A Current Bibliography of Helium-3 Research

S.W. White

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FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

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S.W. White

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

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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. Although the current research emphasis is on the deuterium-tritium reaction (DT), it may not be the best fuel cycle to power fusion reactors in the future. The DT reaction creates large numbers of high energy neutrons as shown in the following reaction:

$$D + T \rightarrow n\ (14.1\ \text{MeV}) + {}^{4}\text{He}\ (3.5\ \text{MeV})\ .$$

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

$$D + {}^{3}\text{He} \rightarrow p\ (14.7\ \text{MeV}) + {}^{4}\text{He}\ (3.7\ \text{MeV})\ .$$

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}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}He fusion reaction have fueled much new research in the past five to ten years.

Research into helium-3 (^{3}He) fusion has increased markedly since the "rediscovery" of large quantities of ^{3}He on the moon by Wittenberg et al. [2] in 1986. Though research into ^{3}He existed previous to this discovery, the number of articles published on ^{3}He fusion was relatively low, approximately 5 per year. From 1988-94, 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}He fusion and resources grows, developing coherent bibliographies becomes cumbersome and time consuming. In order to facilitate and broaden ^{3}He research, a comprehensive library of all ^{3}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 ^{3}He 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. It is a continuation of work began by Crabb, et al. [3] at the University of Wisconsin-Madison in 1993.

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. 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 break down ^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 January 12, 1996 the ^3He library contains 948 bibliographic entries. Figure 1 shows the distribution of articles on ^3He over time and the marked increase in the last eight years is clearly visible. Four entries do not have years associated with them and therefore, are not included in Figure 1. Hard copies of 775 of these articles are currently on file at the University of Wisconsin. In addition, the bibliography contains 89 additional articles from newspapers and popular magazines for a grand total of 1037 articles. The newspapers and magazines are not included in the statistical breakdowns to follow.

Two-thirds of the Total Articles on He-3 Fusion and Resources Have Been Published Since 1986

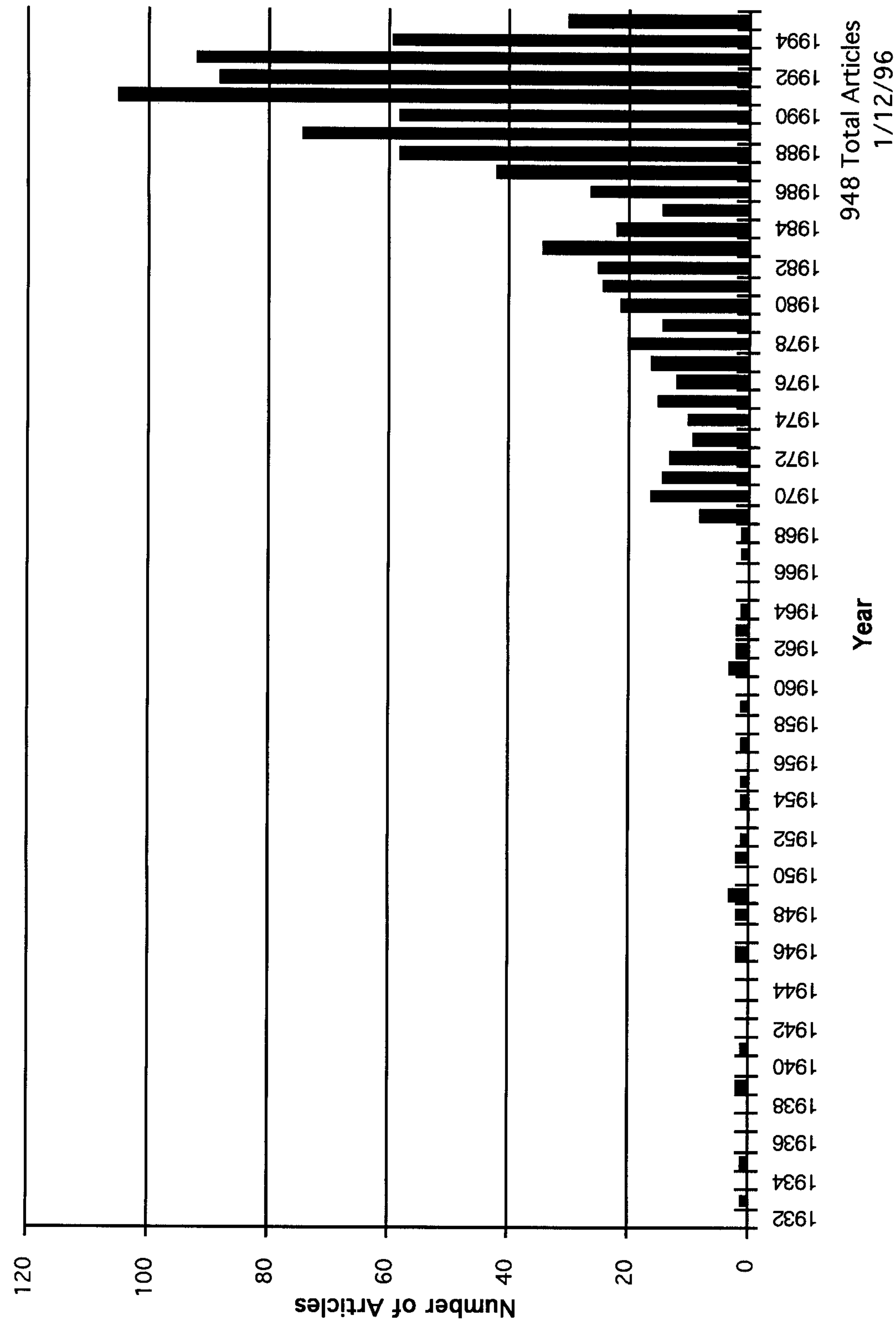


Figure 1

NOTE: The number of articles compiled for 1995 is lower than for previous years because the 1995 figures are not yet complete. This should be corrected sometime in 1996.

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 68% 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. Figure 2 breaks down the contributions by regions of the world.

Over the past nine years, research into ^3He fusion and resources has increased dramatically. Since 1986, 632 articles have been published on ^3He. This is two-thirds of the total number of articles published since the discovery of ^3He in 1939 by Luis Alvarez and Robert Cornog [4, 5].

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

Origin by Country of the He-3 Articles Included in this Survey

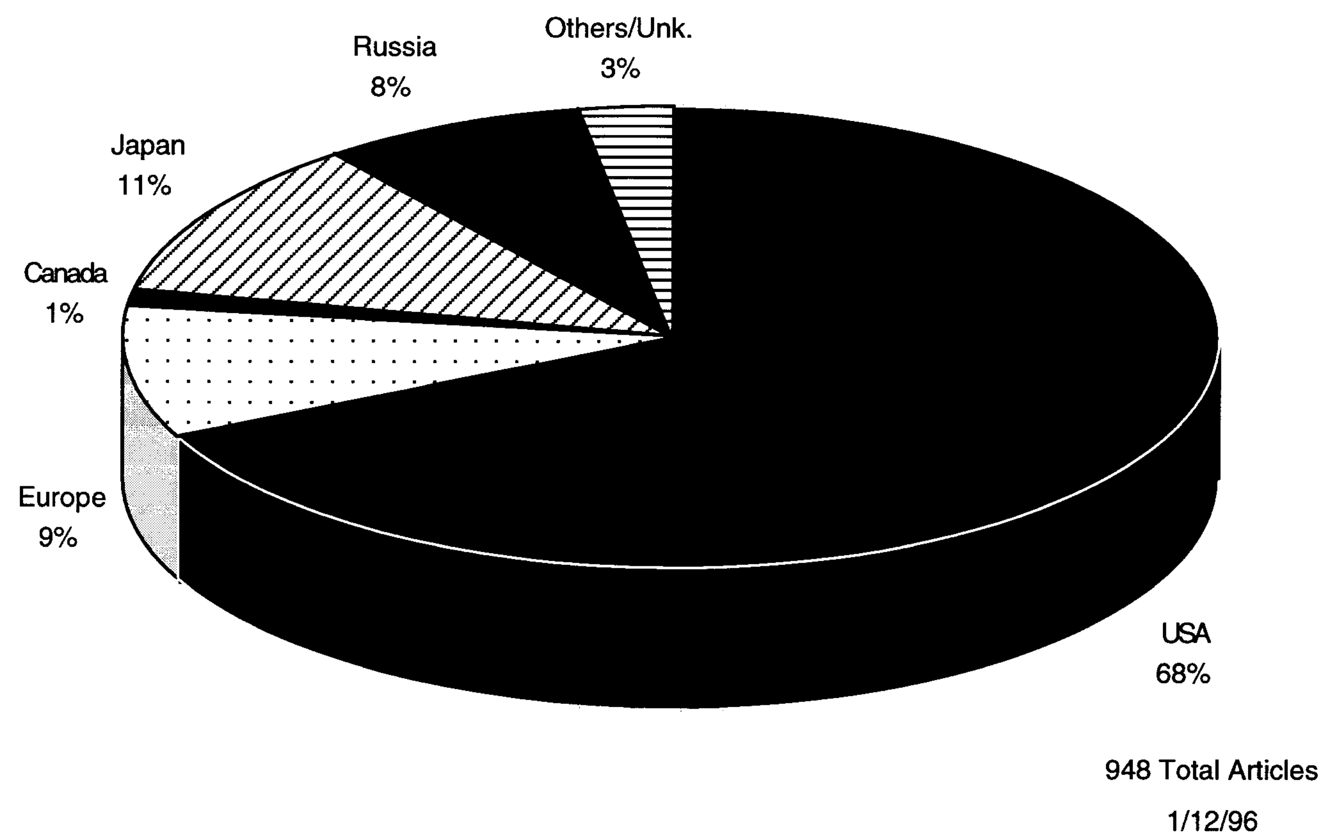


Figure 2

D-^{3}He fusion reactor economy, research in the field was not encouraged. Since 1986, the renewed interest in ^{3}He fusion has made it a legitimate contender for a clean and safe energy source.

III. REACTOR RESEARCH

There are 354 articles on ^{3}He reactors and many different reactor schemes that utilize ^{3}He 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. Virtually every ^{3}He fusion reactor article is based on the D-^{3}He fusion reaction. This reaction is promising practically, as well as for its low neutron output.

The other main ^{3}He fusion reaction is the ^{3}He-^{3}He reaction;

$$^3\text{He} + {}^3\text{He} \rightarrow p + p + {}^4\text{He} \qquad Q = 12.9 \text{ MeV}$$

however, only 20 articles have been written on this fusion reaction. Even though this reaction produces no neutrons and is therefore radiation free, the ^{3}He-^{3}He reaction is currently difficult to sustain in the laboratory. However, it remains a viable long term goal for a radiation free fusion reaction.

Second, it can be seen from Figure 3 that the total number of ^{3}He reactor articles has greatly increased over the past eight years due to the discovery of the aforementioned ^{3}He source on the moon. The number of reactor articles published since 1989 (256) accounts for 71% of the total reactor articles. The interest and research in the ^{3}He reactor field continues to grow because reactors containing this fuel have been shown to be plausible. All areas of ^{3}He fusion reactor research should be continued as they are all important to the further understanding of the practicality of ^{3}He fusion. The breakdown of ^{3}He reactor articles by reactor type is seen in Figure 4.

Tokamaks

Tokamak research has consistently been the area of largest interest throughout the fusion community and that trend continues in the field of ^{3}He reactors. The 151 articles published in the ^{3}He tokamak reactor area are 40% of the total number of reactor articles published. Over the past seven years the number of articles published per year in this field has more than tripled. The article publishing trend is seen in Figure 5; the noticeable jump in articles since 1988 is clearly visible.

He-3 Fusion Has Been Investigated in Many Confinement Concepts

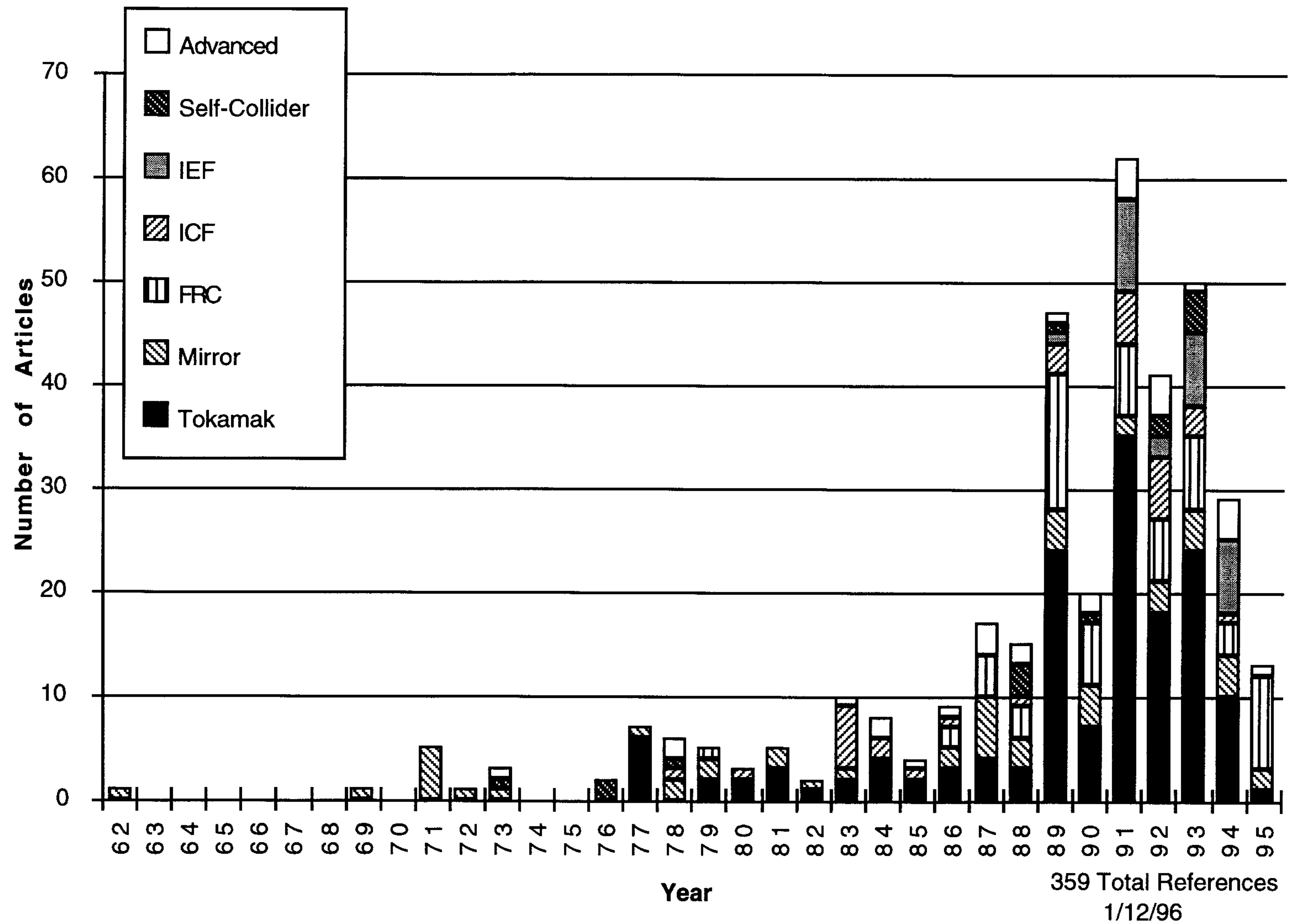


Figure 3

The D-He3 Tokamak Accounts for Approximately 40% of the Total He-3 Reactor Design Articles

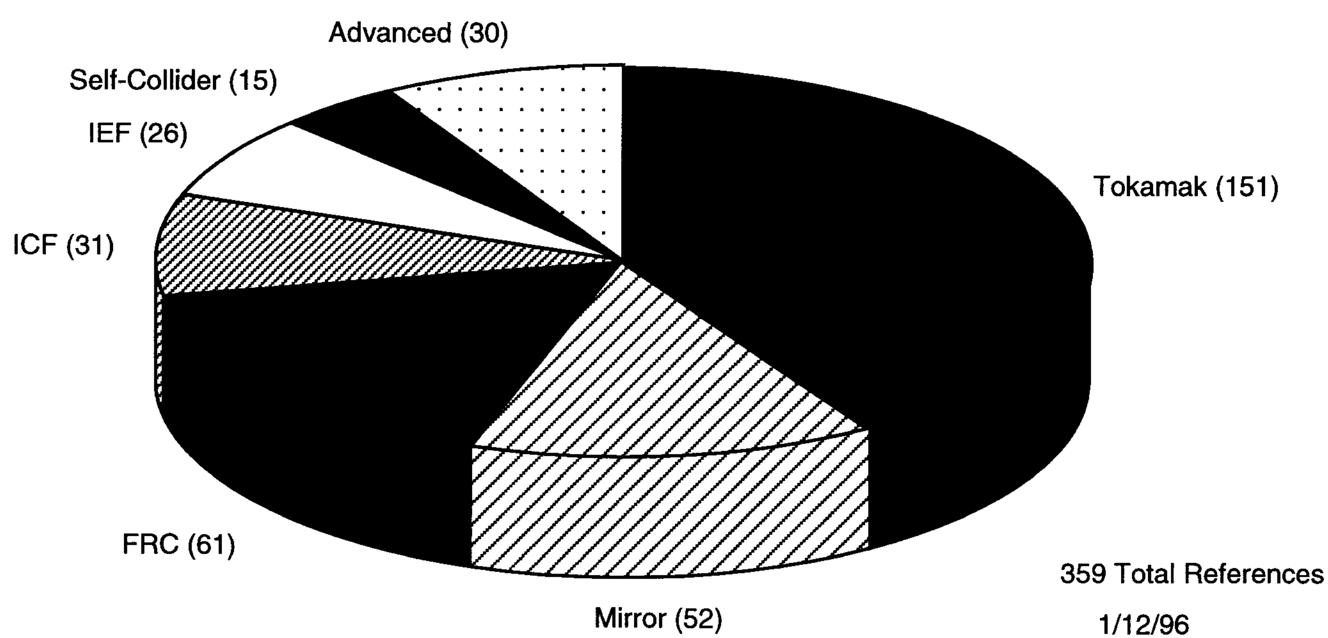
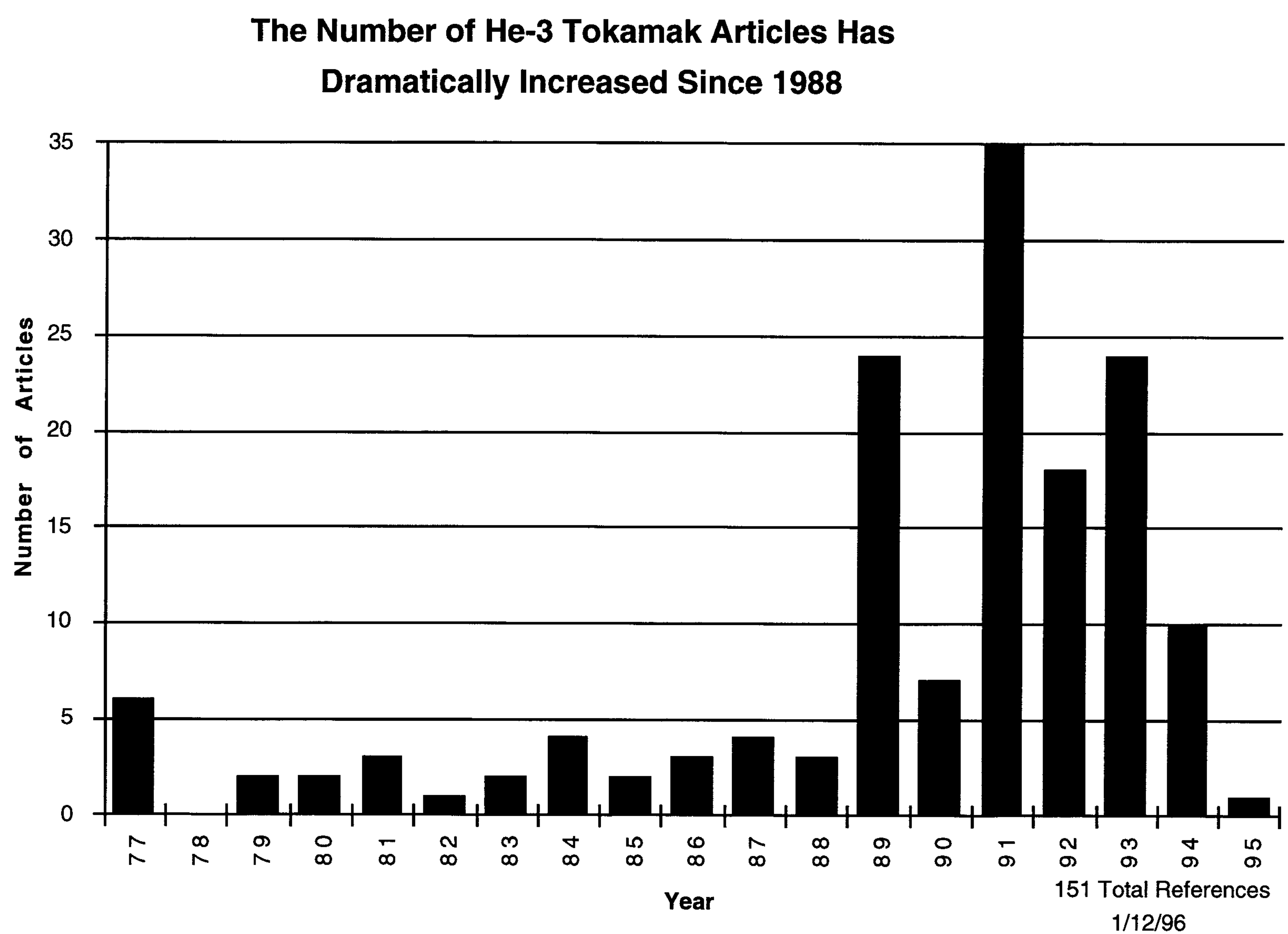


Figure 4



The Number of He-3 Tokamak Articles Has
Dramatically Increased Since 1988
Number of Articles
35
30
25
20
15
10
5
0
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
Year
151 Total References
1/12/96

Figure 5

FRC

Field Reversed Configuration (FRC) is the second leading article generator with 61 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 "rediscovery" of the ^3He resource on the moon. Japan is particularly strong in FRC research as can be seen in Figure 6, accounting for more than half 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 52 articles. Magnetic Mirror reactors have been studied for a long time; the first D-^3He mirror reactor was suggested in 1962 [6]. 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 7 shows the number of ^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 [7]. 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 work in an IEF reactor. The use of ^3He in an IEF fusion reactor is a recent idea as only 26 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 32 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 ion 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

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

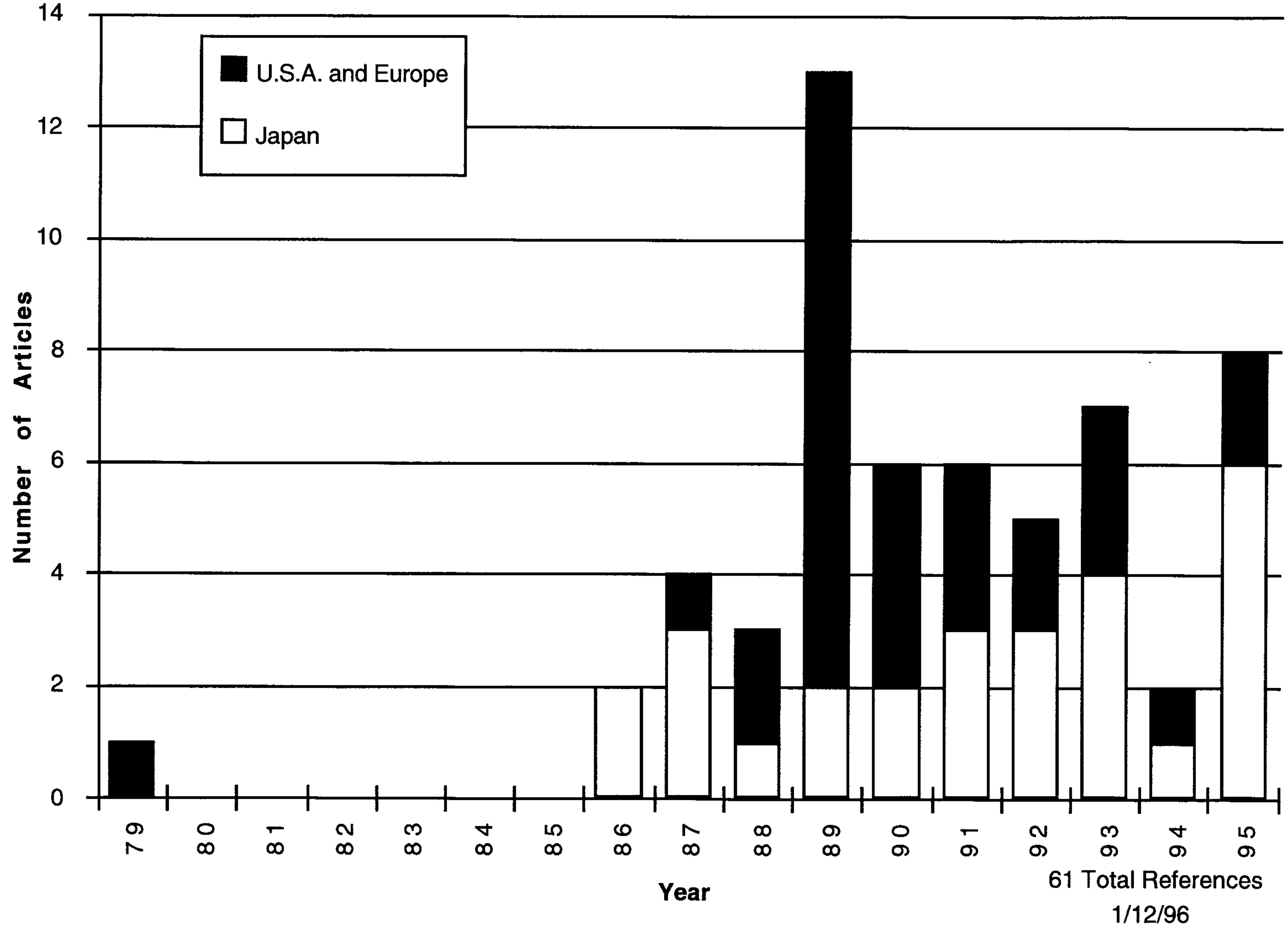


Figure 6

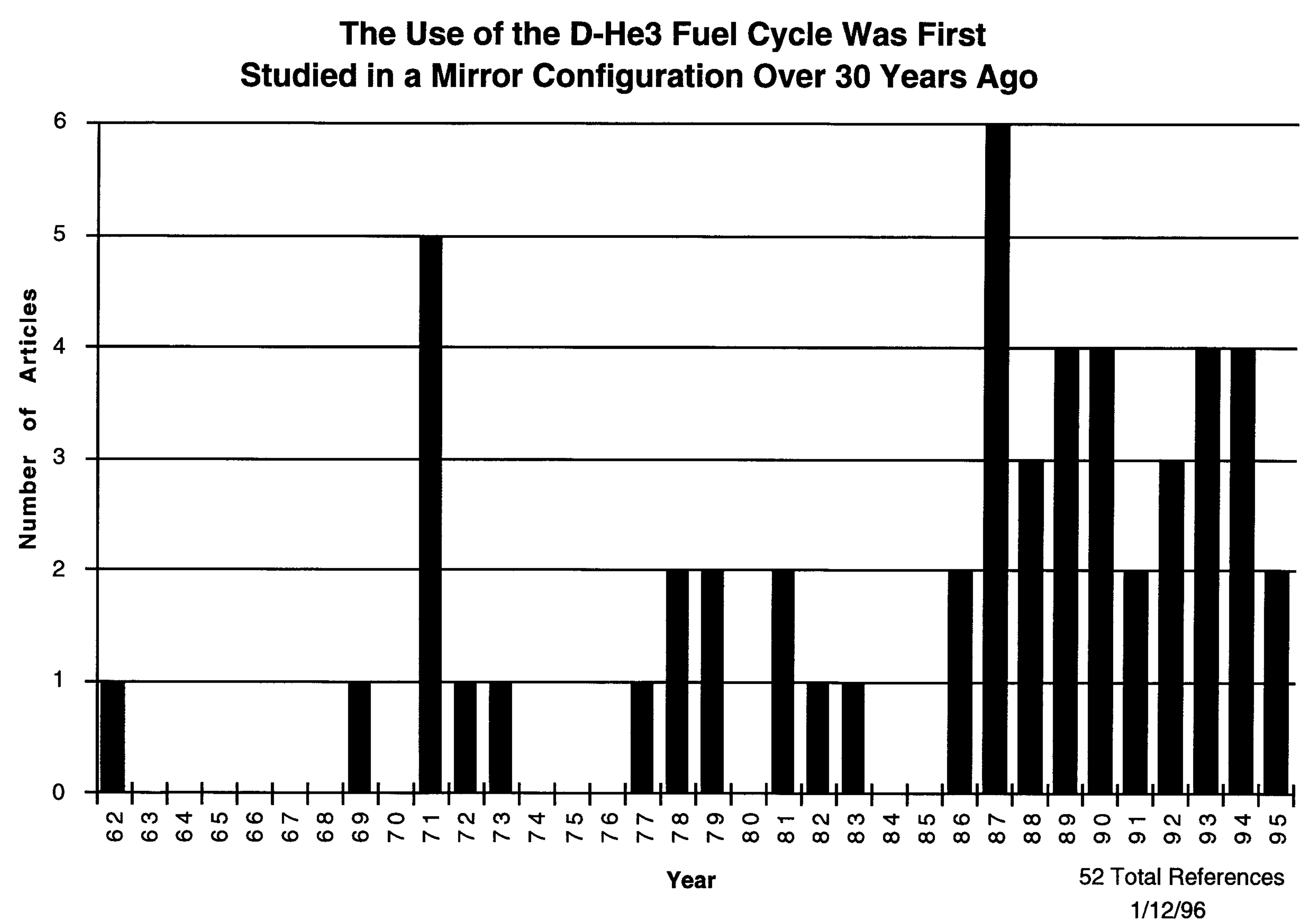

The Use of the D-He3 Fuel Cycle Was First
Studied in a Mirror Configuration Over 30 Years Ago
Number of Articles
0
1
2
3
4
5
6
62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95
Year
52 Total References
1/12/96

Figure 7

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 30 articles on advanced type reactors. Figure 8 is a combined graph showing the ^{3}He reactor articles published for IEF, ICF, Self-Colliders, and Advanced type reactors.

IV. ^{3}He RESOURCES OF THE EARTH AND SPACE

Overall, there are 345 articles on ^{3}He resources in the current bibliography. Of these articles, 166 are concerned with terrestrial resources, 160 with lunar resources, and 55 with space (non-lunar) resources. Quick addition shows that 381 articles have been accounted for; however, since some articles contain information on terrestrial, lunar, and/or space resources, they are included in each category. Figure 9 shows the publishing trends for ^{3}He resource articles over the past 53 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 ^{3}He on Earth as found in oceanic basalts and crusts, volcanic gases, and natural gas wells. Unfortunately, there have not been measurements of sizable quantities of ^{3}He on Earth.

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

The first article reporting ^{3}He on the moon was published in 1969 as a result of Apollo-11 sample analyses [8]. Over the next 16 years, there were scattered reports in the literature about the analysis of samples from other Apollo missions. However, these articles were purely scientific in content and did not connect the lunar ^{3}He to possible uses in fusion reactors.

In the 1980's, the advantages of a D-^{3}He 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 ^{3}He and were also the first to make the correlation between D-^{3}He fusion and ^{3}He on the moon. 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 ^{3}He 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 ^{3}He exist

The Interest in He-3 Fuel Cycles has Increased Since 1988

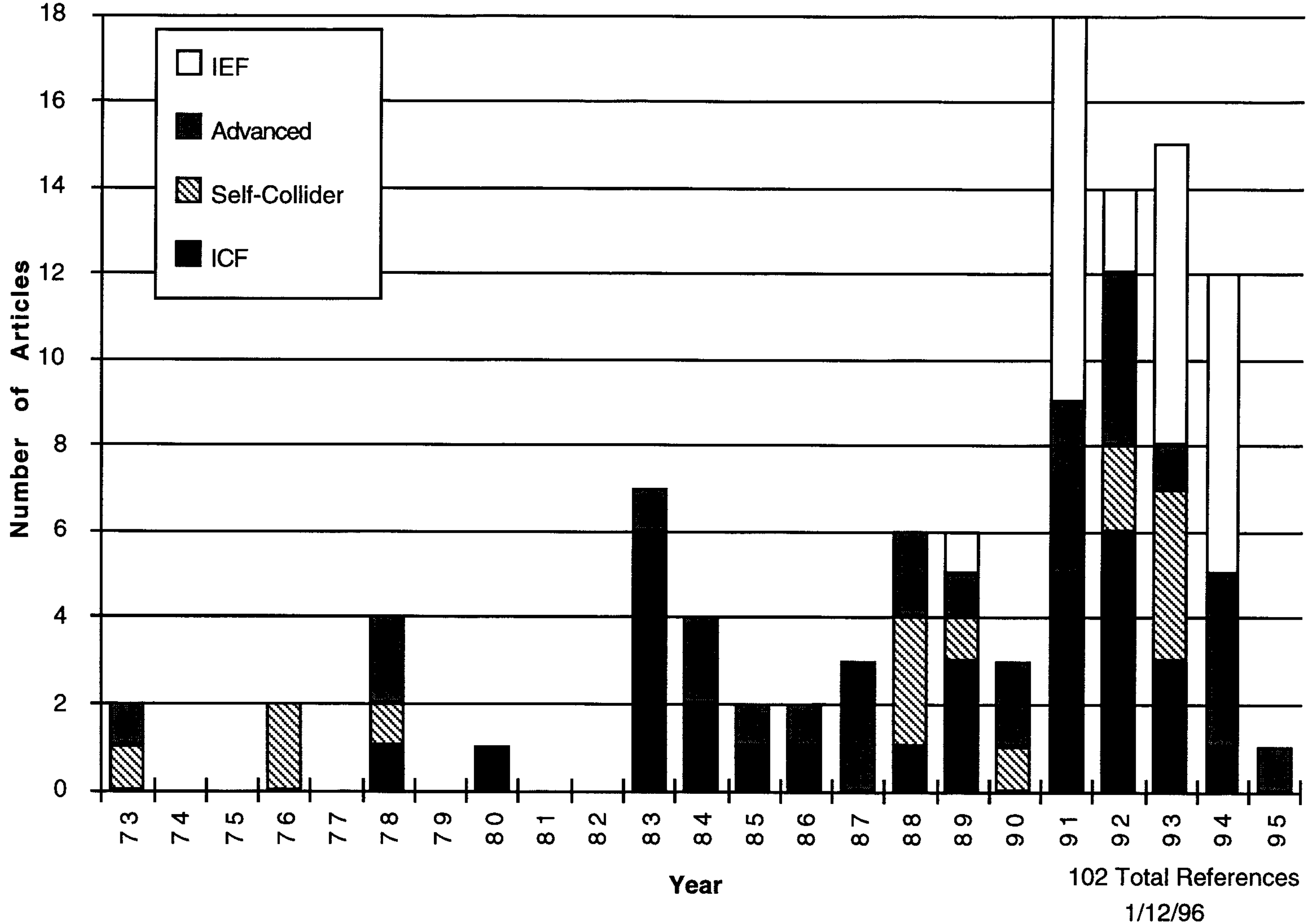


Figure 8

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 166 sources concerning terrestrial sources of ^3He have been found and their publishing trend is shown in Figure 10. 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 [9]. However, the vast majority of articles (158 of 166) have been written since 1969.

Lunar Resources

There are 160 references to lunar ^3He resources, 117 of which have been written since 1986 when the Wittenberg et al. [2] article was first published. Figure 11 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 [8]. Since 1986, ^3He lunar resources articles have primarily dealt with methods of extracting the isotope from the moon and the quantities that actually exist there. Over 80% (140 of 160) of the articles dealing with lunar resources have been published since 1986.

Space Resources

There are 55 references to space resources of ^3He as shown in Figure 12. 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 (40 of 55).

V. FUSION PROPULSION USING ^3He

Space propulsion via the D-^3He fusion reaction has garnered much interest over the years. As evidenced by the 58 articles published over a span of 30 years, the idea behind D-^3He fusion propulsion has long been known. Figure 13 displays this publishing trend for fusion propulsion articles. The first article citing D-^3He as a possible fuel for fusion space propulsion appeared in 1961 by J.R. Roth [10]. Since that time, less than one article a year appeared on the average, in scholarly journals until 1989. However, the period since 1989 has seen 38 of the 58 articles on D-^3He propulsion written. Now that a viable source of ^3He has been found, D-^3He propulsion and exploration of our solar system have become distinct possibilities.

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

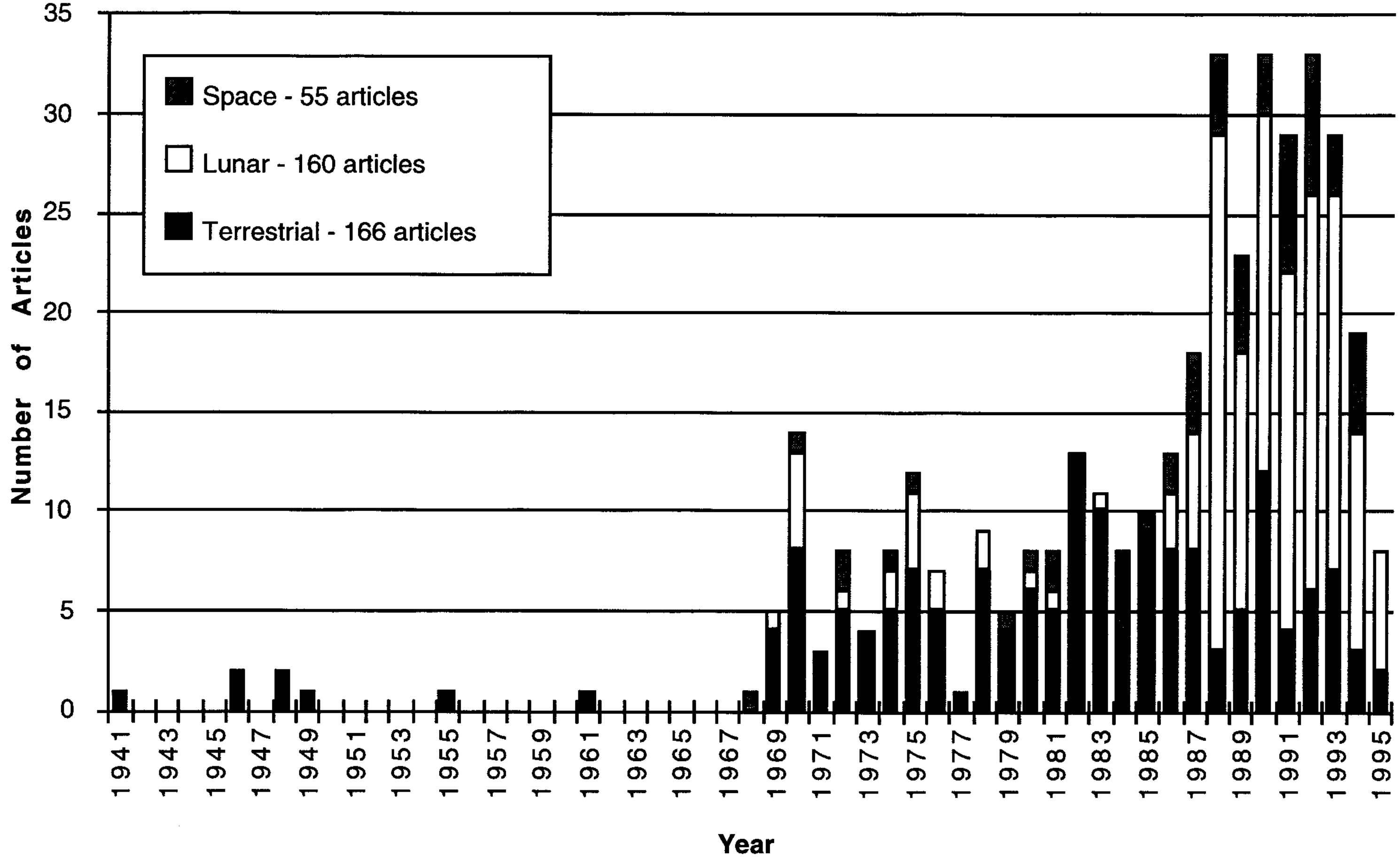
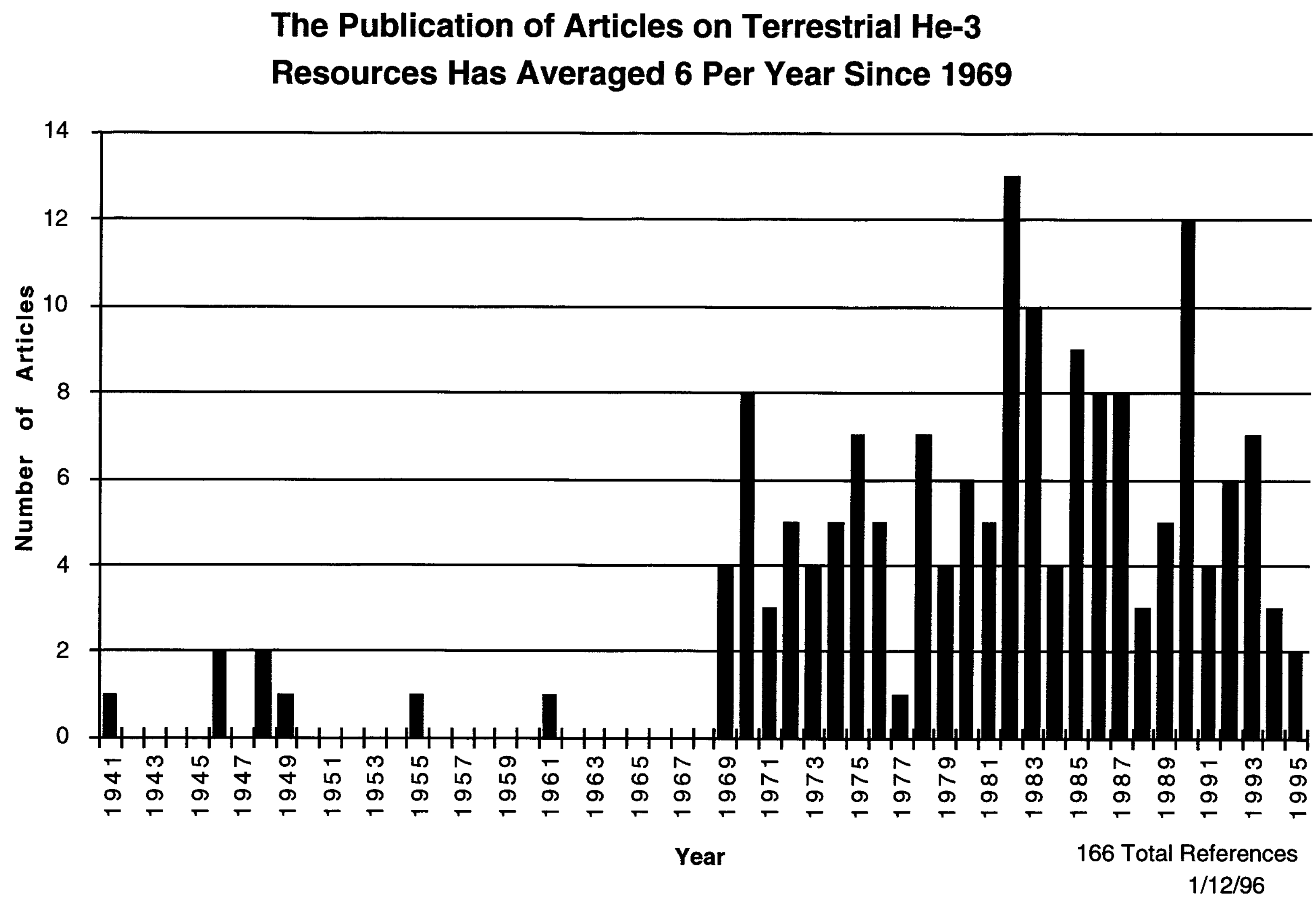


Figure 9



The Publication of Articles on Terrestrial He-3
Resources Has Averaged 6 Per Year Since 1969
Number of Articles
0
2
4
6
8
10
12
14
1941
1943
1945
1947
1949
1951
1953
1955
1957
1959
1961
1963
1965
1967
1969
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
Year
166 Total References
1/12/96

Figure 10

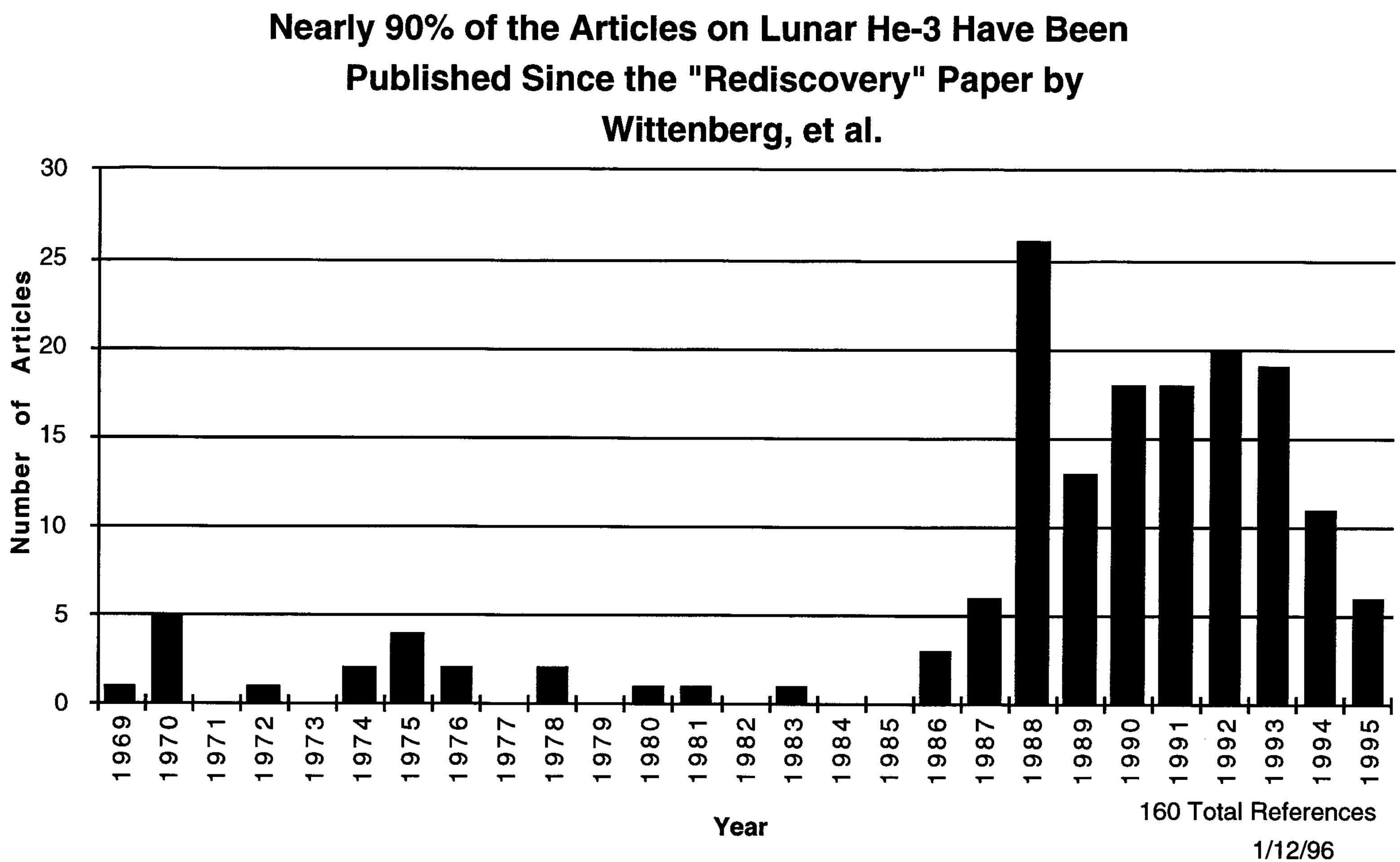

Nearly 90% of the Articles on Lunar He-3 Have Been Published Since the "Rediscovery" Paper by Wittenberg, et al.
Number of Articles
30
25
20
15
10
5
0
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
Year
160 Total References
1/12/96

Figure 11

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

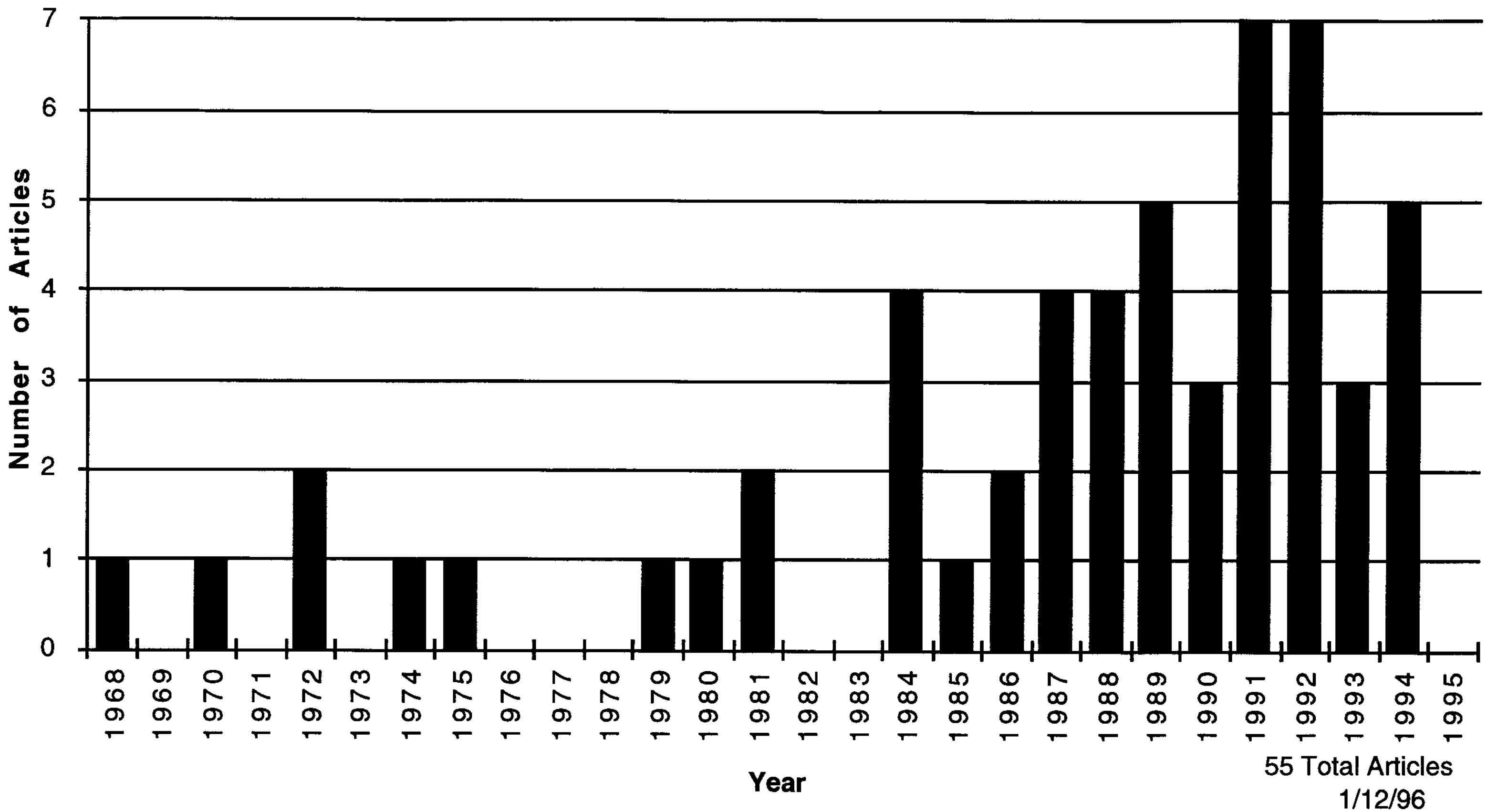


Figure 12

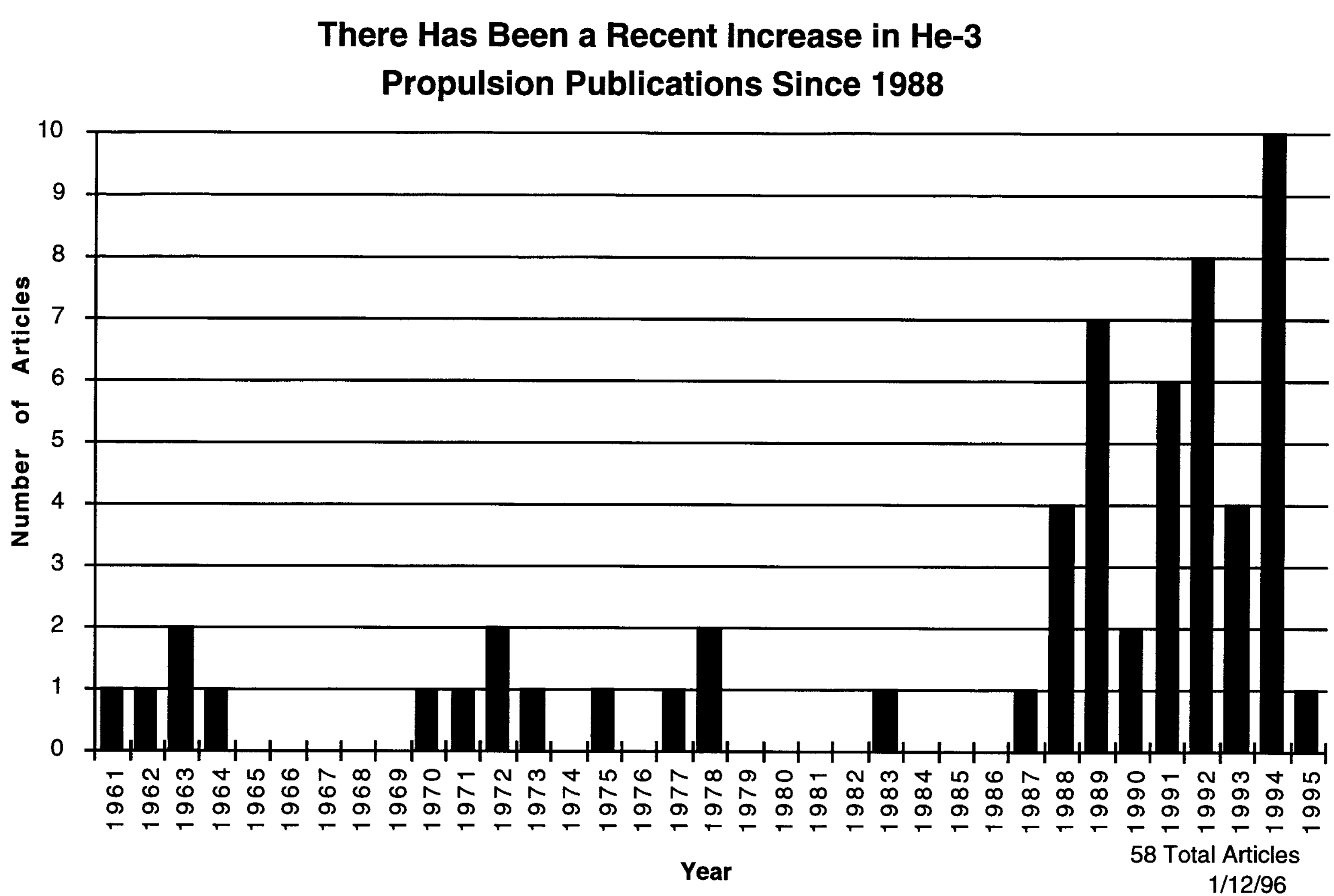

There Has Been a Recent Increase in He-3
Propulsion Publications Since 1988
Number of Articles
0
1
2
3
4
5
6
7
8
9
10
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
Year
58 Total Articles
1/12/96

Figure 13

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 at least 43 original newspaper articles in 25 different newspapers in 15 cities written on ^{3}He fusion and resources. All but two articles are from the U.S., those being from Canada and England. It is assumed that other articles have been written about ^{3}He in other cities and countries, but only those that were brought to the author's attention were listed.

Popular Magazines

There are at least 44 articles published on ^{3}He in popular magazines over the period from 1982-1994. Of these, 36 are from the U.S., while others appear from Norway, Germany, Japan and the United Kingdom. Popular press interest in ^{3}He started in 1986, with 42 of the 43 articles printed since that time. This coincides with the discovery of the moon as a vast ^{3}He resource.

VIII. CONCLUSIONS

From the discovery of ^{3}He in 1939 by Luis Alvarez [4, 5], to the first ^{3}He fusion reactor design in 1962 [6], there was essentially no thought of using ^{3}He to produce energy. However, since the "rediscovery" of large quantities of ^{3}He on the moon in 1986 [2], ^{3}He has become a major research topic in the quest for a clean and safe energy alternative for the future power needs of the world. Currently, research into ^{3}He fusion and resources spans four continents and nineteen countries. To facilitate and expand research in this field, a comprehensive list of all the work completed in the ^{3}He field was needed. This collection of the research papers on this topic in one location provides a vast resource to be tapped by future scientists.

ACKNOWLEDGMENT

The author wishes to acknowledge financial support of this work from the Grainger Corporation and the University of Wisconsin.

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2. Wittenberg, L.J., J.F. Santarius, and G.L. Kulcinski, "Lunar Source of ^{3}He for Commercial Fusion Power." *Fusion Technology*, 1986. **10**(2, pt 1): p. 167-178.

3. Crabb, J.C., *et al.*, "Fifty Years Research in Helium-3 Fusion and Helium-3 Resources (revised)," May 1994. UW-Madison. WCSAR-TR-AR3-9312-1.

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5. Alvarez, L.W. and R. Cornog, "Helium and Hydrogen of Mass 3." *Physical Review*, 1939. **56**: p. 613.

6. Post, R.F., "Critical Conditions for Self-sustaining Reactions in the Mirror Machine." *Nuclear Fusion: 1962 Supplement*, 1962(Part I): p. 99-123.

7. Hirsch, R., "Inertial-Electrostatic Confinement of Ionized Fusion Gases." *Journal of Applied Physics*, 1967. **38**(11): p. 4522-4534.

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9. Hill, R.D., "Production of Helium-3." *Physical Review*, 1941. **59**: p. 103.

10. Roth, J.R., "A Preliminary Study of Thermonuclear Rocket Propulsion." *Journal of the British Interplanetary Society*, 1961. **18**: p. 99-109.

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 bibiliography references from past to present.

Appendix C

Newspaper and popular magazine articles arranged alphabetically by author.

APPENDIX A: Fusion and Resources Bibliography

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

A-I. Helium-3 Fusion Bibliography

[1] "Design of D-^{3}He Commercial Tokamak," UW-Madison, DE90-008252; DOE/ER-52158/1 (1989).

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Appendix A-II. Helium-3 Resources Bibliography

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APPENDIX B: Chronological Bibliography

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