AD-A187 420 FUSION AND ADVANCED FUEL REACTION BIBLIOGRAPHY PARTICLE 1/1
REACTIONS FROM H1 TO B11(U) AIR FORCE AVIONICS LAB
WRIGHT-PATTERSON AFB OH H H PASS AUG 87 AFAL-TR-87-073

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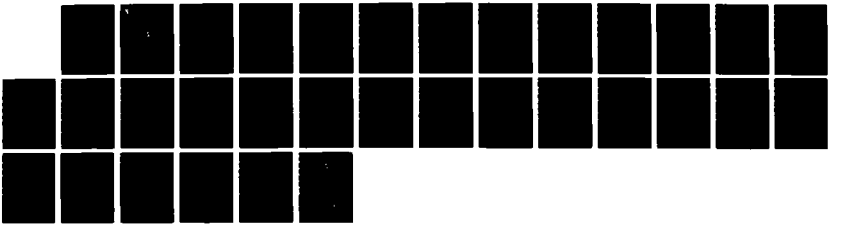

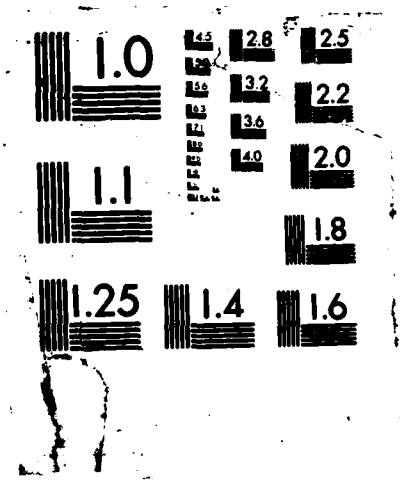
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17 February 1987 to
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Fusion, and Advanced Fuel, Reaction Bibliography

Particle Reactions from H1 to B11

August 1987

Author:
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Approved for Public Release

**Air Force
Astronautics
Laboratory**

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FOREWORD

This document reports on the fusion, and advanced fuel, bibliography compiled as part of the on-going Air Force Astronautics Laboratory (AFAL) program of studying the feasibility of fusion-powered propulsion. AFAL Project Manager was 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.

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The Air Force Astronautics Laboratory has on ongoing program of studying the feasibility of fusion-powered propulsion. This study will first examine nuclear fuels and their associated fuel cycles. The investigated fuels and fuel cycles will then be used to explore present and proposed fusion propulsion concepts. From this study, it will be determined which concepts, if any, will be able to produce fusion propulsion systems using present or near-term technology.

The objective of the work reported herein was to compile a comprehensive list of the experimentally measured nuclear reactions involving the nuclides up to and including B11 (Boron-11). This compilation was performed in order to identify any new fuels and/or fuel cycles that would be potential candidates to replace the presently utilized fuels deuterium and tritium. Also, this project is intended to provide a readily accessable source of information for individuals who are studying fuels, reactions, and fuel cycles.

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11 Continued: BIBLIOGRAPHY - PARTICLE REACTIONS FROM H1 TO B11 (U)

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INTRODUCTION AND SUMMARY

The Air Force Astronautics Laboratory(AFAL) has an ongoing program that is studying the feasibility of fusion powered propulsion. This study will first examine nuclear fuels and their associated fuel cycles. The investigated fuels and fuel cycles will then be used to explore present and proposed fusion propulsion concepts. From this study, it will be determined which concepts, if any, will be able to produce reusable fusion propulsion systems using present or near-term technology.

The reason for the Air Force's interest in fusion propulsion systems is it's potential to achieve high specific impulse (> 1000 s), near zero neutron and gamma-ray production, and environmentally safe exhaust products.

The objective of the work reported in the following pages was to compile a comprehensive list of the experimentally measured nuclear reactions involving the nuclides up to and including B11 (Boron-11). This compilation was used to identify any new fuels and/or fuel cycles that would be potential candidates to replace the presently utilized fuels deuterium and tritium. This project is also intended to provide a readily accessable source of information to assist others who are studying fuels, reactions, and fuel cycles.

The search for reaction data involved the survey of books, technical journals, and national data bases; plus interfacing

with various experts in the field at universities and national laboratories.

A review of the reaction list revealed several nuclides that are likely candidates as fuels for use in fusion powered propulsion systems. These candidate fuels and their corresponding reactions are listed seperately under the heading of "CANDIDATE REACTIONS FOR FUSION PROPULSION SYSTEMS".

FUSION, AND ADVANCED FUEL, REACTION BIBLIOGRAPHY

AFAL has an ongoing fusion propulsion study that partially involves a search to find a fuel cycle which produces very little, if any, neutrons and/or gamma-rays; with most of the energy being released in the form of charged particles. Many different nuclides can be used as a primary fuel, and each has it's advantages and disadvantages. The present fuels that are being used, deuterium and tritium, produce copious amounts of high energy neutrons. Therefore, a fusion propulsion system based on deuterium and tritium is less attractive than other types of advanced propulsion concepts due to the extra weight required for shielding the payload and restricted operations. Thus, the consideration of other fuels to identify reactions that achieve or approach as close as possible the previously stated criteria of minimized neutron and/or gamma production is necessary in order to achieve a viable fusion propulsion system.

Before a propulsion system can be analyzed, the nuclides that will be used as the primary fuel must be chosen. After the primary fuel has been selected, the initial reactions and their products can be determined using this bibliography. Then, using these reaction products, the secondary reactions and their products can be established. This process can be carried out with the tertiary and higher order reactions until a complete fuel cycle is defined.

Once a complete fuel cycle has been defined, the next step

is to determine the cross sections and reactivities in order to choose an operating temperature that will maximize the desirable reactions and minimize the undesirable reactions. Also, using the energy or "Q" values of the reactions involved, an estimate of the energy release produced by the fuel cycle can be computed.

This bibliography is not to be considered a complete set of reactions for the nuclides existing between H1(Proton) and B11 (Boron-11); more nuclides and reactions could be verified in the future. Furthermore, neutron reactions have been considered and are included in this bibliography because they are necessary to completely analyze a fuel cycle.

BACKGROUND

Most of the work to discover nuclear reactions that occur in the isotopic range between H1 and B11 was done in the 1950's. A good reference for this early work is by S. Flugge [Ref. 1]. Since that time there has been no significant work done in this area. This is the first document that assembles all of the significant reactions.

LIST OF SYMBOLS

* = Q(MeV) was calculated using the mass defect formula--

$$Q = [(ma + mb) - (mc + md + ...)]*C$$

where:

a(b,c)d + ... = a + b -> c + d + ...

C = 931.481 MeV/amu

ma = mass of target particle

mb = mass of incident particle

mc, md, ... = masses of reaction products

' = isotope in an excited state

& = gamma-ray

e- = electron

e+ = positron

n = neutron

p = proton

d = deuteron

t = triton

He3,4,5,6 = Helium-3,4,5,6

Li6,7,8 = Lithium-6,7,8

Be7,8,9,10 = Beryllium-7,8,9,10

B9,10,11,12 = Boron-9,10,11,12

C10,11,12,13,14 = Carbon-10,11,12,13,14

N13,14 = Nitrogen-13,14

NEUTRON-INDUCED REACTIONS

These reactions are listed by increasing atomic number of the target nuclide.

n + p -> & + d + 2.21* MeV [Ref. 7]

n + d -> & + t + 6.24* MeV [Ref. 7]

n + d -> p + 2n - 2.32* MeV [Ref. 1]

n + t -> & + H4 + 1.88* MeV [Ref. 7]

n + t -> 2n + d - 6.26* MeV [Ref. 7]

n + t -> 3n + p - 8.48* MeV [Ref. 7]

n + He3 -> & + He4 - 1.25* MeV [Ref. 7]

n + He3 -> 2d - 3.27* MeV [Ref. 7]

n + He3 -> t + p + 0.764 MeV [Ref. 1]

n + He4 -> d + t - 17.6* MeV [Ref. 7]

n + Li6 -> 2n + Li5 -> p + He4 - 25.5* MeV [Ref. 7]

n + Li6 -> n + d + He4 - 1.48* MeV [Ref. 7]

n + Li6 -> t + He4 + 4.6 MeV [Ref. 3]

n + Li6 -> p + He6 -> Li6 + e- + 0.222* MeV [Ref. 1]

n + Li6 -> t + He4 + 4.797 MeV [Ref. 1]
t(2.7) + He4(2.1) = 4.8 MeV [Ref. 4]

n + Li6 -> d + He5 -> n + He4 - 1.38* MeV [Ref. 1]

n + Li6 -> t + He4 + 4.78* MeV [Ref. 1]

n + Li7 -> 2n + Li6 - 7.25* MeV [Ref. 7]

n + Li7 -> 3n + Li5 -> p + He4 - 11.0* MeV [Ref. 7]

n + Li7 -> n + t + He4 - 2.47* MeV [Ref. 7]

n + Li7 -> d + He6 -> Li6 + e- - 4.66* MeV [Ref. 1]

n + Li7 -> t + He5 -> n + He4 - 2.47* MeV [Ref. 1]

n + Li7 -> & + Li8 -> e- + Be8 -> 2He4 + 17.6* MeV [Ref. 1]

n + Li7 -> He4 + H4 - 5.25* MeV [Ref. 7]

n + Be7 -> p + Li7 + 1.62* MeV [Ref. 1]

n + Be7 -> 2He4 + 18.97* MeV [Ref. 1]

n + Be9 -> & + Be10 + 6.84* MeV [Ref. 1]

n + Be9 -> 2n + Be8 -> 2He4 - 1.57* MeV [Ref. 1]

n + Be9 -> p + Li9 -> n + 2He4 - 0.791* MeV [Ref. 7]

n + Be9 -> p + Li9 -> e- + Be9 + 0.271* MeV [Ref. 7]

n + Be9 -> d + Li8 -> e- + Be8 -> 2He4 + 0.922* MeV [Ref. 7]

n + Be9 -> d + Li8 -> 2He4 + 1.43* MeV [Ref. 7]

n + Be9 -> t + Li7 - 10.4* MeV [Ref. 7]

n + Be9 -> He4 + He6 -> Li6 + e- + 2.40* MeV [Ref. 1]

n + B10 -> n + d + 2He4 - 5.87* MeV [Ref. 1]

n + B10 -> 2n + B9 -> p + 2He4 - 8.19* MeV [Ref. 1]

n + B10 -> p + Be10 + 0.224* MeV [Ref. 1]

n + B10 -> d + Be9 - 4.30* MeV [Ref. 1]

n + B10 -> t + Be8 -> 2He4 + 0.323* MeV [Ref. 7]

n + B10 -> He4 + Li7 + 2.786 MeV [Ref. 1]

n + B11 -> & + B12 -> e- + C12 + 16.2* MeV [Ref. 7]

n + B11 -> & + B12 -> He4 + Li8 -> e- + Be8 -> 2He4
+8.95* MeV [Ref. 7]

n + B11 -> & + B12 -> He4 + Li8 -> 2He4 + 9.46* MeV [Ref. 7]

n + B11 -> 2n + B10 - 11.5* MeV [Ref. 7]

n + B11 -> p + Be11 -> e- + B11 + 0.271* MeV [Ref. 7]

n + B11 -> t + Be9 - 9.56* MeV [Ref. 7]

n + B11 -> He4 + Li8 -> e- + Be8 -> 2He4
+ 8.97* MeV [Ref. 1]

PROTON-INDUCED REACTIONS

These reactions are listed by increasing atomic number of the target nuclide.

p + p -> e+ + d + 1.42 MeV [Ref. 1]

p + d -> & + He3 + 5.50 +/- 0.03 MeV [Ref. 1]

p + d -> n + 2p - 2.2 MeV [Ref. 2]
- 2.227 +/- 0.002 MeV [Ref. 1]

p + t -> & + He4 + 19.7 MeV [Ref. 1]

p + t -> n + He3 - 0.76 MeV [Ref. 2]
- 0.764 +/- 0.001 MeV [Ref. 1]

p + t -> 2n + 2p - 8.48* MeV [Ref. 8]

p + t -> n + p + d - 6.26* MeV [Ref. 8]

p + Li6 -> He3 + He4 + 4.02 MeV [Ref. 2]
+ 4.023 MeV [Ref. 1]
He3(2.3) + He4(1.7) = 4.0 MeV [Ref. 4]
He3(2.298) + He4(1.724) = 4.022 MeV [Ref. 5]

p + Li6 -> & + Be7 [Ref. 1,6]
+ 5.606 MeV [Ref. 6]

p + Li7 -> n + Be7 - 1.63 MeV [Ref. 2]
- 1.645 MeV [Ref. 1]

p + Li7 -> 2He4 + 17.5 MeV [Ref. 2]
+ 17.346 MeV [Ref. 1]
He4(8.674) + He4(8.674) = 17.348 MeV [Ref. 5]

p + Li7 -> & + Be8 -> 2He4 + 17.35* MeV [Ref. 1]

p + Li7 -> d + Li6 - 4.93* MeV [Ref. 1]

p + Be7 -> & + B8 + 0.138 MeV [Ref. 6]

p + Be9 -> n + p + Be8 -> 2He4 - 1.67 MeV [Ref. 1]

p + Be9 -> n + B9 -> p + 2He4 - 1.852 MeV [Ref. 1]

p + Be9 -> He4 + Li6 + 2.126 MeV [Ref. 1]
He4(1.275) + Li6(0.850) = 2.125 MeV [Ref. 5]

p + Be9 -> & + B10 [Ref. 1,6]
+ 6.585 MeV [Ref. 6]

p + Be9 -> d + Be8 -> 2He4 [Ref. 1,6]
+ 0.651 MeV [Ref. 6]
d(0.326) + He4(0.163) + He4(0.163)
= 0.652 MeV [Ref. 5]

p + Be9 -> t + Be7 - 12.1* MeV [Ref. 1]

p + B10 -> He4 + Be7 + 1.148 MeV [Ref. 1]

p + B10 -> n + C10 -> B10 + e+ - 4.35 MeV [Ref. 1]

p + B10 -> & + C11 -> B11 + e+ [Ref. 1,6]
+ 8.690 MeV [Ref. 6]

p + B10 -> d + B9 -> p + 2He4 - 5.87* MeV [Ref. 1]

p + B10 -> t + B8 -> e+ + Be8 -> 2He4 - 1.00 MeV [Ref. 1]

p + B10 -> He3 + Be8 -> 2He4 [Ref. 1,6]
- 0.442 MeV [Ref. 6]

p + B11 -> He4 + Be8 -> 2He4 + 8.585 MeV [Ref. 1]

p + B11 -> 3He4 + 8.7 MeV [Ref. 4]
He4(2.888)+He4(2.888)+He4(2.888)
= 8.664 MeV [Ref. 5]

p + B11 -> n + C11 -> B11 + e+ - 2.762 MeV [Ref. 1]

p + B11 -> & + C12 [Ref. 1,6]
+ 15.956 MeV [Ref. 6]

p + B11 -> d + B10 - 9.10 MeV [Ref. 1]

DEUTERON-INDUCED REACTIONS

These reactions are listed by increasing atomic number of the target nuclide.

d + d -> 2n + 2p - 4.45* MeV [Ref. 8]

d + d -> n + p + d - 2.22* MeV [Ref. 8]

d + d -> n + He3 + 3.27 MeV [Ref. 2,3]
n(2.45) + He3(0.82) = 3.27 MeV [Ref. 3,4,5]

d + d -> p + t + 4.03 MeV [Ref. 2,3]
p(3.02) + t(1.01) = 4.03 MeV [Ref. 3,4,5]

d + t -> & + He5 -> n + He4 + 17.6* MeV [Ref. 7]

d + t -> n + p + t - 2.2 MeV [Ref. 2]

d + t -> 2n + He3 - 3.0 MeV [Ref. 2]

d + t -> n + He4 + 17.6 MeV [Ref. 2,3]
n(14.1) + He4(3.5) = 17.6 MeV [Ref. 3,4,5]

d + t -> & + n + He4 + 17.589 MeV [Ref. 6]

d + He3 -> & + Li5 -> p + He4 + 18.4* MeV [Ref. 8]

d + He3 -> n + p + He3 - 2.2 MeV [Ref. 2]

d + He3 -> p + He4 + 18.4 MeV [Ref. 2]
+ 18.3 MeV [Ref. 3]
p(14.7) + He4(3.6) = 18.3 MeV [Ref. 3,4]
p(14.681) + He4(3.670) = 18.351 MeV [Ref. 5]

d + He4 -> n + p + He4 - 2.2 MeV [Ref. 2]

d + He4 -> p + He5 -> n + He4 - 2.22* Mev [Ref. 8]

d + Li6 -> & + n + Be7 + 3.38* MeV [Ref. 8]

d + Li6 -> n + He3 + He4 + 1.72 MeV [Ref. 2]
n(1.134) + He3(0.378) + He4(0.284)
= 1.796 MeV [Ref. 5]

d + Li6 -> n + Be7 + 3.34 MeV [Ref. 2]
+ 3.40 MeV [Ref. 1]
n(2.957) + Be7(0.423) = 3.380 MeV [Ref. 5]

d + Li6 -> p + Li7 + 5.02 MeV [Ref. 2]
+ 5.027 MeV [Ref. 1]
p(4.398) + Li7(0.628) = 5.026 MeV [Ref. 5]

d + Li6 -> p + Li7' -> & + Li7 + (4.54 + 0.45) MeV [Ref. 2]

d + Li6 -> p + t + He4 + 2.557 MeV [Ref. 6]

d + Li6 -> t + Li5 -> p + He4 + (0.9 + 1.6) MeV [Ref. 2]
t(0.539)+ p(1.618) + He4(0.404)
= 2.561MeV [Ref. 5]

d + Li6 -> He3 + He5 -> n + He4 + 1.79* MeV [Ref. 8]

d + Li6 -> 2He4 + 22.4 MeV [Ref. 2,4]
+ 22.39 MeV [Ref. 1]
He4(11.187) + He4(11.187) = 22.374 MeV [Ref. 5]

d + Li7 -> & + 2n + Be7 - 3.87* MeV [Ref. 8]

d+Li7 -> & + p + Li8 -> e- + Be8 -> 2He4 + 15.4*MeV [Ref. 8]

d + Li7 -> & + p + Li8 -> 2He4 + 15.9* MeV [Ref. 8]

d + Li7 -> 2n + Be7 - 3.869 MeV [Ref. 6]

d + Li7 -> n + Be8 -> 2He4 + 15.0 Mev [Ref. 2,1]
n(10.082)+He4(2.521)+He4(2.521)
= 15.124MeV [Ref. 5]

d + Li7 -> p + Li8 -> e- + Be8 -> 2He4
+ (-0.26 + 16.0) MeV [Ref. 2]

d + Li7 -> t + Li6 - 0.995 MeV [Ref. 2]

d + Li7 -> He4 + He5 -> n + He4 + 14.2 MeV [Ref. 1]

d + Be7 -> p + 2He4 + 16.766 MeV [Ref. 6]
p(11.179)+He4(2.795)+He4(2.795)
= 16.769 MeV [Ref. 5]

d + Be9 -> & + B11 + 15.8* MeV [Ref. 8]

d + Be9 -> p + Be10 + 4.588 MeV [Ref. 1]

d + Be9 -> n + B10 + 4.35 MeV [Ref. 1]

d + Be9 -> t + Be8 -> 2He4 + 4.68* MeV [Ref. 8]

d + Be9 -> He4 + Li7 + 7.153 MeV [Ref. 1]

d + B10 -> p + B11 + 9.235 MeV [Ref. 1]

d + B10 -> n + C11 -> B11 + e+ + 6.6 MeV [Ref. 1]

d + B10 -> He4 + Be8 -> 2He4 + 17.86 MeV [Ref. 1]

d + B11 -> n + C12 + 13.8 MeV [Ref. 1]

d + B11 -> 2n + C11 - 4.99* MeV [Ref. 8]

d + B11 -> p + B12 -> e- + C12 + 1.137 MeV [Ref. 1]

d + B11 -> p + B12 -> He4 + Li8 -> e- + Be8 -> 2He4
+ 1.137 MeV [Ref. 1]

d + B11 -> He4 + Be9 + 8.018 MeV [Ref. 1]

TRITON-INDUCED REACTIONS

These reactions are listed by increasing atomic number of the target nuclide.

t + t -> n + He5 -> n + He4 + 11.4 MeV [Ref. 2]

t + t -> 2n + He4 + 11.4 MeV [Ref. 2]
+ 11.3 MeV [Ref. 4]
n(5.034)+ n(5.034) + He4(1.259)
= 11.327MeV [Ref. 5]

t + He3 -> d + He4 + 14.3 MeV [Ref. 2]
d(9.5) + He4(4.8) = 14.3 MeV [Ref. 4]
d(9.546) + He4(4.773) = 14.319 MeV [Ref. 5]

t + He3 -> p + He5 -> n + He4 + (11.3 + 1.0) MeV [Ref. 2]
p(11.9) + He5(2.4) = 14.3 MeV [Ref. 4]

t + He3 -> n + p + He4 + 12.1 MeV [Ref. 2,4]
n(5.374)+ p(5.374) + He4(1.344)
= 12.092 MeV [Ref. 5]

t + He3 -> n + Li5 -> p + He4 + (10.3 + 1.8) MeV [Ref. 2]

t + He4 -> & + Li7 + 2.467 MeV [Ref. 6]

t + He4 -> n + Li6 - 4.784 MeV [Ref. 6]

t+ Li6 -> & + p + Li8 -> e- + Be8 -> 2He4 +16.4*MeV [Ref. 8]

t + Li6 -> & + p + Li8 -> 2He4 + 16.9* MeV [Ref. 8]

t + Li6 -> d + Li7 + 0.995 MeV [Ref. 2]

t + Li6 -> 2n + Be7 - 2.876 MeV [Ref. 6]

t + Li6 -> d + Li7' -> & + Li7 + (0.509 + 0.45) MeV [Ref. 2]

t + Li6 -> d + Li7 + 0.994 MeV [Ref. 6]

t + Li6 -> p + Li8 -> e- + 2He4 + 0.800 MeV [Ref. 2]

t + Li6 -> n + Be8 -> 2 He4 + 16.0 MeV [Ref. 2]

t + Li6 -> n + 2He4 + 16.0 MeV [Ref. 2]

t + Li6 -> & + Be9 + 17.7* MeV [Ref. 1]

t + Li6 -> He4 + He5 -> n + He4 + 16.1* MeV [Ref. 1]

t+Li7 -> & + d + Li8 -> e- + Be8 -> 2He4 + 11.4*MeV [Ref. 8]

t + Li7 -> & + d + Li8 -> 2He4 + 11.9* MeV [Ref. 8]

t + Li7 -> 2n + 2He4 + 8.88 MeV [Ref. 2]
n(6.049)+n(6.049)+He4(1.512)+ He4(1.512)
= 15.122 MeV [Ref. 5]

t + Li7 -> n + Be9 + 10.52 MeV [Ref. 2]

t + Li7 -> 2n + Be8 -> 2He4 + 3.83 MeV [Ref. 2]

t + Li7 -> n + He4 + He5 -> n + He4 + (8.08 + 1.0) MeV [Ref. 2]

t + Li7 -> p + Li9 -> e- + Be9 + 10.7* MeV [Ref. 8]

t + Li7 -> p + Li9 -> n + 2He4 + 9.65* MeV [Ref. 8]

t + Li7 -> d + Li8 -> e- + Be8 -> 2He4 + 11.4* MeV [Ref. 8]

t + Li7 -> d + Li8 -> 2He4 + 11.9* MeV [Ref. 8]

t + Li7 -> He4 + He6 -> e- + Li6 + 9.83 MeV [Ref. 2]

t + Be7 -> p + n + 2He4 [Ref. 5]
p(4.204)+n(4.204) +He4(1.051)+ He4(1.051)
= 10.510 MeV [Ref. 5]

t + Be9 -> n + B11 + 9.56* MeV [Ref. 8]

t + B10 -> Be7 + He6 -> e- + Li6 + 3.36* MeV [Ref. 8]

t + B10 -> p + B12 -> e- + C12 + 19.2* MeV [Ref. 8]

t + B10 -> p + B12 -> He4 + Li8 -> e- + Be8 -> 2He4
+ 11.9*MeV [Ref. 8]

t + B10 -> p + B12 -> He4 + Li8 -> 2He4 + 11.4* MeV [Ref. 8]

t+ B10 -> p + He4 + Li8 -> e- + Be8 -> 2He4
+ 11.9* MeV [Ref. 8]

t + B10 -> p + He4 + Li8 -> 2He4 + 11.4* MeV [Ref. 8]

t + B11 -> 2He4 + He6 -> e- + Li6 + 3.36* MeV [Ref. 8]

HELIUM-3--INDUCED REACTIONS

These reactions are listed by increasing atomic number of the target nuclide.

$^3He + {}^3He \rightarrow p + {}^5Li \rightarrow p + {}^4He + (11.0 + 1.8)$ MeV [Ref. 2]

$^3He + {}^3He \rightarrow 2p + {}^4He + 12.8$ MeV [Ref. 2]
$p(5.716) + p(5.716) + {}^4He(1.429) = 12.861$ MeV [Ref. 5]

$^3He + {}^4He \rightarrow \gamma + {}^7Be + 1.588$ MeV [Ref. 6]

$^3He + {}^6Li \rightarrow p + {}^8Be \rightarrow 2{}^4He + 16.8$ MeV [Ref. 2]

$^3He + {}^6Li \rightarrow p + {}^8Be' \rightarrow \gamma + 2{}^4He + (13.9 + 2.9)$ MeV [Ref. 2]

$^3He + {}^6Li \rightarrow \gamma + {}^9B \rightarrow p + 2{}^4He + 16.9^*$ MeV [Ref. 1]

$^3He + {}^6Li \rightarrow n + {}^8B \rightarrow e^+ + {}^8Be \rightarrow 2{}^4He + 15.6^*$ MeV [Ref. 1]

$^3He + {}^6Li \rightarrow d + {}^7Be$ [Ref. 1,6]
$+ 0.112$ MeV [Ref. 6]

$^3He + {}^6Li \rightarrow p + 2{}^4He$ [Ref. 1,6]
$+ 16.878$ MeV [Ref. 6]
$p(12.390) + {}^4He(2.245) + {}^4He(2.245) = 16.880$ MeV [Ref. 5]

$^3He + {}^7Li \rightarrow {}^4He + {}^6Li + 13.3^*$ MeV [Ref. 1]

$^3He + {}^7Li \rightarrow n + {}^9B \rightarrow p + {}^8Be \rightarrow 2{}^4He + (9.3 + 0.3)$ MeV [Ref. 2]

$^3He + {}^7Li \rightarrow n + p + {}^8Be \rightarrow 2{}^4He + (9.5 + 0.1)$ MeV [Ref. 2]
$n(3.852) + p(3.852) + {}^4He(1.512) + {}^4He(1.512) = 10.728$ MeV [Ref. 5]

$^3He + {}^7Li \rightarrow p + {}^9Be + 11.2$ MeV [Ref. 2]

$^3He + {}^7Li \rightarrow d + {}^8Be \rightarrow 2{}^4He + (11.7 + 0.1)$ MeV [Ref. 2]

$^3He + {}^7Li \rightarrow t + {}^7Be - 0.881^*$ MeV [Ref. 8]

$He3 + Be7 \rightarrow 2p + 2He4$ [Ref. 5]
$p(4.510) + p(4.510) + He4(1.127) + He4(1.127) = 11.274$ MeV [Ref. 5]

$He3 + Be9 \rightarrow n + He4 + Be7 + 0.014^{*}$ MeV [Ref. 8]

$He3 + Be9 \rightarrow 2n + C10 \rightarrow e+ + B10 - 2.43^{*}$ MeV [Ref. 8]

$He3 + Be9 \rightarrow p + B11 + 10.3^{*}$ MeV [Ref. 1]

$He3 + Be9 \rightarrow n + C11 \rightarrow e+ + B11 + 9.02^{*}$ MeV [Ref. 1]

$He3 + Be9 \rightarrow He4 + Be8 \rightarrow 2He4 + 19.0^{*}$ MeV [Ref. 1]

$He3 + B10 \rightarrow p + C12 + 19.7^{*}$ MeV [Ref. 1]

$He3 + B10 \rightarrow t + C10 \rightarrow e+ + B10 - 0.530^{*}$ MeV [Ref. 8]

$He3 + B10 \rightarrow He4 + B9 \rightarrow p + 2He4 + 12.4^{*}$ MeV [Ref. 1]

$He3 + B10 \rightarrow d + C11 \rightarrow e+ + B11 + 4.73^{*}$ MeV [Ref. 1]

$He3 + B10 \rightarrow Li6 + Be7 - 2.87^{*}$ MeV [Ref. 8]

$He3 + B11 \rightarrow p + C13 + 13.2^{*}$ MeV [Ref. 1]

$He3 + B11 \rightarrow d + C12 + 10.6^{*}$ MeV [Ref. 1]

HELIUM-4--INDUCED REACTIONS

These reactions are listed by increasing atomic number of the target nuclide.

He4 + Li6 -> & + B10 [Ref. 1,6]
+ 4.460 MeV [Ref. 6]

He4 + Li6 -> p + Be9 - 2.125 MeV [Ref. 6]

He4 + Li6 -> d + 2He4 - 1.473 MeV [Ref. 6]

He4 + Li7 -> & + B11 + 8.65* MeV [Ref. 1]

He4 + Li7 -> n + B10 - 2.76* MeV [Ref. 8]

He4 + Be9 -> n + He4 + Be8 -> 2He4 - 1.57* MeV [Ref. 8]

He4+ Be9 -> p + B12 -> e- + C12 - 6.92 MeV [Ref. 1]

He4+ Be9 -> p + B12 -> He4 + Li8 -> e-+ Be8 -> 2He4
- 6.92 MeV [Ref. 1]

He4 + Be9 -> n + C12 + 5.71 MeV [Ref. 1]
n(5.263) + C12(0.439) = 5.702 MeV [Ref. 5]

He4 + Be9 -> d + B11 - 7.95* MeV [Ref. 1]

He4 + B10 -> p + C13 + 4.08 MeV [Ref. 1]

He4 + B10 -> n + N13 -> e+ + C13 + 2.73* MeV [Ref. 1]

He4 + B10 -> d + C12 + 1.40* MeV [Ref. 1]

He4 + B11 -> n + N14 + 0.159* MeV [Ref. 1]

He4 + B11 -> p + C14 + 0.75 MeV [Ref. 1]

LITHIUM-6--INDUCED REACTIONS

These reactions are listed by increasing atomic number of the target nuclide.

Li6 + Li6 -> p + B11 + 12.215 MeV [Ref. 6]
p(11.200) + B11(1.018) = 13.218 MeV [Ref. 5]

Li6 + Li6 -> n + He4 + Be7 +1.906 MeV [Ref. 6]
n(1.370) + He4(0.342) + Be7(0.196)
= 1.908 MeV [Ref. 5]

Li6 + Li6 -> 3He4 + 20.896 MeV [Ref. 6]
He4(6.967)+He4(6.967) +He4(6.967)
= 20.901 MeV [Ref. 5]

Li6 + Li6 -> n + C11 -> B11 + e+ + 9.450 MeV [Ref. 6]
n(8.665) + C11(0.788) = 9.453 MeV [Ref. 5]

Li6 + Li6 -> d + B10 + 2.985 MeV [Ref. 6]
d(2.489) + B10(0.498) = 2.987 MeV [Ref. 5]

Li6 + Li6 -> t + B9 + 0.805 MeV [Ref. 6]
t(0.606) + B9(0.202) = 0.808 MeV [Ref. 5]

CANDIDATE REACTIONS FOR FUSION PROPULSION SYSTEMS

Using the reaction bibliography as a reference, the following charged particle reactions listed on the next four pages were chosen to be of special interest for advanced reactors for propulsion based on the following criteria:

1) Reaction produces no neutrons.
2) Reaction produces no gamma-rays.
3) Reactions are exothermic.
4) Reacting isotopes occuring naturally on Earth.

There were many other reactions that met the criteria of 1, 2, and 3, but couldn't be included because one of the reacting isotopes doesn't occur naturally on Earth in sufficient quantities to be extracted economically from present sources, i.e., Helium-3 and tritium.

These reactions are arranged in ascending order by the atomic number of the incident particle. All reactions are of equal value with respect to this list.

This list will be used as the starting point for further study to determine the best fuel cycle to use for a fusion powered propulsion system.

PROTON-INDUCED REACTIONS

p + p -> e+ + d + 1.42 MeV

p + Li6 -> He3 + He4 + 4.02 MeV

p + Li7 -> 2He4 + 17.5 MeV

p + Be9 -> He4 + Li6 + 0.651 MeV

p + Be9 -> d + Be8 -> 2He4 + 0.651 MeV

p + B10 -> He4 + Be7 + 1.148 MeV

p + B11 -> He4 + Be8 -> 2He4 + 8.585 MeV

p + B11 -> 3He4 + 8.7 MeV

DEUTERON-INDUCED REACTIONS

d + d -> p + t + 4.03 MeV

d + Li6 -> p + Li7 + 5.02 MeV

d + Li6 -> t + Li5 -> p + He4 + 2.5 MeV

d + Li6 -> 2He4 + 22.4 MeV

d + Li6 -> p + t + He4 + 2.557 MeV

d + Li7 -> p + Li8 -> e- + Be8 -> 2He4 + 15.74 MeV

d + Be7 -> p + 2He4 + 16.766 MeV

d + Be9 -> p + Be10 + 4.588 MeV

d + Be9 -> t + Be8 -> 2He4 + 4.68 MeV

d + Be9 -> He4 + Li7 + 7.153 MeV

d + B10 -> p + B11 + 9.235 MeV

d + B10 -> He4 + Be8 -> 2He4 + 17.86 MeV

d + B11 -> p + B12 -> e- + C12 + 1.137 MeV

d + B11 -> p + B12 -> He4 + Li8 -> e- + Be8 -> 2He4 + 1.137 MeV

d + B11 -> He4 + Be9 + 8.018 MeV

HELIUM-4--INDUCED REACTIONS

$$He^4 + B^{10} \rightarrow p + C^{13} + 4.08 \text{ MeV}$$

$$He^4 + B^{10} \rightarrow d + C^{12} + 1.40 \text{ MeV}$$

$$He^4 + B^{11} \rightarrow p + C^{14} + 0.75 \text{ MeV}$$

LITHIUM-6--INDUCED REACTIONS

Li6 + Li6 -> p + B11 + 12.215 MeV

Li6 + Li6 -> 3He4 + 20.896 MeV

Li6 + Li6 -> d + B10 + 2.985 MeV

Li6 + Li6 -> t + B9 -> p + 2He4 + 0.805 MeV

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