

Interim Report  
for the period  
June 1988 to  
January 1989

# Thermonuclear Reaction Bibliography with Cross Section Data for Four Advanced Reactions

March 1989

Author:  
L. T. Cox, Jr.

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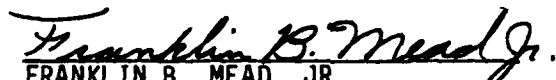
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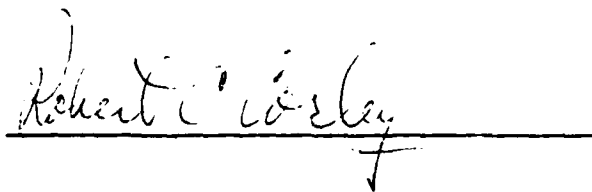
This interim report was submitted by Larry T. Cox, Jr. documenting work he performed while working at the Air Force Astronautics Laboratory (AFAL), Edwards AFB, CA. AFAL Project Manager is Dr Frank Mead.

This report has been reviewed and is approved for release and distribution in accordance with the distribution statement on the cover and on the DD Form 1473.

  
FRANKLIN B. MEAD, JR.  
Project Manager

  
CLARENCE J.C. COLEMAN, JR., CAPT, USAF  
Chief, Advanced Concepts Branch

FOR THE COMMANDER



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<p>The Air Force Astronautics Laboratory (AFAL) is exploring the feasibility of fusion-powered propulsion, and is playing a vital role in the push for its development. This report builds on the earlier work of Jim Pass who assembled a bibliography of all known thermonuclear reactions involving reactant particles up to and including B<sup>11</sup> (Boron-11). However, in the report presented here, the neutron-induced reactions have been eliminated. A few reactions which are new to the earlier report have been found and are included.</p> <p>This report will form the basis for future reports generated from this study. In these future reports, fuel cycles, reaction rates, nuclear scattering, and ignition temperatures will be addressed. Included in this interim report are cross section data for four of the more attractive, in terms of safety, reactions. Graphs showing the data are also presented herein, including one which compares the cross section data curves of the four reactions. All of the data sets are analyzed and recommendations for future cross section work are made.</p>			
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## INTRODUCTION AND SUMMARY

The Air Force Astronautics Laboratory (AFAL) is exploring the feasibility of fusion-powered propulsion and is continuing to play a vital role in the push for its development. A 3-year study entitled "Fusion Fuel Cross Section" is now underway at the AFAL. For this study, cross section data for advanced fuels is being collected and a computer program will be developed to utilize the information in an extension of the results obtained in the "Barn Book" [Ref. 1]. During the study there will be interim reports published to show progress and to provide up-to-date information with a final report published at the end of the study.

This interim report builds on the earlier work of Jim Pass [Ref. 2] who assembled a bibliography of all known thermonuclear reactions involving reactant particles up to and including  $B^{11}$  (Boron-11). In this report the neutron-induced reactions have been eliminated. In later work, reaction specifics including cross sections, reaction parameters, and curve-fit equations will be compiled, developed, and tabulated for the reactions. Throughout the study conclusions will be made concerning which data are most accurate and which reactions seem to be the best candidates for propulsion fuels, thus giving researchers an idea of where to focus their work. The reports which evolve will serve as valuable references for anyone studying advanced thermonuclear reactions and their respective characteristics.

Many reasons justify Air Force interest in advanced fusion propulsion. In particular, the limits of chemical systems are driving factors to search for a new alternative. Several aspects of fusion push for its development. These include high specific impulse (1500 to 10,000 seconds), limited neutron and gamma-ray production, high thrust, and environmentally safe exhaust products. Such possibilities will enable space missions never before realized and will greatly enhance or make more efficient current Air Force missions.

This report includes reaction lists which have been cross-referenced extensively to insure accuracy. Cross section data have been compiled to produce plots for some of the reactions viewed as promising because of negligible production of harmful radiation. An assessment of the data which is currently available for each of these chosen reactions is included. Additional data will be continually collected for all the reactions listed. Ultimately the final report will include comprehensive information for each reaction.

Compiling the reaction list involved a re-examination of most of the references used in the earlier report [Ref. 2] as well as a detailed inspection of additional thermonuclear reaction references. If a reaction listed in the earlier report could not be found in available resources, the source referenced in the earlier report is referenced once again. As additional sources become available in the future, the reactions in question will be checked for their accuracy. The search for, and interpretation of, cross section data involved contacting fusion experts at various universities and national laboratories. Two national laboratories were of particular help in this effort. Brookhaven National Laboratory [Ref. 3] provided access to its huge nuclear cross section data file, and Los Alamos National Laboratory [Ref. 4] contributed its latest cross section data, which was fitted using R-Matrix analysis. In addition, the Fusion Studies Laboratory of the University of Illinois at Urbana-Champaign was timely in sending up-to-date data for the  $\text{He}^3\text{-He}^3$  reaction.

Some interesting developments have emerged. Differences between previously published data and the data available here are presented, and other notable points are discussed in the section entitled "CROSS SECTION NOTES AND GRAPHS." An assessment of the available data and recommendations for further research accompany it. Future aims of the study are roughly outlined as well.

## THERMONUCLEAR REACTION BIBLIOGRAPHY

On the next few pages are lists of possible fuels for fusion propulsion systems. Neutron-induced reactions have been excluded from the bibliography, as the aim of this interim report is to look closely at cross section data for a few hopeful reactions. Later in this study, a report which includes the neutron-based reactions may be published as a tool for determining the constituent reactions of a fuel cycle. Until such a time, consult the earlier bibliography [Ref. 2] for this information. Neutron reactions are also documented in other sources, such as S. Flugge's work [Ref. 5].

### BACKGROUND

Since the 1950's, no large efforts have been made to discover thermonuclear reactions in the isotopic range between  $H^1$  and  $B^{11}$ . Thus, the works of S. Flugge [Ref. 5] and others remain important sources to this day. Current efforts exploit these known reactions, but do not attempt to find new ones. Thus, the compilation presented here should not be viewed as complete. There may be additional reactions remaining to be found, and increased interest in fusion may lead to their discovery. It should be noted that many independent data sources comprise Ref. 3, a fact which should explain seemingly conflicting information in the following pages. This may also surface in reference to other sources.

LIST OF SYMBOLS [Ref. 2]

$Q$  =  $Q$ (MeV) values taken from Ref. 2 or calculated using the mass defect formula:

$$Q = [(m_a + m_b) - (m_c + m_d + \dots)] * C$$

$$C = 931.481 \text{ MeV/amu}$$

$m_a$  = mass of target particle

$m_b$  = mass of incident particle

$m_c, m_d, \dots$  = masses of reaction products

The two notations for a thermonuclear reaction are related as follows:



where the species within the parentheses are the particles of smallest reactant mass (b) and smallest initial product mass (c). The second notation is used in conjunction with the cross section graphs.

Other symbols used:

\* = isotope in excited state

$\gamma$  = gamma-ray

$e^-$  = electron

$e^+$  = positron

n = neutron

p = proton

d = deuteron

t = triton

---> = this arrow separates reactants and products

--> = reaction product preceding this arrow decays as follows

$He^{3,4,5,6}$  = Helium-3,4,5,6

$Li^{5,6,7,8}$  = Lithium-5,6,7,8

$Be^{7,8,9,10}$  = Beryllium-7,8,9,10

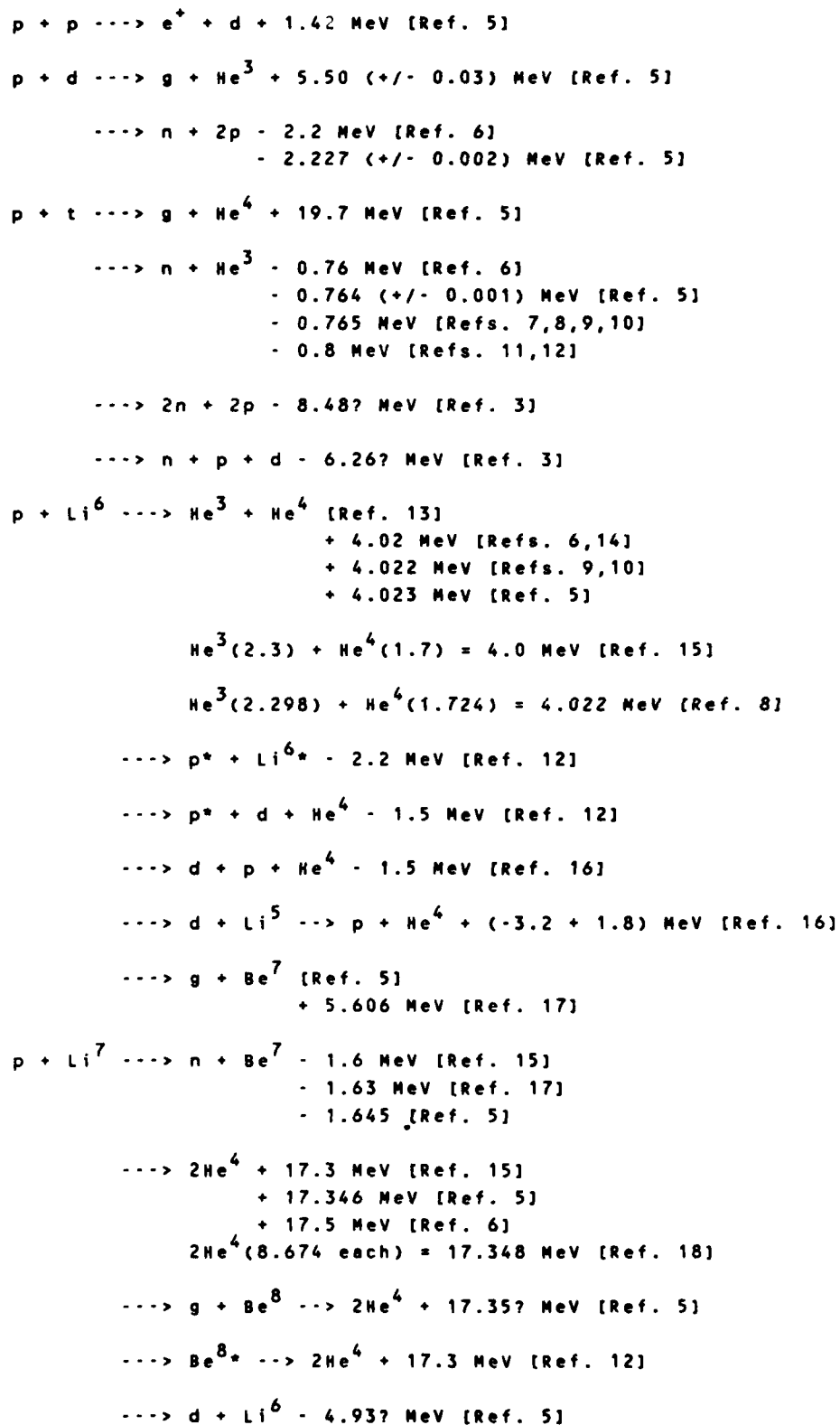
$B^{9,10,11,12}$  = Boron-9,10,11,12

$C^{10,11,12,13,14}$  = Carbon-10,11,12,13,14

$N^{13,14}$  = Nitrogen-13,14

NOTE: All reactions are listed by increasing atomic number of the target nuclide. For a reaction with more than one branch, reactant particles are listed only once, with each branch's products given on a separate line.

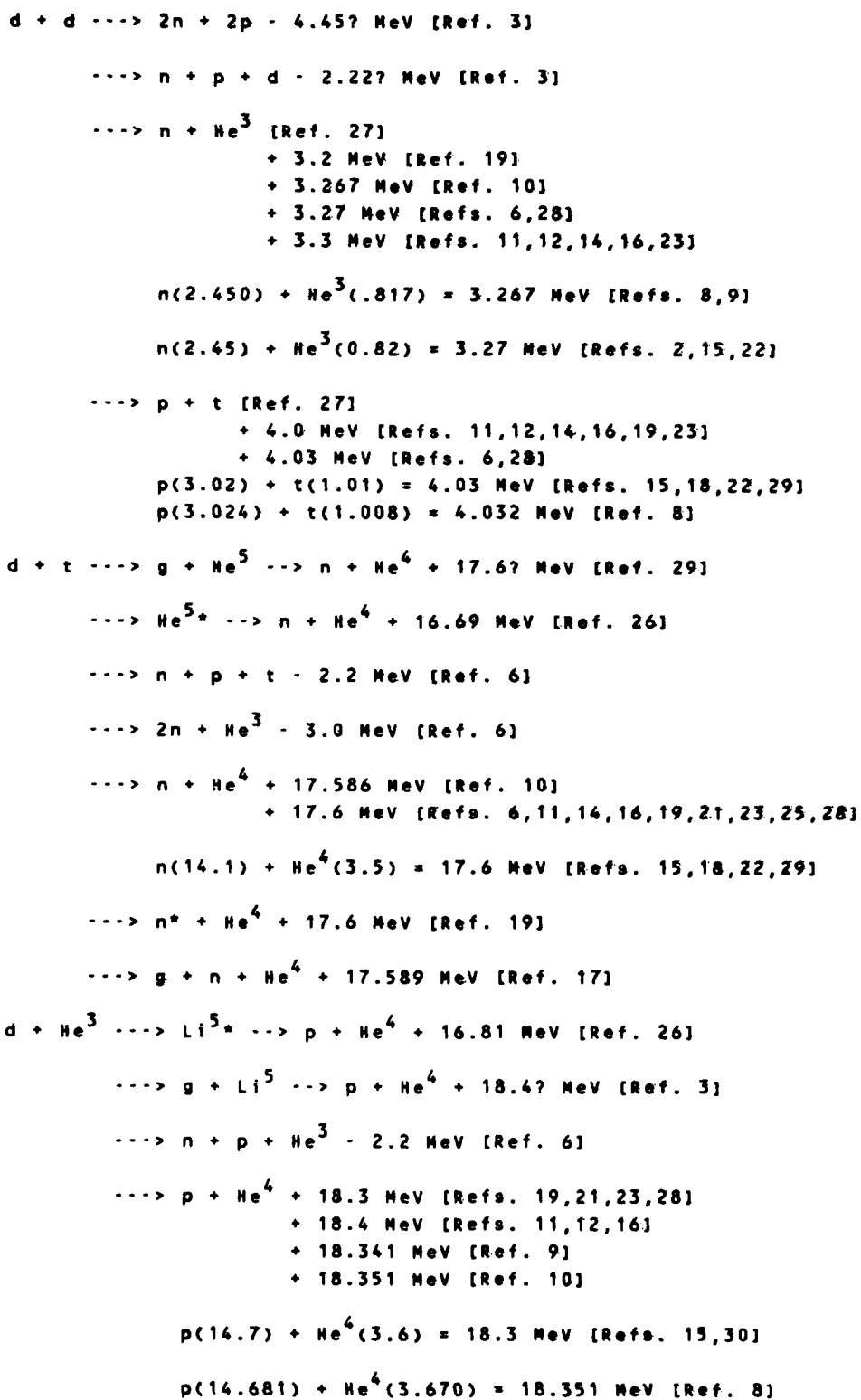
PROTON-INDUCED REACTIONS



$p + \text{Be}^7 \rightarrow g + \text{B}^8 + 0.138 \text{ MeV [Ref. 17]}$   
 $p + \text{Be}^9 \rightarrow n + p + \text{Be}^8 \rightarrow 2\text{He}^4 - 1.67 \text{ MeV [Ref. 5]}$   
 $\rightarrow n + \text{B}^9 \rightarrow p + 2\text{He}^4 - 1.852 \text{ MeV [Ref. 5]}$   
 $\rightarrow \text{He}^4 + \text{Li}^6 + 2.1 \text{ MeV [Refs. 19,20]}$   
 $\quad + 2.125 \text{ MeV [Ref. 9]}$   
 $\quad + 2.126 \text{ MeV [Ref. 5]}$   
 $\quad + 2.13 \text{ MeV [Ref. 14]}$   
 $\text{He}^4(1.275) + \text{Li}^6(0.850) = 2.125 \text{ MeV [Ref. 18]}$   
 $\rightarrow g + \text{B}^{10} \text{ [Ref. 5]}$   
 $\quad + 6.585 \text{ MeV [Ref. 17]}$   
 $\rightarrow d + 2\text{He}^4 + 0.56 \text{ MeV [Ref. 14]}$   
 $\quad + 0.7 \text{ MeV [Refs. 19,20]}$   
 $\rightarrow d + \text{Be}^8 \rightarrow 2\text{He}^4 \text{ [Ref. 5]}$   
 $\quad + 0.651 \text{ [Ref. 17]}$   
 $\rightarrow t + \text{Be}^7 - 12.17 \text{ MeV [Ref. 5]}$   
 $\rightarrow \text{B}^{10}(6.88) - .295 \text{ MeV [Ref. 20]}$   
 $p + \text{B}^{10} \rightarrow \text{He}^4 + \text{Be}^7 + 1.148 \text{ MeV [Ref. 5]}$   
 $\quad + 1.147 \text{ MeV [Ref. 9]}$   
 $\rightarrow n + \text{C}^{10} \rightarrow \text{B}^{10} + e^+ - 4.35 \text{ MeV [Ref. 5]}$   
 $\rightarrow g + \text{C}^{11} \rightarrow \text{B}^{11} + e^+ \text{ [Ref. 5]}$   
 $\quad + 8.690 \text{ MeV [Ref. 17]}$   
 $\rightarrow d + \text{B}^9 \rightarrow p + 2\text{He}^4 - 5.877 \text{ MeV [Ref. 5]}$   
 $\rightarrow t + \text{B}^8 \rightarrow e^+ + \text{Be}^8 \rightarrow 2\text{He}^4 - 1.00 \text{ MeV [Ref. 5]}$   
 $\rightarrow \text{He}^3 + \text{Be}^8 \rightarrow 2\text{He}^4 \text{ [Ref. 5]}$   
 $\quad - 0.442 \text{ MeV [Ref. 17]}$

$p + B^{11} \rightarrow He^4 + Be^8(\text{ground state}) \rightarrow 2He^4$  [Ref. 21]  
 $\rightarrow He^4 + Be^{8*}$  [Ref. 21]  
 $\rightarrow He^4 + Be^8 \rightarrow 2He^4 + 8.585 \text{ MeV}$  [Ref. 5]  
 $\rightarrow 3He^4$  [Ref. 21]  
 $\quad + 8.7 \text{ MeV}$  [Refs. 15,19,21,22,23,24,25]  
 $\quad + 8.68 \text{ MeV}$  [Ref. 14]  
 $3He^4(2.888 \text{ each}) = 8.664 \text{ MeV}$  [Ref. 9]  
 $\rightarrow n + C^{11} \rightarrow B^{11} + e^+ - 2.762 \text{ MeV}$  [Ref. 5]  
 $\rightarrow g + C^{12}$  [Ref. 5]  
 $\quad + 15.956 \text{ MeV}$  [Ref. 17]  
 $\rightarrow d + B^{10} - 9.10 \text{ MeV}$  [Ref. 5]  
 $\rightarrow C^{12*} + 16.11 \text{ MeV}$  [Ref. 26]  
 $\quad + 16.58 \text{ MeV}$  [Ref. 26]

DEUTERON-INDUCED REACTIONS



$d + \text{He}^3 \rightarrow p(14.68) + \text{He}^4(3.67) = 18.35 \text{ MeV [Ref. 7]}$   
 $d + \text{He}^4 \rightarrow n + p + \text{He}^4 - 2.2 \text{ MeV [Ref. 6]}$   
 $\rightarrow p + \text{He}^5 \rightarrow n + \text{He}^4 - 2.227 \text{ MeV [Ref. 3]}$   
 $d + \text{Li}^6 \rightarrow g + n + \text{Be}^7 + 3.38? \text{ MeV [Ref. 3]}$   
 $\rightarrow n + \text{He}^3 + \text{He}^4 + 1.72 \text{ MeV [Ref. 6]}$   
 $\quad + 1.796 \text{ MeV [Refs. 9,10]}$   
 $\quad + 1.8 \text{ MeV [Refs. 11,12,19]}$   
 $n(1.134) + \text{He}^3(0.378) + \text{He}^4(0.284) = 1.796 \text{ MeV [Refs. 2,8]}$   
 $\rightarrow n + \text{Be}^7 + 3.34 \text{ MeV [Ref. 6]}$   
 $\quad + 3.40 \text{ MeV [Refs. 5,11,12,16,19]}$   
 $n(2.957) + \text{Be}^7(0.423) = 3.380 \text{ MeV [Refs. 8,9]}$   
 $\rightarrow n + \text{Be}^7 \rightarrow n + \text{He}^3 + \text{He}^4 + 6.28? \text{ MeV [Ref. 13]}$   
 $\rightarrow p + \text{Li}^7 + 5.0 \text{ MeV [Refs. 11,12,16,19]}$   
 $\quad + 5.02 \text{ MeV [Ref. 6]}$   
 $\quad + 5.026 \text{ MeV [Refs. 9,10]}$   
 $\quad + 5.027 \text{ MeV [Ref. 5]}$   
 $p(4.398) + \text{Li}^7(0.628) = 5.026 \text{ MeV [Refs. 8,18]}$   
 $\rightarrow p + \text{Li}^7 \rightarrow p + t + \text{He}^4 + 4.73? \text{ MeV [Ref. 13]}$   
 $\rightarrow p + \text{Li}^7 \rightarrow g + \text{Li}^7 + (4.54 + 0.45) \text{ MeV [Ref. 6]}$   
 $\rightarrow p + t + \text{He}^4 + 2.557 \text{ MeV [Ref. 17]}$   
 $\quad + 2.561 \text{ MeV [Refs. 9,10]}$   
 $\quad + 2.6 \text{ MeV [Refs. 11,12,16,19]}$   
 $\rightarrow t + \text{Li}^5 \rightarrow p + \text{He}^4 + (0.9 + 1.6) \text{ MeV [Ref. 6]}$   
 $t(0.539) + p(1.618) + \text{He}^4(0.404) = 2.561 \text{ MeV [Refs. 8,18]}$   
 $\rightarrow \text{He}^3 + \text{He}^5 \rightarrow n + \text{He}^4 + (0.8 + 1.0) \text{ MeV [Ref. 16]}$   
 $\rightarrow 2\text{He}^4 + 22.373 \text{ MeV [Ref. 10]}$   
 $\quad + 22.39 \text{ MeV [Ref. 5]}$   
 $\quad + 22.4 \text{ MeV [Refs. 6,11,12,15,16,19,22]}$   
 $2\text{He}^4(11.187 \text{ each}) = 22.374 \text{ MeV [Refs. 8,9,18]}$   
 $d + \text{Li}^7 \rightarrow g + 2n + \text{Be}^7 - 3.87? \text{ MeV [Ref. 3]}$   
 $\rightarrow g + p + \text{Li}^8 \rightarrow e^- + \text{Be}^8 \rightarrow 2\text{He}^4 + 15.4? \text{ MeV [Ref. 3]}$   
 $\quad \rightarrow 2\text{He}^4 + 15.9? \text{ MeV [Ref. 3]}$   
 $\rightarrow 2n + \text{Be}^7 - 3.869 \text{ MeV [Ref. 17]}$

$d + Li^7 \rightarrow n + Be^8 \rightarrow 2He^4 + 15.0 \text{ MeV [Refs. 5,6]}$   
 $n(10.082) + 2He^4(2.521 \text{ each}) = 15.124 \text{ MeV [Ref. 18]}$   
 $\rightarrow p + Li^8 \rightarrow e^- + Be^8 \rightarrow 2He^4 + (-0.26 + 16.0) \text{ MeV [Ref. 6]}$   
 $\rightarrow t + Li^6 - 0.995 \text{ MeV [Ref. 6]}$   
 $\rightarrow He^4 + He^5 \rightarrow n + He^4 + 14.2 \text{ MeV [Ref. 5]}$   
 $\rightarrow Be^9 + 16.674 \text{ MeV [Ref. 26]}$

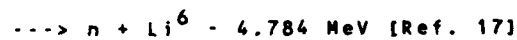
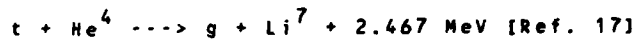
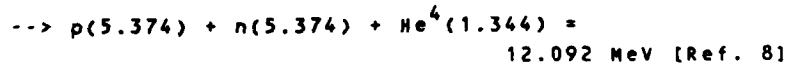
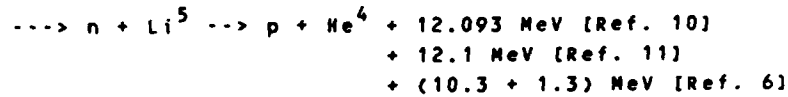
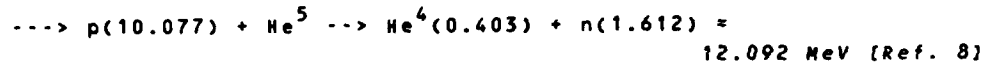
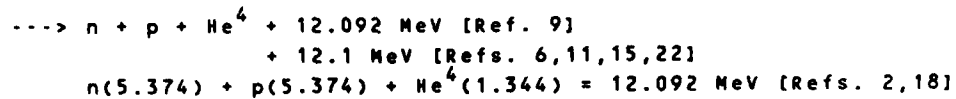
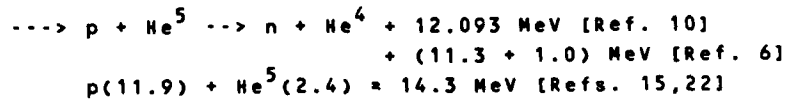
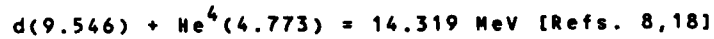
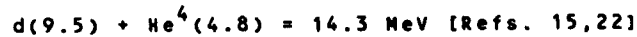
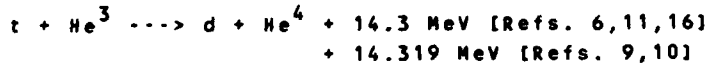
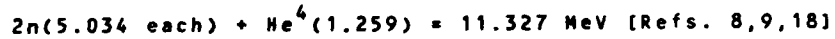
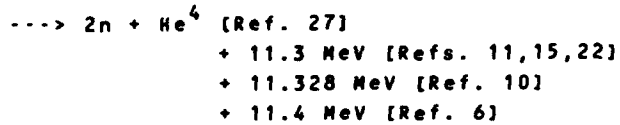
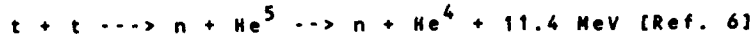
$d + Be^7 \rightarrow p + 2He^4 + 16.7 \text{ MeV [Ref. 16]}$   
 $+ 16.766 \text{ MeV [Ref. 17]}$   
 $p(11.179) + 2He^4(2.795 \text{ each}) = 16.769 \text{ MeV [Ref. 18]}$

$d + Be^9 \rightarrow \alpha + B^{11} + 15.87 \text{ MeV [Ref. 3]}$   
 $\rightarrow p + Be^{10} + 4.588 \text{ MeV [Ref. 5]}$   
 $\rightarrow n + B^{10} + 4.35 \text{ MeV [Ref. 5]}$   
 $\rightarrow t + Be^8 \rightarrow 2He^4 + 4.687 \text{ MeV [Ref. 3]}$   
 $\rightarrow He^4 + Li^7 + 7.153 \text{ MeV [Ref. 5]}$

$d + B^{10} \rightarrow p + B^{11} + 9.235 \text{ MeV [Ref. 5]}$   
 $\rightarrow n + C^{11} \rightarrow B^{11} + e^+ + 6.6 \text{ MeV [Ref. 5]}$   
 $\rightarrow He^4 + Be^8 \rightarrow 2He^4 + 17.86 \text{ MeV [Ref. 5]}$

$d + B^{11} \rightarrow n + C^{12} + 13.8 \text{ MeV [Ref. 5]}$   
 $\rightarrow 2n + C^{11} - 4.997 \text{ MeV [Ref. 3]}$   
 $\rightarrow p + B^{12} \rightarrow e^- + C^{12} + 1.137 \text{ MeV [Ref. 5]}$   
 $\rightarrow He^4 + Li^8 \rightarrow e^- + Be^9 \rightarrow 2He^4$   
 $+ 1.137 \text{ MeV [Ref. 5]}$   
 $\rightarrow He^4 + Be^9 + 8.018 \text{ MeV [Ref. 5]}$

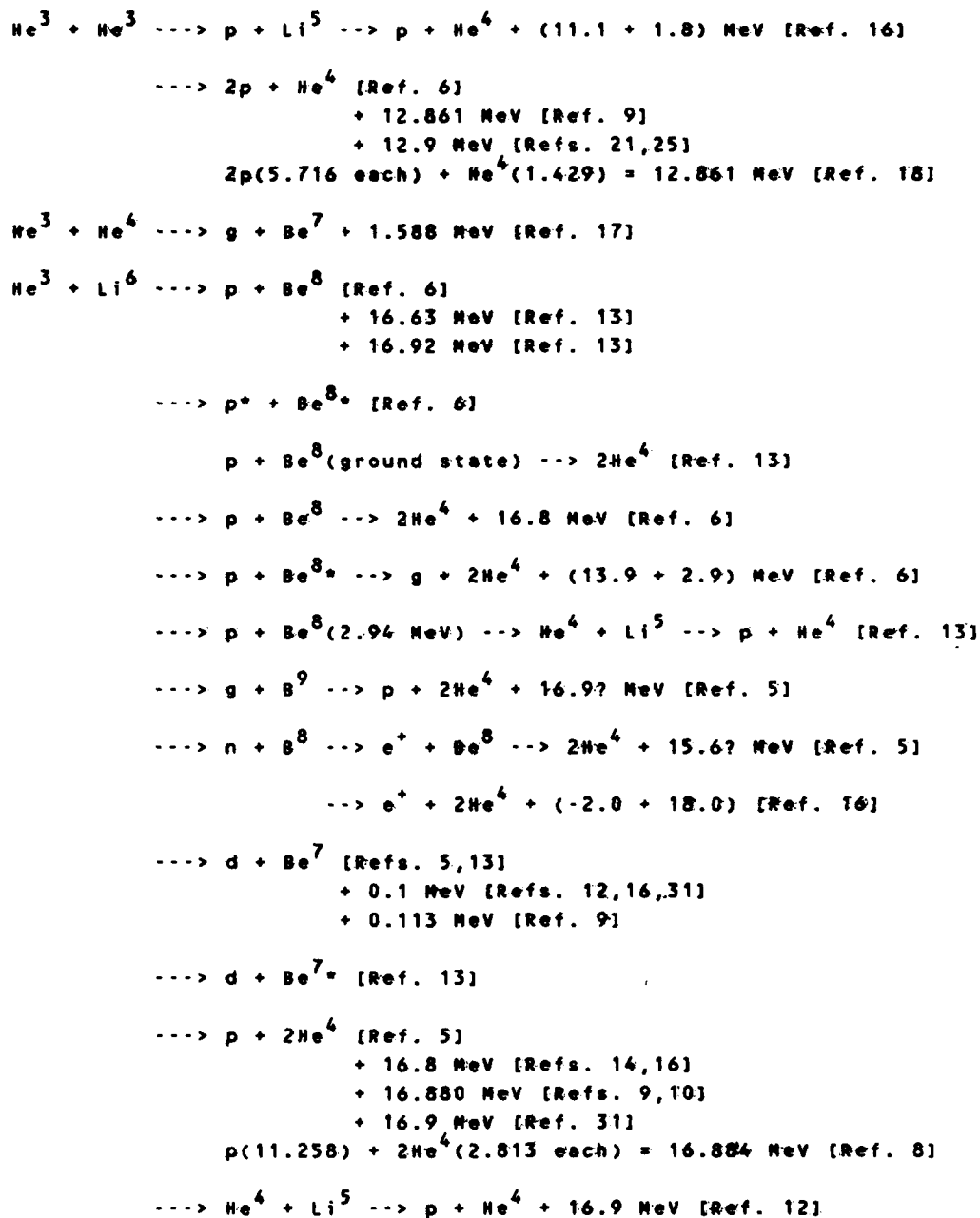
TRITON-INDUCED REACTIONS



$t + Li^6 \rightarrow g + p + Li^8 \rightarrow e + Be^8 \rightarrow 2He^4 + 16.47 \text{ MeV [Ref. 3]}$   
 $\rightarrow 2He^4 + 16.97 \text{ MeV [Ref. 3]}$   
 $\rightarrow d + Li^7 + 0.994 \text{ MeV [Ref. 17]}$   
 $\quad + 0.995 \text{ MeV [Ref. 6]}$   
 $\quad + 1.0 \text{ MeV [Refs. 12, 16]}$   
 $\rightarrow d + Li^{7*} \rightarrow g + Li^7 + (0.509 + 0.45) \text{ MeV [Ref. 6]}$   
 $\rightarrow 2n + Be^7 - 2.876 \text{ MeV [Ref. 17]}$   
 $\rightarrow p + Li^8 + 0.8 \text{ MeV [Ref. 16]}$   
 $\rightarrow e + 2He^4 + 0.800 \text{ MeV [Ref. 6]}$   
 $\rightarrow n + Be^8 \rightarrow 2He^4 + 16.0 \text{ MeV [Ref. 6]}$   
 $\rightarrow n + 2He^4 + 16.0 \text{ MeV [Ref. 6]}$   
 $\quad + 16.1 \text{ MeV [Ref. 16]}$   
 $\rightarrow g + Be^9 + 17.77 \text{ MeV [Ref. 5]}$   
 $\rightarrow He^4 + He^5 \rightarrow n + He^4 + 16.17 \text{ MeV [Ref. 5]}$   
 $t + Li^7 \rightarrow g + d + Li^8 \rightarrow e^- + Be^8 \rightarrow 2He^4 + 11.47 \text{ MeV [Ref. 3]}$   
 $\rightarrow 2He^4 + 11.97 \text{ MeV [Ref. 3]}$   
 $\rightarrow 2n + 2He^4 \text{ [Ref. 6]}$   
 $\rightarrow 2n + 2He^4 + 8.88 \text{ MeV [Ref. 6]}$   
 $\quad 2n(6.049 \text{ each}) + 2He^4(1.512 \text{ each}) = 15.122 \text{ MeV [Ref. 18]}$   
 $\rightarrow n + Be^9 + 10.4 \text{ MeV [Ref. 12]}$   
 $\quad + 10.52 \text{ MeV [Ref. 6]}$   
 $\rightarrow 2n + Be^8 \rightarrow 2He^4 + 8.83 \text{ MeV [Ref. 6]}$   
 $\rightarrow 2n + 2He^4 + 8.8 \text{ MeV [Ref. 12]}$   
 $\rightarrow n + He^4 + He^5 \rightarrow n + He^4 + (8.08 + 1.0) \text{ MeV [Ref. 6]}$   
 $\rightarrow p + Li^9 \rightarrow e^- + Be^9 + 10.77 \text{ MeV [Ref. 3]}$   
 $\rightarrow n + 2He^4 + 9.657 \text{ MeV [Ref. 3]}$   
 $\rightarrow d + Li^8 \rightarrow e^- + Be^8 \rightarrow 2He^4 + 11.47 \text{ MeV [Ref. 3]}$   
 $\rightarrow 2He^4 + 11.97 \text{ MeV [Ref. 3]}$   
 $\rightarrow He^4 + He^6 \rightarrow e^- + Li^6 + 9.83 \text{ MeV [Ref. 6]}$



### HELIUM-3-INDUCED REACTIONS

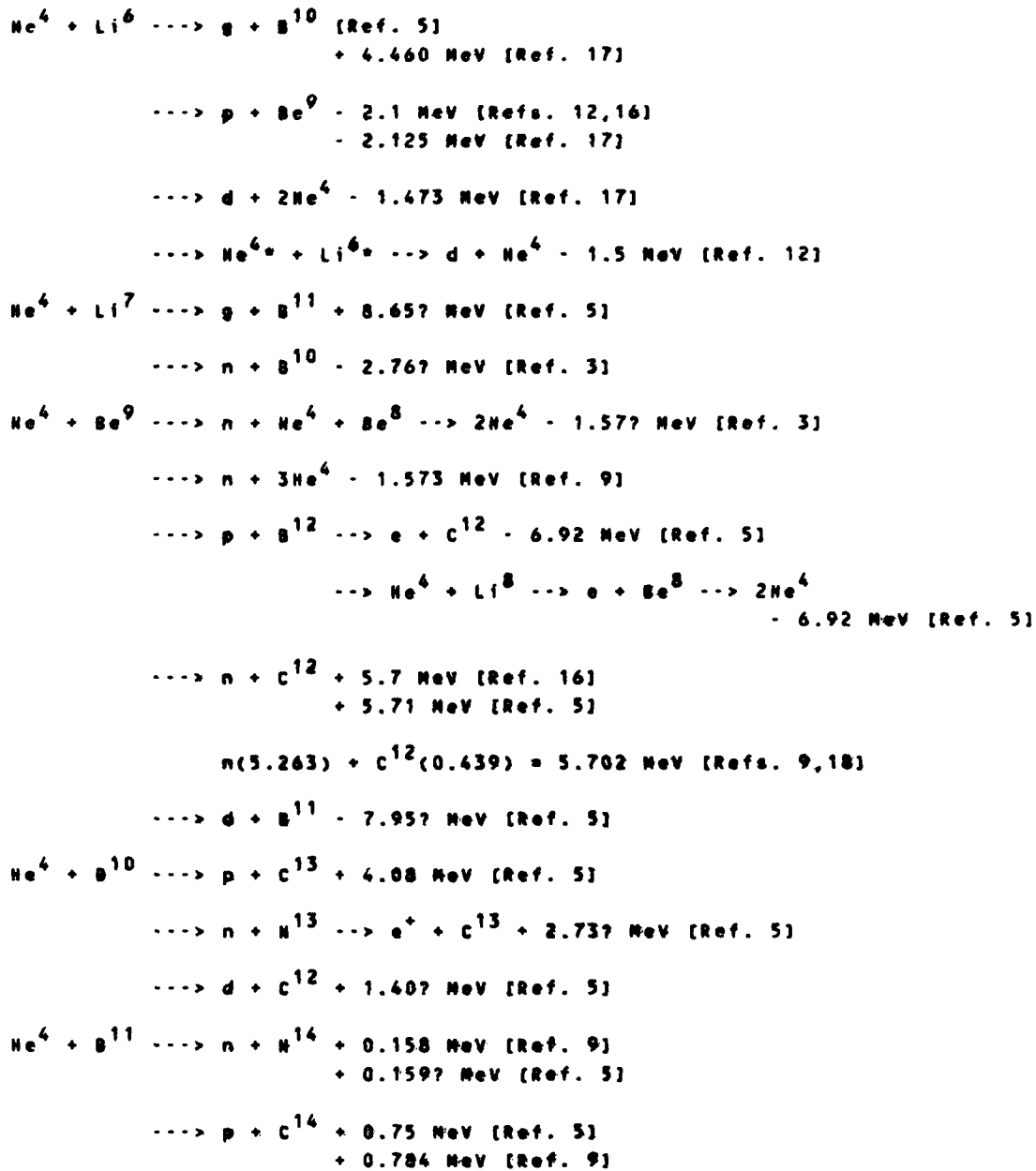


$\text{He}^3 + \text{Li}^7 \rightarrow n + \text{B}^9 \rightarrow p + \text{Be}^8 \rightarrow 2\text{He}^4 + (9.3 + 0.3) \text{ MeV [Ref. 6]}$   
 $\rightarrow n + p + \text{Be}^8 \rightarrow 2\text{He}^4 + (9.5 + 0.1) \text{ MeV [Ref. 6]}$   
 $n(3.852) + p(3.852) + 2\text{He}^4(1.512) = 10.728 \text{ MeV [Ref. 18]}$   
 $\rightarrow p + \text{Be}^9 + 11.2 \text{ MeV [Ref. 6]}$   
 $\rightarrow d + \text{Be}^8 \rightarrow 2\text{He}^4 + (11.7 + 0.1) \text{ MeV [Ref. 6]}$   
 $\rightarrow t + \text{Be}^7 - 0.881? \text{ MeV [Ref. 3]}$   
 $\rightarrow 2p + 2\text{He}^4 \text{ [Ref. 18]}$   
 $2p(4.510 \text{ each}) + 2\text{He}^4(1.127 \text{ each}) = 11.274 \text{ MeV [Ref. 18]}$   
 $\rightarrow \text{He}^4 + \text{Li}^6 + 13.3 \text{ MeV? [Ref. 5]}$

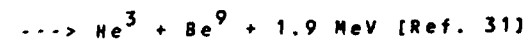
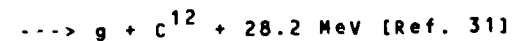
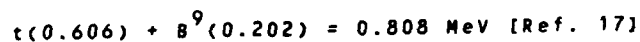
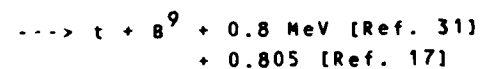
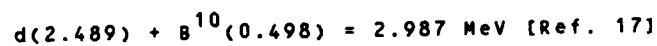
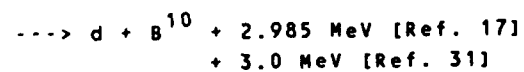
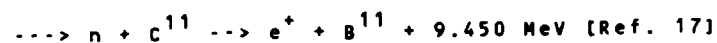
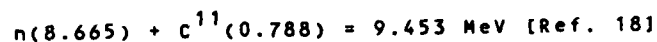
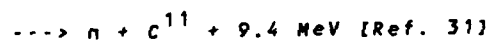
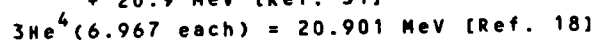
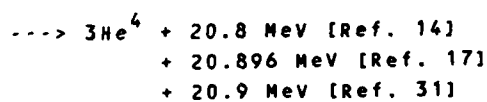
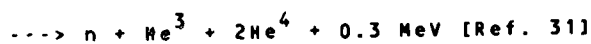
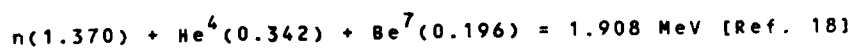
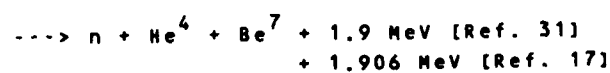
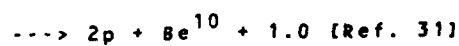
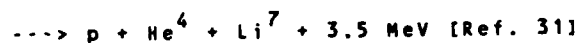
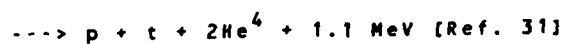
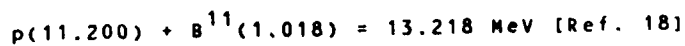
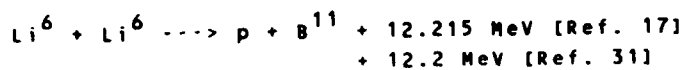
$\text{He}^3 + \text{Be}^9 \rightarrow n + \text{He}^4 + \text{Be}^7 + 0.014? \text{ MeV [Refs. 3, 26]}$   
 $\rightarrow 2n + \text{C}^{10} \rightarrow e^+ + \text{B}^{10} - 2.43? \text{ MeV [Ref. 3]}$   
 $\rightarrow p + \text{B}^{11} + 10.3? \text{ MeV [Ref. 5]}$   
 $\rightarrow p + \text{B}^{11*} + 10.32 \text{ MeV [Ref. 26]}$   
 $\rightarrow n + \text{C}^{11} \rightarrow e^+ + \text{B}^{11} + 9.02? \text{ MeV [Ref. 5]}$   
 $\rightarrow \text{He}^4 + \text{Be}^8 \rightarrow 2\text{He}^4 + 19.0? \text{ MeV [Ref. 5]}$   
 $\rightarrow \text{He}^4 + \text{Be}^{8*} + 18.94 \text{ MeV [Ref. 26]}$

$\text{He}^3 + \text{B}^{10} \rightarrow p + \text{C}^{12} + 19.7? \text{ MeV [Ref. 5]}$   
 $\rightarrow p + \text{C}^{12*} + 19.67 \text{ [Ref. 26]}$   
 $\rightarrow t + \text{C}^{10} \rightarrow e^+ + \text{B}^{10} - 0.530? \text{ MeV [Ref. 3]}$   
 $\rightarrow \text{He}^4 + \text{B}^9 \rightarrow p + 2\text{He}^4 + 12.4? \text{ MeV [Ref. 5]}$   
 $\rightarrow d + \text{C}^{11} \rightarrow e^+ + \text{B}^{11} + 4.73? \text{ MeV [Ref. 5]}$   
 $\rightarrow \text{Li}^6 + \text{Be}^7 - 2.87? \text{ MeV [Ref. 3]}$   
 $\rightarrow p + \text{C}^{13} + 13.2? \text{ MeV [Ref. 5]}$   
 $\rightarrow d + \text{C}^{12} + 10.6? \text{ MeV [Ref. 5]}$

HELIUM-4 (ALPHA-PARTICLE)-INDUCED REACTIONS



LITHIUM-6-INDUCED REACTIONS



## CROSS SECTIONS FOR PROMISING PROPULSION REACTIONS

### PROMISING REACTIONS/CRITERIA

On the following pages the cross sections for some of the more attractive reactions for propulsion are investigated. Some characteristics of an ideal reaction for a propulsion system include the following:

1. No neutron production.
2. No gamma-ray production.
3. Exothermic in nature.
4. Achievable ignition.

The reactions examined were chosen mainly because they produce minimal amounts of harmful radiation (criteria 1 and 2). All of the reactions are exothermic (3), which is an obvious propulsion system requirement. Achieving ignition (4) is the sticking point which should be resolved as containment technology advances.

Four reactions are considered: 1)  $d\text{-He}^3$ , 2)  $\text{He}^3\text{-He}^3$ , 3)  $p\text{-Li}^6$ , and 4)  $p\text{-B}^{11}$ . The  $d\text{-He}^3$  reaction will likely be the first of these to be utilized. It produces some neutrons, but methods to reduce them, such as spin polarization, are being researched.  $\text{He}^3\text{-He}^3$  would be the ideal choice for propulsion because it is completely aneutronic. At this time, however, it seems to be an unignitable reaction, as illustrated by the compiled data. Both  $p\text{-Li}^6$  and  $p\text{-B}^{11}$  come close to being aneutronic, but ignition seems to be the major obstacle because of the high bremsstrahlung and cyclotron radiation energy loss.

### CROSS SECTION NOTES AND GRAPHS

Graphed data for the  $d\text{-He}^3$  reaction are shown in Figure 1. This reaction has been documented in many sources and is the object of a number of research projects. As can be seen, the curve is well-defined by the closely-agreeing sources of data. There is some discrepancy as to where the maximum occurs, as it varies from 720 to 818 mb at the peak energy. Methods now need to be devised to minimize neutron production. It is currently planned for neutron-producing branches of this reaction to be considered in a future report. The remaining concern is being able to achieve the approximately 0.45 MeV temperature at which the reaction reaches its resonance peak. It is at this point where the the highest probability of the maximum reaction rate is obtained. If not obvious from the graph, the dashed line corresponds to the curve obtained from the "Barn Book" [Ref. 1].

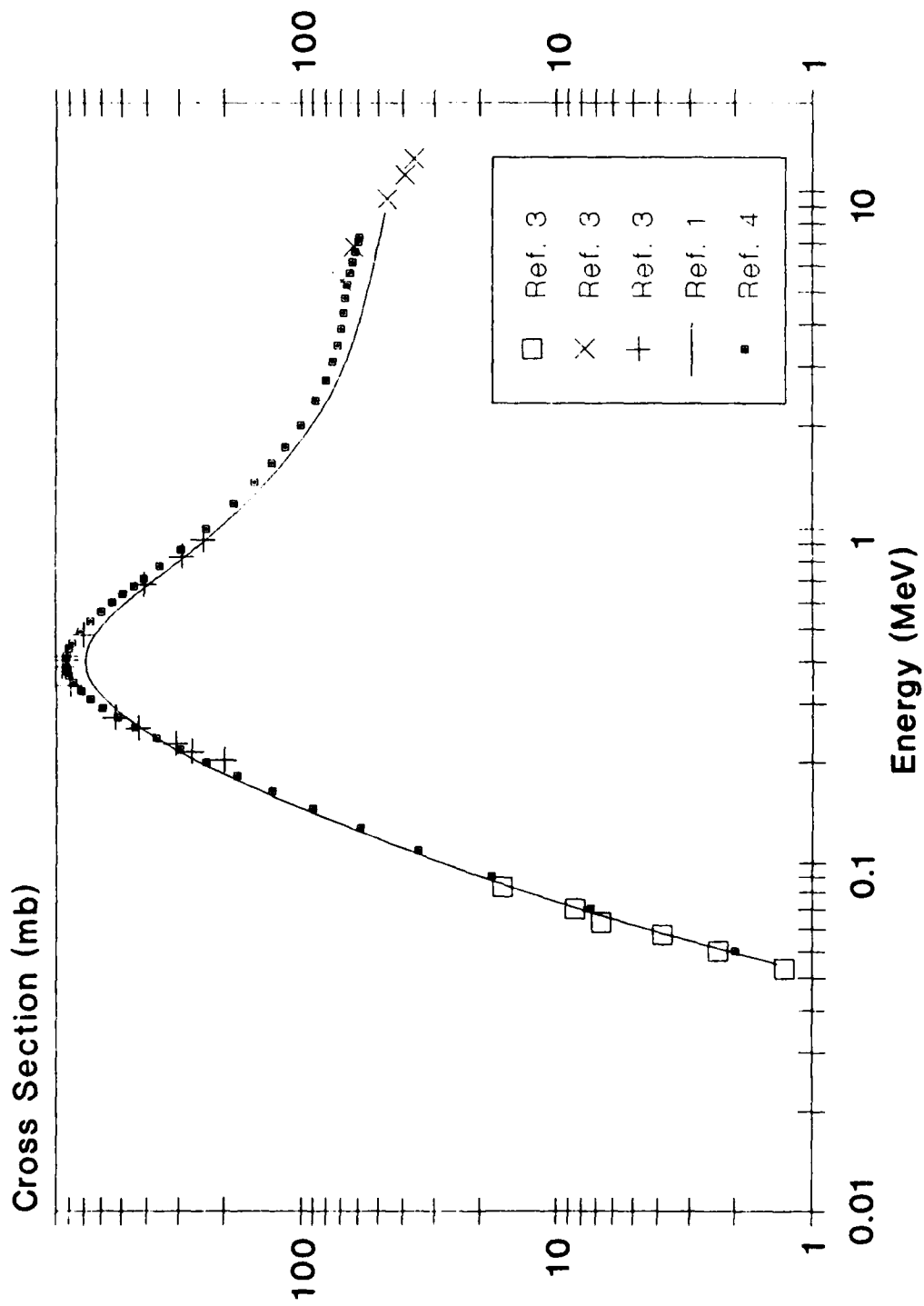


Fig. 1.  $\text{He}^3(d,p)\text{He}^4$  Cross Section

The cross section data for  $\text{He}^3\text{-He}^3$  are shown in Figure 2. Data points found by Good in 1954 are shown as boxes. The curve shown was determined by Dwarakanath's 1971 data (dots) and Pritzker's 1976 data (X's) [Ref. 32]. No curve peaks (maxima) are readily apparent--the only possibility being along the level curve portion in the range of 8 to 10.4 MeV. A temperature of this magnitude is beyond the limits of present confinement technology. Thus, it is apparent that this reaction may not be ignitable, at least not in the near future. Even so, additional data may provide a breakthrough by revealing a peak in the cross section curve along the level portion.

Another reaction which needs more data to adequately define the cross section curve is the  $\text{p-Li}^6$  reaction, shown in Figure 3. The latest findings [Ref. 4] show a well-fit curve for the reaction. For the energy range common to the two sets of data, the shape of the curve is similar. Additional data for the peak region is needed so a precise cross section value can be determined for use in experiments. There is also a gamma-ray producing branch, but no significant data was found. The Ref. 3 curve is shown without data points for clarity.

Figures 4 and 5 show the  $\text{p-B}^{11}$  reaction. The favorable branch,  $\text{B}^{11}(\text{p},3\text{He}^4)$ , is represented in Figure 4. According to recent data collected at Los Alamos [Ref. 33] and graphs from Ref. 34, a resonance may exist at a lower energy than previously noted in such sources as the Barn Book [Ref. 1]. Though not shown on the Ref. 4 curve, this unproven spike appears at 0.162 MeV. Otherwise, the general shapes of the two curves are roughly similar. At lower energies, the differences begin to grow quite large. In Figure 5 the less favorable  $\text{B}^{11}(\text{p},\text{n})\text{C}^{11}$  branch is detailed. The data set denoted by the "X's" is small and departs decidedly from the other data curves. One point (0.2 MeV, 2.5 mb) from this set was omitted on the graph in order to narrow the spectrum of temperatures shown, thereby increasing detail of the curves. The other two data sets appear as though they could blend into a single curve, if the higher-energy set is viewed as a continuance of the first. If Figure 5 is compared to the favorable branch in Figure 4, it can be concluded that the unwanted branch's cross sections fall off rapidly as energy drops, provided the "X" data points are ignored. It would seem that by staying at temperatures below 3 MeV, the neutron-producing branch would not become a significant factor.

Figure 6 is a graph showing the comparative cross sections for each of the four fuels. The  $\text{He}^3\text{-He}^3$  curve is a reprint of the earlier graph formed from the Dwarakanath and Pritzker data. All other curves in Figure 6 show the Los Alamos R-matrix data analysis results [Refs. 4,33]. Some data points have been omitted from Figure 6 to maintain clarity;  $\text{d-He}^3$  is shown without them altogether. For  $\text{p-B}^{11}$  the accepted maximum is reached at 0.625 MeV with a cross-section of 800 mb.  $\text{D-He}^3$  exhibits a peak of approximately 847 mb at 0.426 MeV. Finally,  $\text{p-Li}^6$  peaks at a stable 219 mb from 1.76 to 1.81 MeV. In the future a more precise curve will be determined for each fuel, after additional cross-section data is obtained. Brookhaven National Laboratory [Ref. 3], Los Alamos National Laboratory [Refs. 4,33], the Barn Book [Ref. 1], and the AEP Barnbook [Ref. 32] were the main sources of data for these graphs. It should be noted that data from the Barn Book are shown as curves without points in Figs. 1 and 4, as was done in the reference itself.

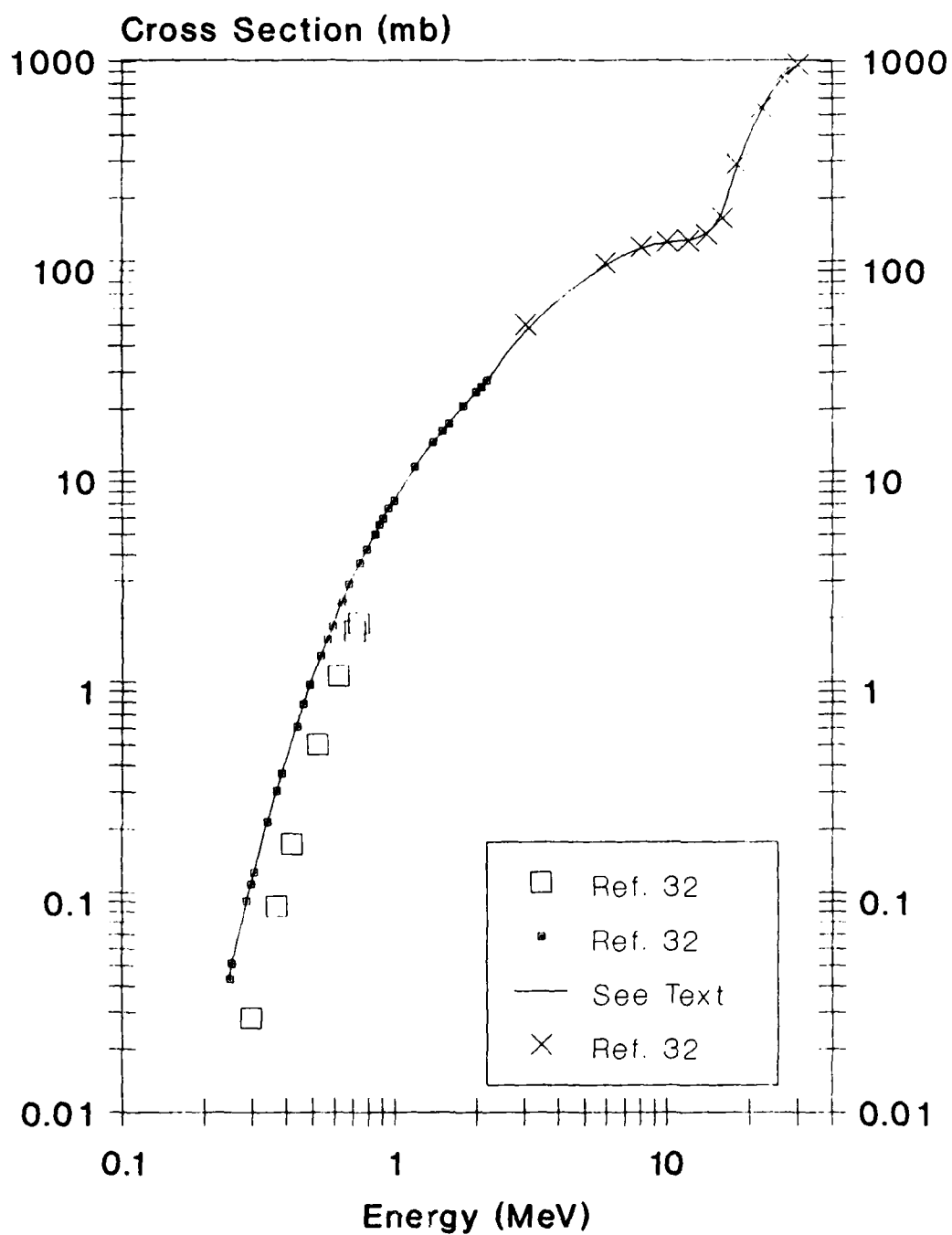


Fig. 2. He3(He3,2p)He4 Cross Section

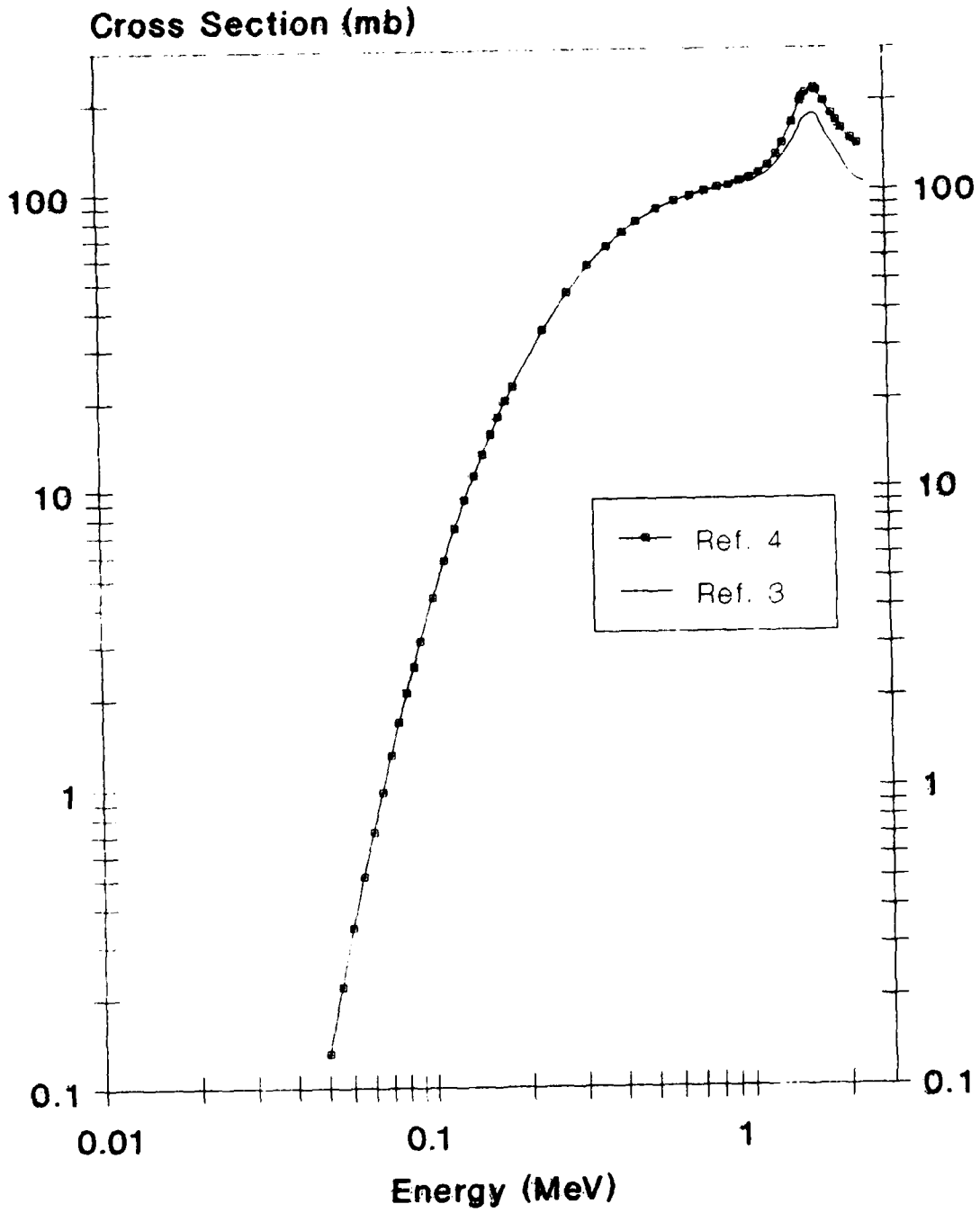


Fig. 3.  $\text{Li6}(p,\text{He3})\text{He4}$  Cross Section

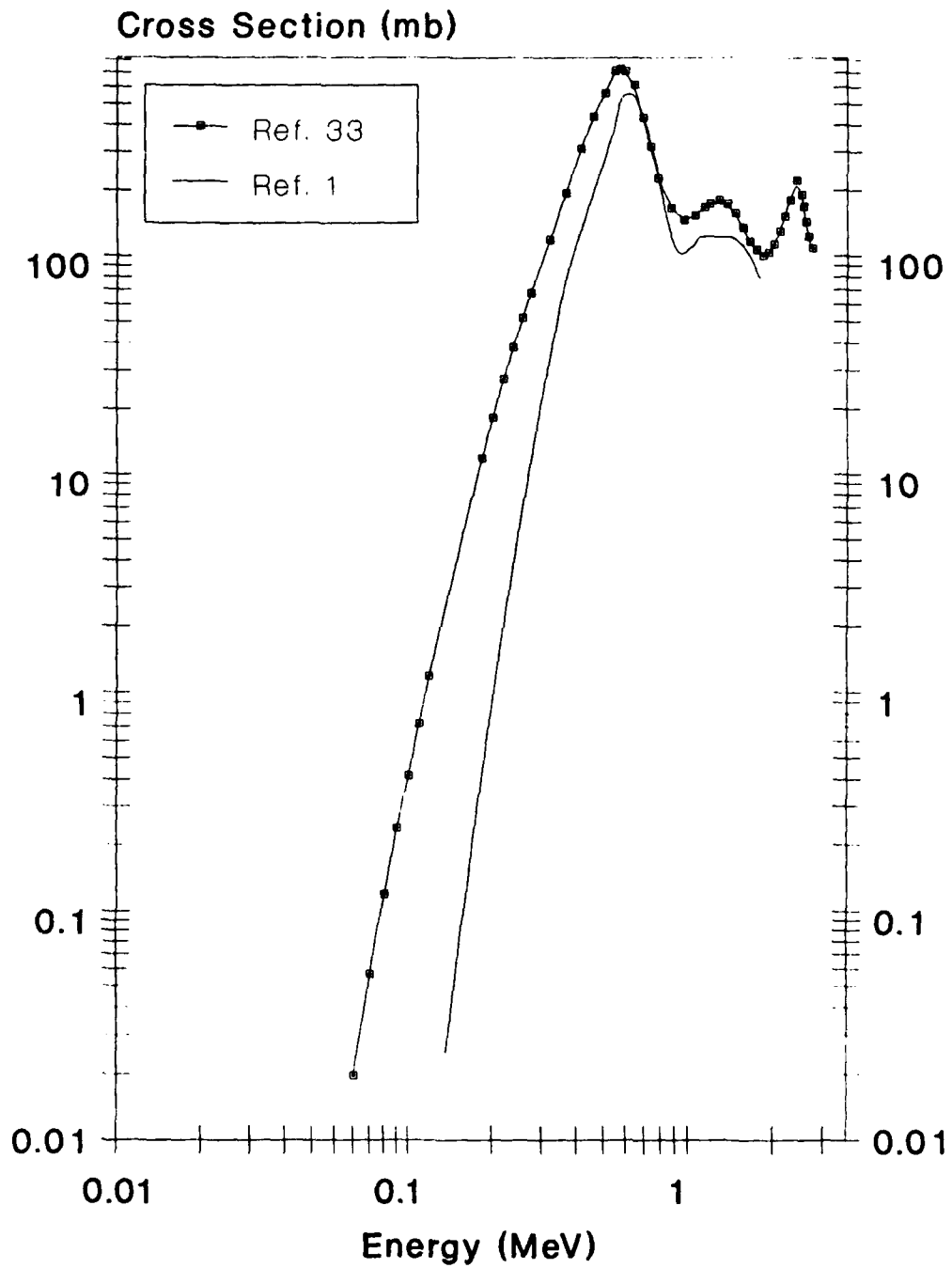
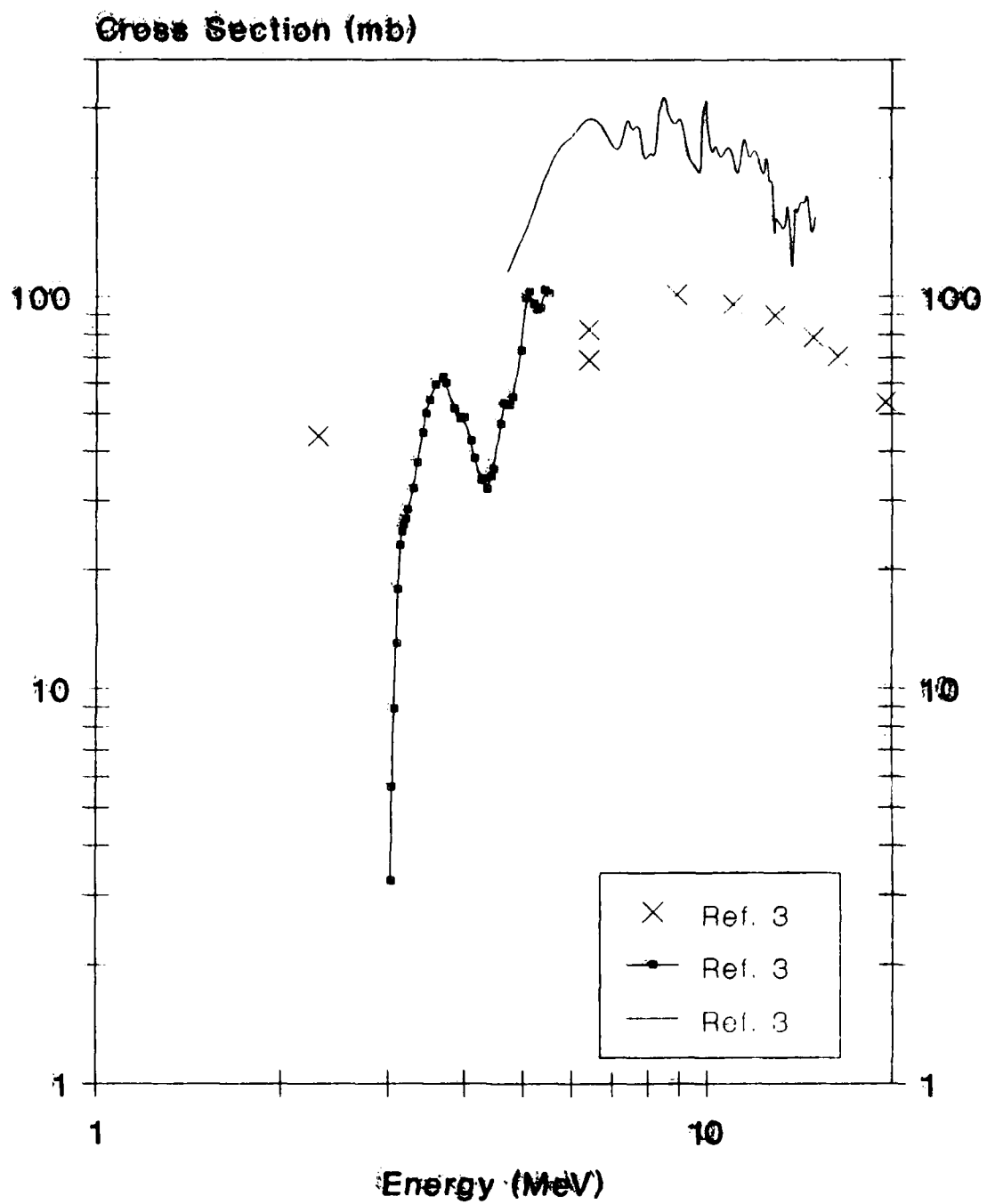


Fig. 4.  $B_{11}(p,3He_4)$  Cross Section



**Fig. 5. B11(p,n)C11 Cross Section**

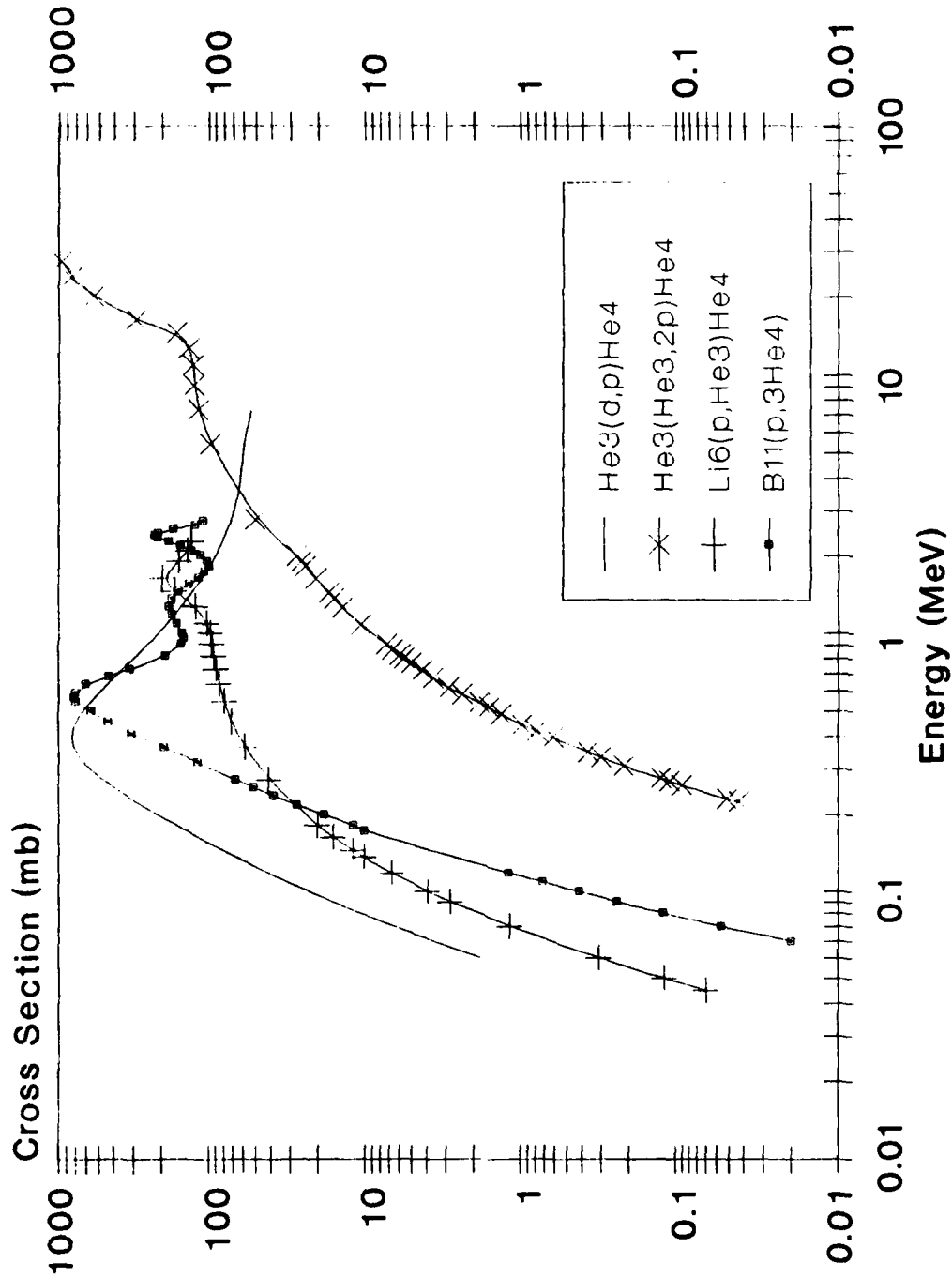


Fig. 6. Comparative Cross Sections

## CONCLUSIONS, RECOMMENDATIONS, AND STUDY OUTLOOK

During this initial phase of the study, a great deal has been learned about thermonuclear reactions and the meanings of their cross sections. Already several conclusions about available cross section information can be drawn. First, most of the references that have been consulted were generally 10 to 20 years old, some even older. This may be due to the fact that only recently has a genuine effort been started to make fusion space propulsion a reality. However, most of the data presented here is less than 10 years old. Secondly, the safety involved with an advanced fuel that is aneutronic has been, and will continue to be, a major factor in the push for its development. Finally, it is surprising that no significant work has been done since the 1950's to discover new reactions using the simple bombardment technique. It should be fairly obvious, though, that the number of reactions is quite plentiful, and the number which may await discovery should not be large in number.

The conclusions basically center around the cross section information which has been published and is presented here. The  $d\text{-He}^3$  initial reaction's cross section data from many sources agree well, so there is a solid foundation for anyone attempting to ignite it. The other reactions which have been included here are not so well defined.  $\text{He}^3\text{-He}^3$  needs much more research in order to truly determine its feasibility. Other than unknown resonance peaks, a problem which needs consideration is the unavailability of  $\text{He}^3$  for reaction. Recent studies [Refs. 35,36,37] indicate the moon to be a potential source of  $\text{He}^3$ . This makes its labeling as a futuristic fuel quite appropriate.  $p\text{-Li}^6$  and  $p\text{-B}^{11}$  need additional sources of cross section data to determine if resonance peaks exist at energies below those currently indicated by cross section data. Each of them has a harmful radiation-producing branch that must be investigated in more detail. This will allow researchers to be sure that the cross sections of these unwanted reactions are negligible when compared with the cross sections of the more favorable branches at ignition energies.

From these conclusions some recommendations can be presented for additional research in the cross section field. Spin-polarization and other methods to reduce neutron production in the  $d\text{-He}^3$  reaction should continue to be addressed, as this reaction appears to be an excellent candidate due to the closely-agreeing data and low ignition energy it possesses. Mining the moon and the outer planets for reactant fuels such as  $\text{He}^3$  should continue to be investigated for feasibility. If the  $\text{He}^3$  reactions are found to be ignitable, a plan for obtaining the  $\text{He}^3$  needed would already have a great start. Precise measurements for each reaction near its lowest-energy resonance peak should be one focus of additional research in the area. Another focal point should be the cross-section measurements for the radioactive particle-producing branches of each reaction. In the case of  $p\text{-B}^{11}$ , the possible lower energy resonance needs to be investigated more fully, as it has encountered mixed reviews concerning its validity. As is obvious, a lower resonance energy will enable fusion to become a reality sooner than expected and will relieve some of the stress on containment technology.

In the future, this study will involve obtaining cross sections and reactivities for additional advanced reactions. All of this data will be fitted to curves and presented along with discussion about which sets of data are best. Based on this data, and with parameters such as nuclear scattering and various sources of radiation loss taken into account, new ignition temperatures will be calculated for each of the reactions. Additional sources for reactions will continue to be consulted, so an up-to-date reaction bibliography will exist. Eventually, complete fuel cycles will be detailed to provide complete information for researchers attempting to develop reactions into feasible fuel systems. Much of the new information will be the basis for computer programs written to aid in the calculation of new ignition temperatures and reactivities.

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