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Assessing a new direction for fusion☆

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Abstract

The principal application proposed for fusion for the past 40 years has been the central station, electrical power generation plant. However, the sizable increases that were forecast for future electrical power demands have not been realized to date. Only coal power plants have been increasing (3%/year) generating capacity (Annual Energy Outlook, 1998) [1]. Likewise, the ability of fusion to deliver economical electrical power has not been credibly postulated, much less demonstrated. Together these two factors have stagnated the commercialization of fusion power. It is now time for a reassessment of what fusion can best do for the world. Fusion, with a practically inexhaustible energy supply, has many unique properties that enable a wide variety of useful products. A study by the ARIES team is underway to review possible fusion applications and assess those with the potential to provide useful and worthwhile new products. A roadmap of possible applications has been developed to assess the utilization of the unique properties of the fusion process. The potential product categories are energy production (fuel, electricity, heat), space propulsion, altered or transmuted material properties (transmutation, waste treatment, tritium production), chemical compound dissociation (waste treatment, ore reduction, refining), and direct use of fusion nuclear products (radiography, lithography, radiotherapy, activation analyses). An evaluation methodology based on the success and failure of previous large, national and international technology development projects was developed to assess and recommend encouraging fusion product applications. A list of significant attributes was defined to describe and characterize projects that are likely to succeed or fail in the global marketplace. These attributes were assigned weights according to their perceived value to the national or global enterprise. An additive utility theory methodology was used to qualitatively evaluate the proposed applications in terms of market potential, environmental considerations, economic impact, risk and public perception. Quantified values were assigned to each potential fusion application and market to make more intelligent decisions on the allocation of future resources. Incorporating some of the long term market trends suggested in the December 1997 Kyoto Climate Change Conference, the most favored fusion applications were found to be the production of hydrogen fuels, transmutation of nuclear wastes and dissociation of chemical compounds, all slightly ahead of electricity production. The results from this decision analysis process will help balance the benefits of success against the risks of failure to help select promising products for future study.

Keywords: Electrical power; Energy production; Fusion applications

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1. Introduction

The US Department of Energy (DOE) has funded a study within the Advanced Reactor Innovation and Evaluation Study (ARIES) project to assess other non-electric fusion applications to provide worthwhile new products.

Historically, the main thrust of DOE and the ARIES project has been to investigate the ability of fusion to generate electricity. But the ability to forecast a technically and economically attractive fusion electrical generation power plant has not been forthcoming. The ability to control the fusion process and convert the fusion energy into economic electrical power has remained an elusive goal. Fusion has the potential to be a very safe and abundant energy source, but the realization of this potential is very challenging and costly. Electrical power from fusion [2] remains above the cost of electricity from contemporary energy sources.

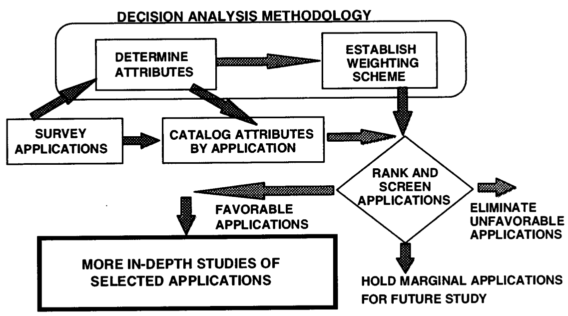

Fig. 1. Assessment of fusion products and markets.

Table 1
Potential fusion products

Neutrons	Charged particles	Radiation
Hydrogen	Hydrogen	Hydrogen
Process heat	Waste processing	Waste sterilization
Rocket propulsion	Rocket propulsion	Rocket propulsion
Electricity + space power	Electricity + space power	
Potable water	Potable water	
Fissile fuel	Ore reduction	
Transmuted waste	Transmuted waste	
Tritium	Destruction of chemical warfare agents	
Radioisotopes	Radioisotopes	
Detection and remote sensing	Detection and remote sensing	Detection and remote sensing
Neutron radiography + tomography	Radiography + tomography	
Radiotherapy	Radiotherapy	Radiotherapy
Neutron activation analyses/testing	Proton activation analyses/testing	Radiation testing
Altered material properties	Altered material properties	
	Lithography	Lithography

In the past, fusion has been proposed to be utilized to provide end products other than electricity. This study investigated other uses or products that could be produced with fusion energy, and result in useful and worthwhile end products for mankind. Fig. 1 illustrates the study flow. The first step in the process was to survey and catalogue the potential applications for fusion. Next, a decision analysis methodology was developed to evaluate very dissimilar product applications. This decision analysis methodology was validated with other prior large programs that have succeeded or failed. Following validation, the fusion applications were assessed with the methodology. Rank ordering of the alternate fusion products determined the most promising products to pursue.

2. Survey of fusion application products

There have been several prior studies that surveyed the opportunities for fusion to provide a range of applications and products. EPRI sponsored a review of the status and options for fusion in 1977 [3], which provided the starting point for this study. A more recent assessment of near-term commercial opportunities from long range fusion research [4] was conducted by G.L. Kulcinski and was incorporated in our database. Several advocates for various applications have contributed to the understanding of their concepts, products and markets. Table 1 is a compilation of the fusion products that may be obtained from the various forms of fusion energy. There is similarity among

Table 2
Large national and international projects assessed

US supersonic transport
Superconducting super collider
Jumbo jet (Super 747 category)
High definition TV (analog and digital)
Manned moon and Mars landing

Table 3
Decision criteria attributes

	Relative value
Market factors	
Necessity	High (3)
Uniqueness	High (3)
Market potential	High (3)
Environmental factors	
Depletion of valued resources	High (3)
Environmental impact	High (3)
Economic factors	
Competitive product	Moderate (2)
Improvement in GNP	Low (1)
Risk factors	
Investment for return of capital	Moderate (2)
Maturity of technology	Moderate (2)
Time to market	Moderate (2)
Public perception	
National/company prestige	High (3)
Public/governmental support	High (3)

products which may be produced with neutrons, charged particles and radiation. But there are also unique products associated with each of the forms of fusion energy. Obviously, some alternate fusion confinement concepts would be better matched with certain products.

3. Decision analysis methodology

One of the key steps in the assessment is formulating an appropriate decision analysis methodology to evaluate the potential fusion products shown in Table 1. As noted in Fig. 1, the first step was to determine the attributes that characterize a successful endeavor versus an endeavor that fails to meet the perceived expectations of the customer and/or decision maker (performance, schedule or cost). Table 2 presents a set of large national and international projects that were selected as being of the same magnitude of fusion development.

The projects in Table 2 were examined to determine the customers expectations, if they met those expectations, and if they were successful. Key features, benefits and risks were identified and examined. From that examination, a set of attributes was identified that would characterize the potential project and help guide the decision maker as to the benefits and risk in deciding to undertake (support) the project. Some of the attributes could be measured directly, such as economics and schedule, but others are indirect values such as good will and strategic advantage. Table 3 lists the general categories determined from the examination and the detailed attributes adopted for this assessment. Weighting values were assigned to each of the attributes according to the perceived importance to the decision makers.

Once the attributes were selected, both multiplicative and additive utility functions [5] were considered for use in the decision analysis methodology. The multiplicative utility function was deemed to be inappropriate because a score of zero in any single attribute would disqualify the product from further consideration. This might be very appropriate for well defined product concepts where they might have a fatal flaw or could not reach a mandatory threshold value. But at this stage in the definition of the fusion products, a score of zero should not eliminate a product from consideration because it might be capable of improving that particular attribute. Instead, an additive utility function would penalize the product with a zero score, but not eliminate it from further consideration. Therefore, the decision analysis methodology was determined to be:

$$\text{SCORE} = \Sigma(\text{attribute weight}) \times (\text{attribute value})$$

$$\text{Weights} = 1 \text{ to } 3; \text{ values } = -5 \text{ to } +5$$

The attribute values for each product were established to be on a scale of -5 (for the least attractive attribute) to $+5$ (for the most attractive attribute). The use of positive and negative attribute values is completely arbitrary, but this approach helps the evaluator to judge positive and negative attributes. Each of the attributes was assigned a qualitative description (least attractive, neutrally attractive and most attractive) to keep the evaluation unbiased. This methodology was tested with the prior projects listed in Table 2, and the results correlated well with historical data. Thus, the methodology was validated for use on the proposed fusion products.

4. Fusion product evaluation results

The choice of a fusion confinement concept is immaterial in assessing the market factors, the public perception factors, and many of the environmental factors. But when the risk factors of investment, technology maturity and time to market were considered, a confinement concept had to be mated with the product to complete the assessment. The intent was to evaluate a complete range of possible products. However, only a limited number of the products and confinement concepts that were most likely to yield a competitive and successful product were evaluated.

In the preliminary analysis, 17 fusion products were evaluated with this methodology. Table 4 illustrates the selected fusion products (shown in the first row) and the evaluation data used to describe and evaluate those products. The second row lists the key assumptions for each product, such as confinement concept and processes assumed. The left-hand column lists the attributes that are addressed for each product. The associated attribute weighting factors are shown in the second column. The individual attribute values for each product are shown in the corresponding spreadsheet cells.

This process was first completed by the author. Next, it was reviewed by a small assessment group from the ARIES team and then by the entire ARIES project team and some guests from the University of Wisconsin Fusion Technology Institute. Meanwhile, several product advocates reviewed the methodology and assessment. Comments from all these sources were integrated into the preliminary assessment data shown in Table 4. The weighted sum scores for each product are shown on the bottom row of the table. A rank-ordered graph of these scores is shown and discussed in Section 5.

5. Discussion and summary

The weighted sum data from the decision analysis methodology shown in Table 4 was rank-ordered and displayed in Fig. 2. These data indicate that hydrogen production would be the most desirable fusion product, decreasing down to the fusion–fission breeder reactor as the least desirable under the present circumstances.

To understand why these products are evaluated as such, one has to examine the attributes and weighting methodology used. Very few of the products were rated at the maximum positive value and none at the maximum negative value. The concepts that scored well had several attributes that scored high. They were thought to be able to be developed in a shorter time and had more mature technology and good public support. They also required less investment capital to reach the market. Conversely, the breeder application was not viewed as being needed in the US market place, a large investment is required, time to market would be very long, and the technology is also not mature. Interestingly, the two electrical generating plants (the large, central station plant and the smaller, local generating plant) are judged to be nearly identical by trading off the better cost of electricity for the larger plant versus the smaller investment, shorter technical maturity and shorter time to market of the smaller plant.

This analysis should not be considered as a final evaluation result; rather it is intended to be used as a tool to assess the relative merits of each product. It helps highlight where improvements could be made to enhance the value, merit and perception of the product. As fusion technology advances, product developments mature, investment strategies change and public

Table 4
Preliminary fusion product evaluation results

	Weight:	Hydrogen fuels	Transmutation of nuclear waste	Dissociationof chemical compounds	Electricity,central station	Electricity, local station	Propulsion	Process heat	Detection, remote sensing	Radio isotopes	Desalination, fresh water	Radiotherapy	Activation analyses	Ore reduction, refining	Lithography	Radiography	Tritium production	Fusion–fission breeder
Attribute	Assumptions:	Use HTE + electricity generation	Transmutation and power generation, no fuel recycle	Industrial chemical waste, chemical weapon waste	Central station power plant	Small generating plant	Charged particles from tandem mirror, deep space probe	Heat only, no cogeneration	Land mines, remote surveying		Desalinate with electrodialysis + fusion-generated-electricity	Neutron and proton	Neutron and proton	Only difficult ore reduction and refining	Applicable to smaller chips and nanomachine	Neutron and proton	For other fusion plants + defense programs	Breeder + transmutation fuel recycle
Necessity	3	3	2	2	2	1	1	1	2	2	2	1	2	1	2	1	1	−2
Uniqueness	3	4	4	3	2	2	5	1	3	2	0	3	4	1	2	3	4	3
Market potential	3	4	4	3	3	2	2	1	3	2	3	2	2	1	2	1	2	2
Resources	3	4	1	1	3	2	0	2	0	1	4	0	0	2	0	0	3	3
Environment	3	5	4	5	4	4	0	4	0	0	2	0	0	2	0	0	0	1
Competitive	2	−2	0	−2	−2	−4	2	−1	1	−2	−2	−2	1	−3	−3	−2	2	−1
Helps GNP	1	4	2	2	3	2	1	3	1	1	1	1	0	2	1	1	1	2
Investment	2	−4	−2	−1	−4	−2	−3	−3	−1	−1	−2	−1	−2	−1	−1	−1	−2	−3
Technical maturity	2	−4	−2	−2	−3	−2	−2	−2	−1	−1	−3	−1	−2	−2	−1	−1	−3	−4
Time to market	2	−4	−2	−2	−3	−2	−2	−2	−2	−1	−3	−1	−1	−2	−1	−1	−2	−4
Prestige	3	4	3	2	3	3	4	2	1	1	2	1	1	1	1	1	−1	1
Public support	3	4	2	4	3	4	2	2	1	3	1	3	0	2	2	2	−1	−1
Weighted sum	+145	60	50	48	39	36	33	26	25	24	23	21	19	16	16	15	15	−1

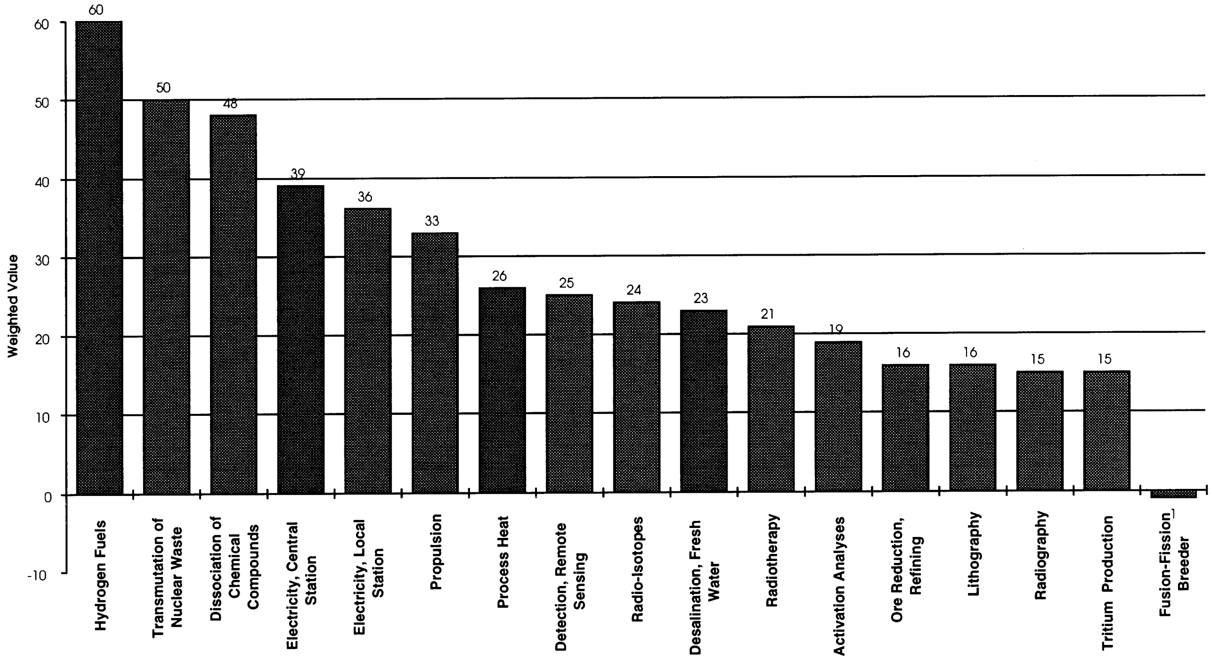

Fig. 2. Ranked weighted values of fusion products.

needs evolve, this tool could be altered to reassess the attractiveness of the alternate fusion products.

The results of the fusion application assessment would suggest that it might be beneficial to further investigate and develop the higher ranked products such as production of hydrogen fuels, transmutation of nuclear waste, dissociation of difficult chemical compounds, detection and remote sensing and propulsion for interplanetary transfer and deep space probes. Some of the alternate fusion confinement schemes and advanced fuels may be well suited to these applications.

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