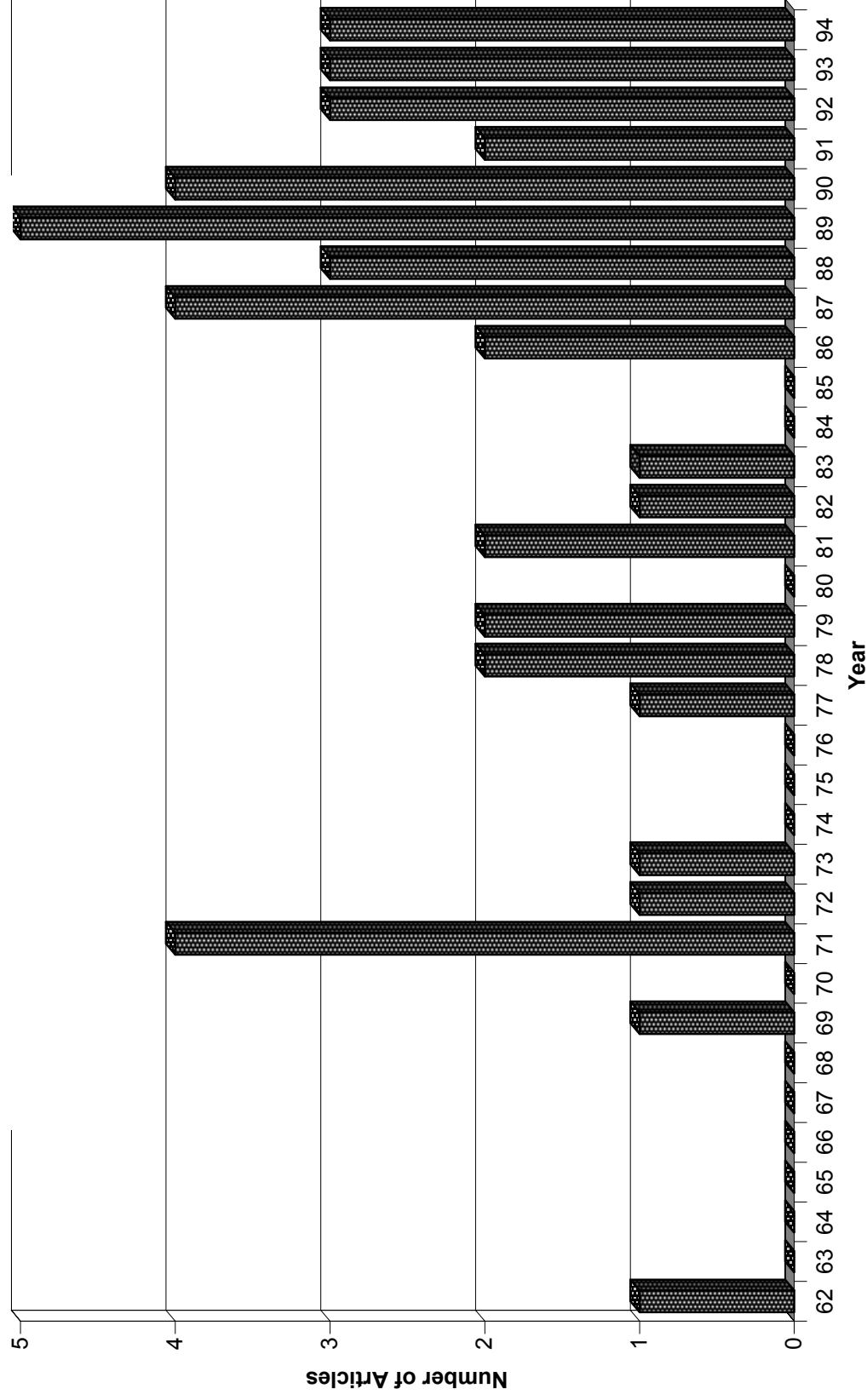


Figure 5

**The Use of the D-He3 Fuel Cycle Was First Studied in a Mirror
Configuration over 30 Years Ago**



4/25/94
46 Total References

Figure 6

The Interest in He-3 Fuel Cycles has Increased in the Past 6

Years

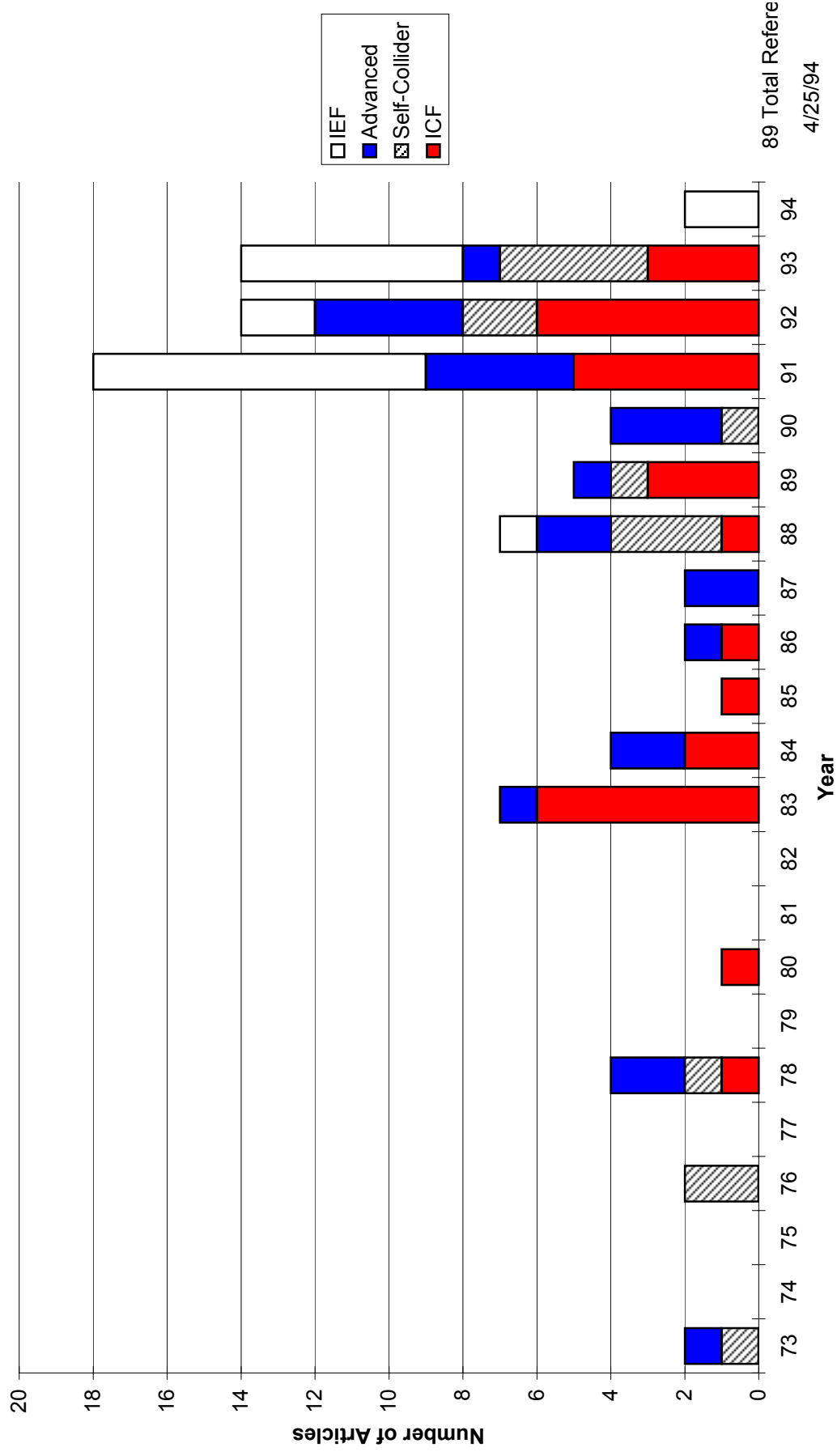


Figure 7

The Interest in Lunar He-3 Resources Started with the U.S. Apollo Program and Increased Rapidly After the 1986 Connection to Fusion Was Made

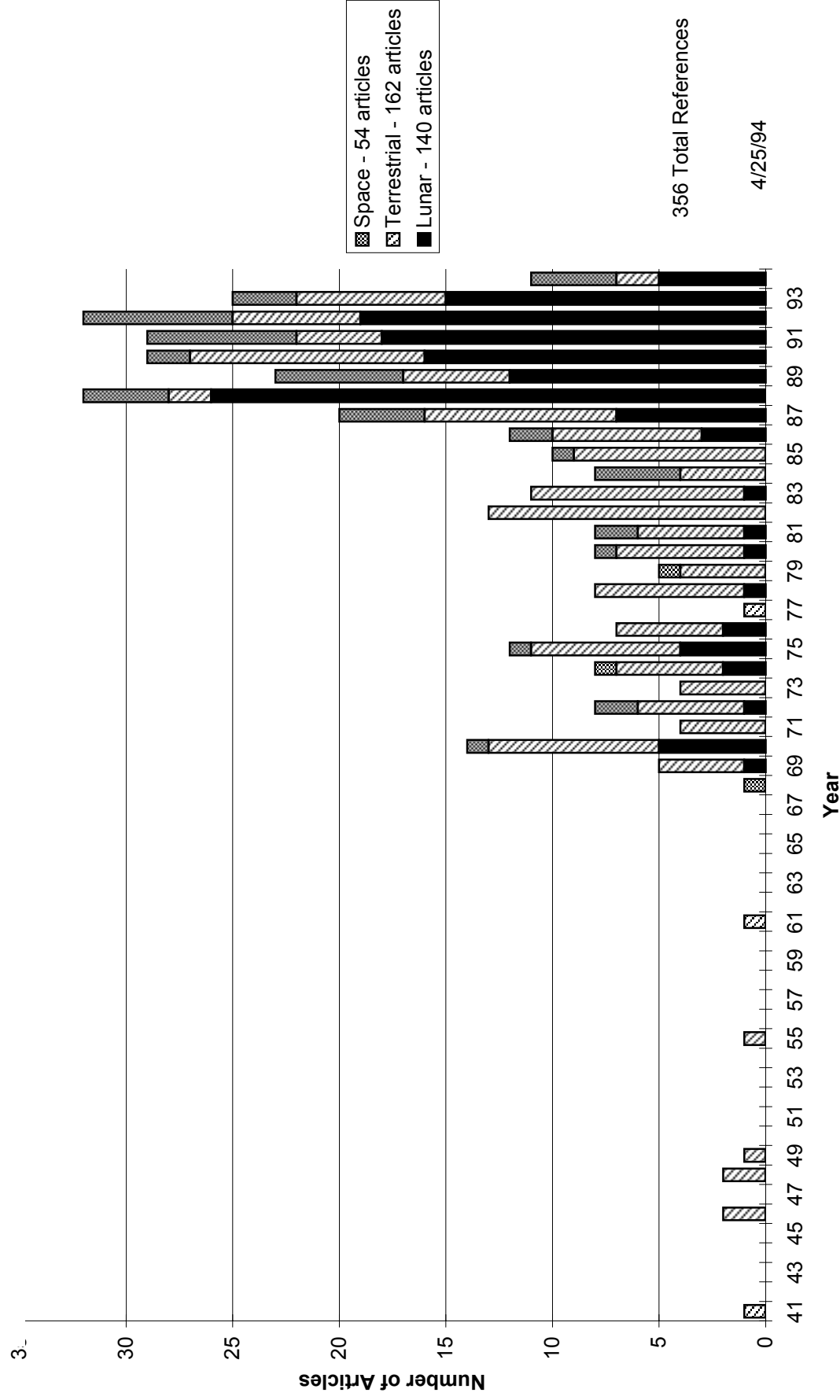
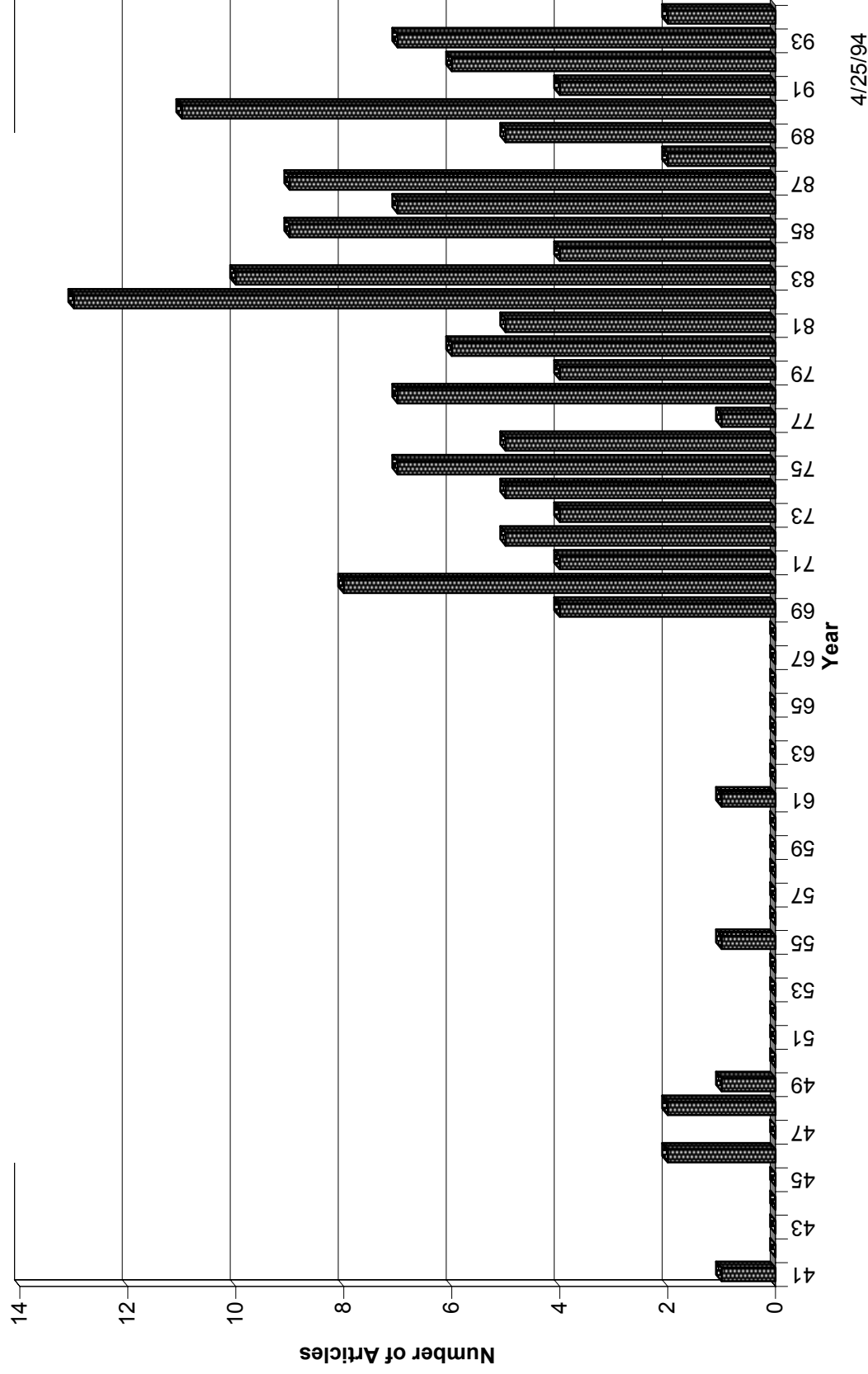


Figure 8

The Publication of Articles on Terrestrial He-3 Resources Has Averaged 6 Per Year Since 1969



162 Total References

Figure 9

**Over 80% of the Articles on Lunar He-3 Have Been Published Since the "Rediscovery"
Paper by Wittenberg et al.**

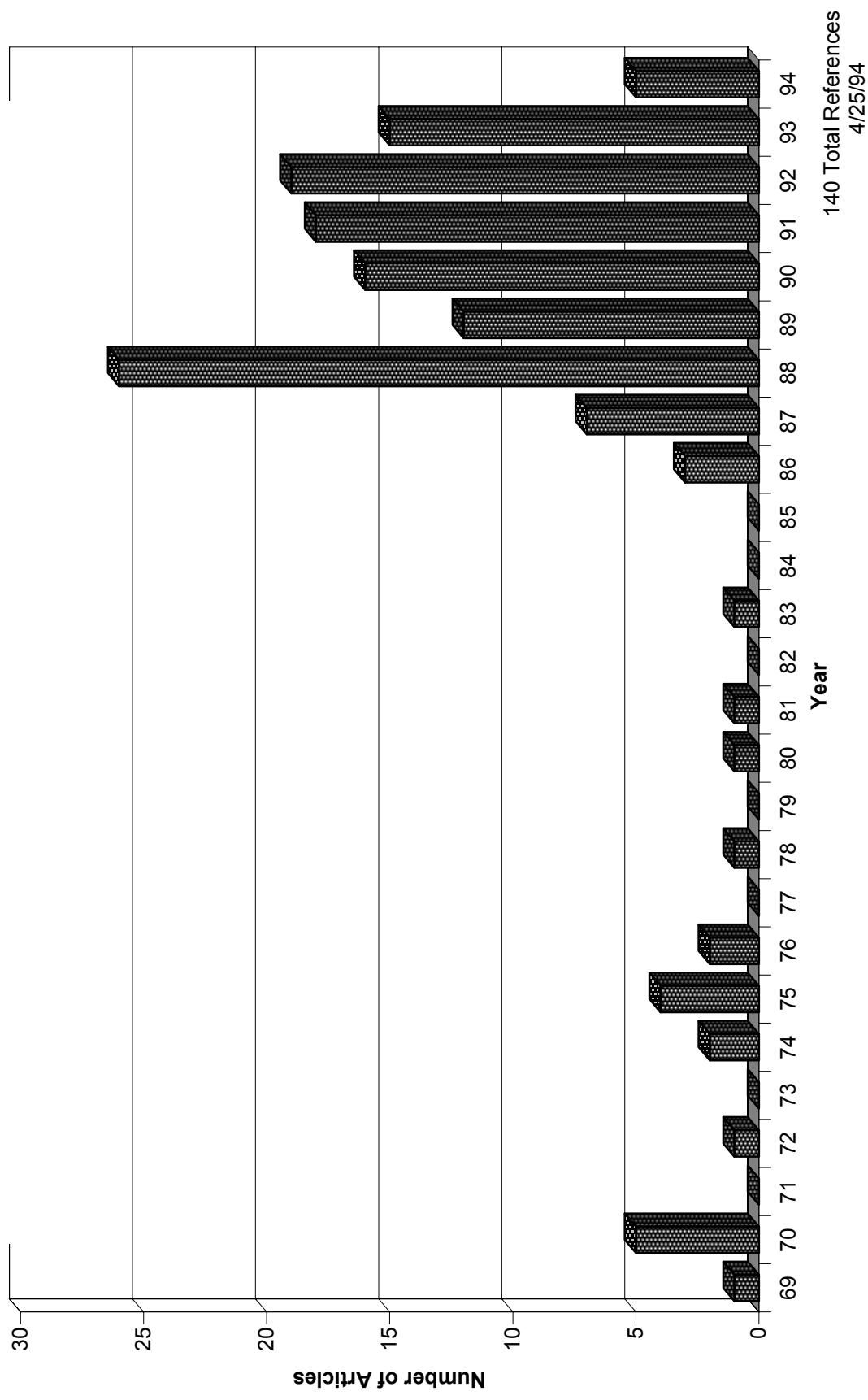


Figure 10

There Has Been a Substantial Number of Publications Concerning Extra-Terrestrial He-3 Resources Beyond the Moon

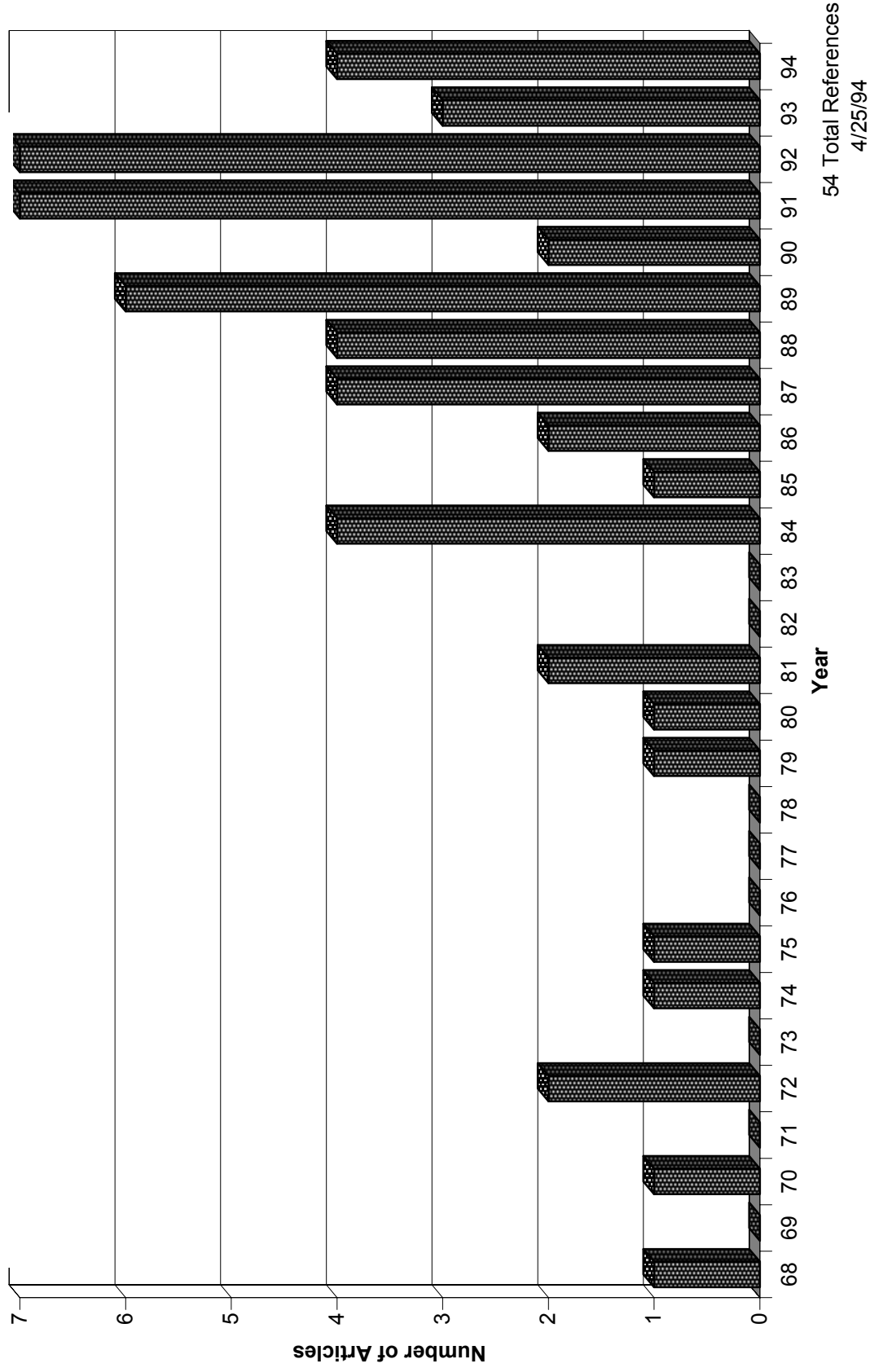


Figure 11

**There Has Been a Recent Increase in He-3 Propulsion
Publications Since 1988**

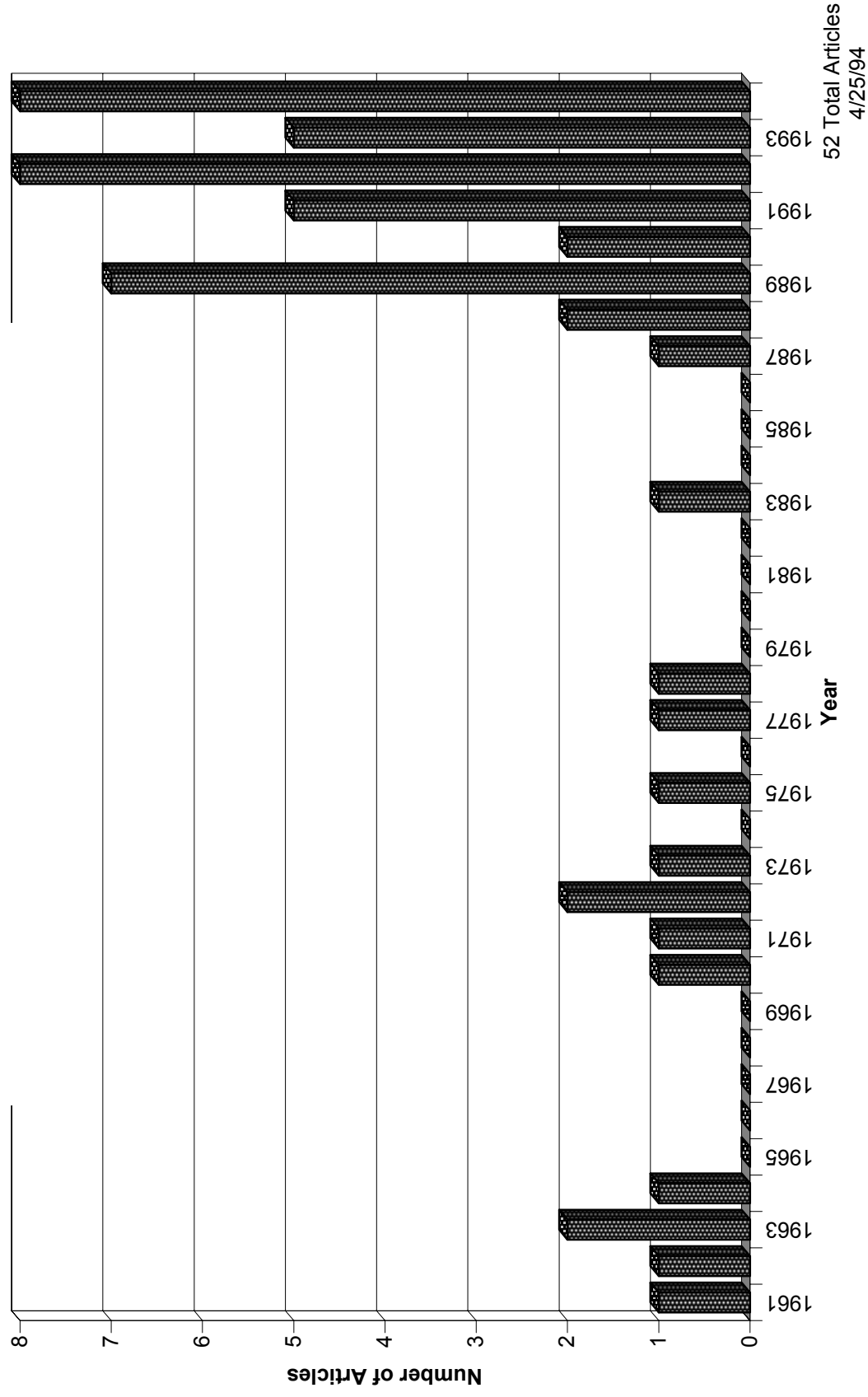


Figure 12

APPENDICES

A-C

Appendix A

I. Helium-3 Fusion Bibliography

An alphabetical listing of articles on ^3He fusion topics.

II. Helium-3 Resources Bibliography

An alphabetical listing of articles on ^3He resources of earth, moon, and space.

Appendix B

Chronological listing of bibliography references from past to present.

Appendix C

Newspaper and popular magazine articles arranged alphabetically by author.

APPENDIX A

APPENDIX I: Fusion and Resources Bibliography

Appendix I divides articles on ^3He fusion and articles on ^3He resources of earth, moon, and space. This generates two lists arranged in alphabetical order by author.

I. Helium-3 Fusion Bibliography

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APPENDIX B

APPENDIX II: Chronological Bibliography

Appendix II is a chronological listing from past to present of all articles on ^3He fusion and resources.

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APPENDIX C

APPENDIX III: Newspaper and Magazine Bibliography

Appendix III is a listing of newspaper and popular magazine articles arranged alphabetically by author.

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