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U.S. Fusion Energy Future

by

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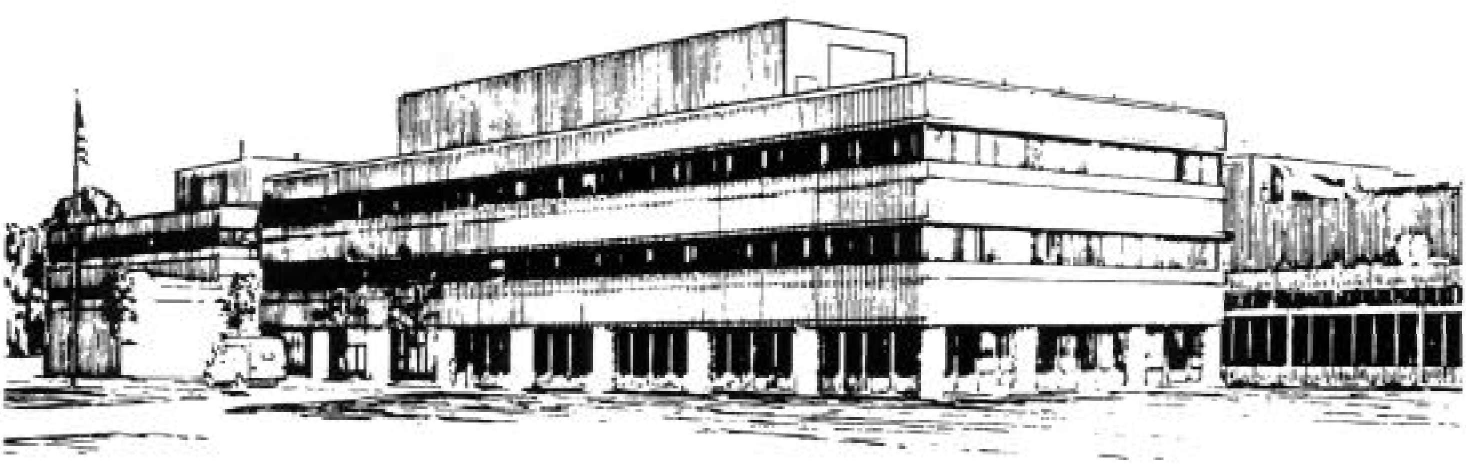

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U. S. FUSION ENERGY FUTURE

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ABSTRACT

Fusion implementation scenarios for the United States have been developed. The dependence of these scenarios on both the fusion development and implementation paths has been assessed. A range of implementation paths has been studied. The deployment of CANDU fission reactors in Canada and the deployment of fission reactors in France have been assessed as possible models for U.S. fusion deployment. The waste production and resource (including tritium) needs have been assessed. The conclusion that can be drawn from these studies is that it is challenging to make a significant impact on energy production during this century. However, the rapid deployment of fission reactors in Canada and France support fusion implementation scenarios for the U.S. with significant power production during this century. If we can meet the schedule requirements then the resource needs and waste production are found to be manageable problems.

I. INTRODUCTION

The objective of the studies that form the basis for this report is to assess the implications of implementing fusion power production near the middle of this century as input to the development of a fusion energy vision. One goal is to determine what is necessary to implement a fusion power system of facilities that would produce significant power before the end of this century. The assessment takes into account a range of implementation starting times and ramp rates. Particular attention is given to the historic basis for implementing high technology systems. Consideration is given to those aspects of fusion implementation that are of most interest to the general public. The primary elements of importance to the public include cost, safety, resource needs and positive and negative impacts on the environment (e.g. carbon dioxide emission reduction and waste production). One objective of this effort is to translate the more complicated scientific issues into terms that are meaningful to the public. This report focuses on electrical production in the United States. Using the International Panel on Climate Control objective for limiting carbon dioxide we can draw the general conclusion that a large fraction of the electrical production must come from non carbon dioxide producing sources if we are to meet carbon dioxide limitation objectives.

The period for fusion implementation must be preceded by an extended period of fusion development. For this study we used the international study lead by M.A. Abdou [1] as the bases for the elements of the development path as well as a realistic schedule for executing these elements. This schedule is in rough agreement with fusion development plans in Japan and Europe [e.g. 2].

The primary source of energy demand projections that was used as a basis for this assessment was the World Energy Council/IIASA Global Energy Perspectives [3]. The World Energy Council (WEC) tables provide insight into projections of levels of energy production from specific sources. The implied environmental improvements (e.g. carbon dioxide reduction) from fusion implementation drew heavily on the work of the Intergovernmental Panel on Climate Change [4]. The WEC projections do not show the United States specifically but include the U.S. with the rest of North America and we use the projections in this form. Figure 1 shows the projection for North American and world electrical power consumption through this century. It is worth noting that the projected growth in electrical consumption for North America is much slower than areas that include developing countries. A significant fraction of the North American (and world) electricity production will need to be from non-carbon dioxide producing power sources such as fusion. We will compare potential fusion implementation scenarios with figure 1 as a measure of their significance.

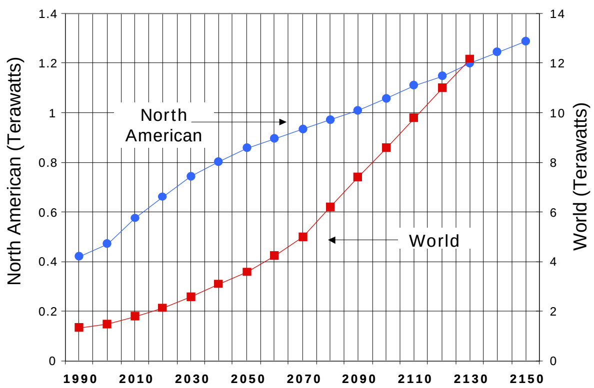

Fig. 1. IIASA/WEC Electricity Production Projections

II. DEVELOPMENT PATH

The overall implementation scenario for fusion can be divided into the development phase and the implementation phase. There is obviously significant overlap between these phases with development tapering off but continuing in parallel with implementation. The important connections between development and implementation are the date when an implementable reactor is available for reproduction along with the general characteristics of this reactor. As stated previously we assumed a development sequence and schedule that are consistent with the Abdou study [1] but modified to include recent ITER developments. We used ARIES RS [5] as representative of the fusion reactor to be implemented.

Figure 2 shows the development phase assumed for this study. The development schedule requires both expeditious construction of ITER and a Volume Neutron Source (VNS). The schedule is based to a large extent on the assumption that the development option is a tokamak configuration. If there is a transition to another configuration it would very likely extend the development schedule.

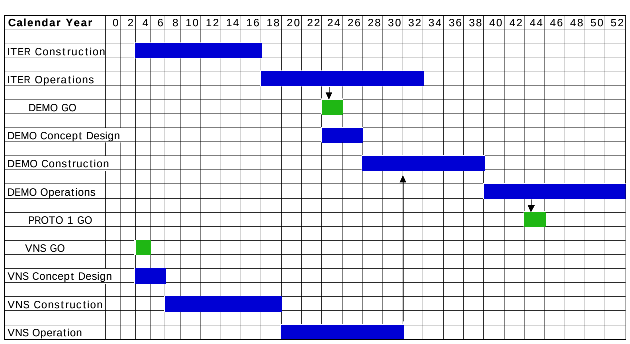

Fig. 2. Fusion Development Path

The development schedule shows the construction and operation of the fusion DEMO. There are varying interpretations as to the commercial nature of the DEMO and to what extent the DEMO is followed by what the Europeans call a PROTO, which will be further cloned into multiple commercial fusion plants. The issue of substance is when fusion power plants multiply and spread through the electrical utility industry. For the purpose of this study we assume that the first multiple plants begin appearing about 2050, however, we delayed any rapid growth in fusion power production until 2070 to allow for commercial development and acceptance of the plant design.

III. IMPLEMENTATION OPTIONS

The actual growth of fusion power production will not be describable by a simple analytical function. However, it is reasonable to use analytic functions for the purpose of projecting and assessing power production scenarios. Two functional options come to mind: linear and exponential growth. There is a historical basis for both of these options. As shown in figure 3 it has been found that over long time scales the growth of most of the energy sources roughly track an exponential form [6]. For later reference it should be noted that from figure 3 over the short time scale of fission power development there is little correspondence between fission power growth and an exponential function.

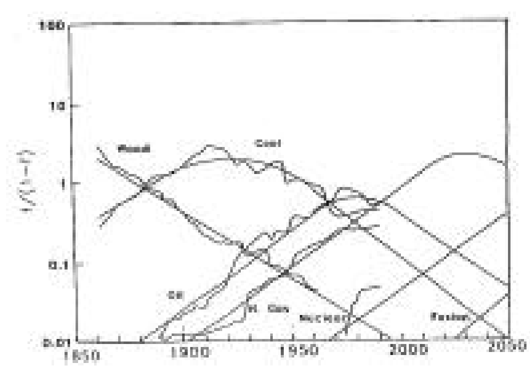

Fig. 3. Fraction, f, of world energy sources expressed as f/(1 - f).

If we choose an exponential form then the parameter choices are the magnitude and date of the starting point and the doubling time. Figure 4 shows curves starting in 2050 with a one gigawatt plant and various possible doubling times. We see that to achieve a significant power production this century with the starting parameters chosen it will require doubling times that are less than ten years. The problem with exponential growth models is the relatively small absolute growth early in the implementation.

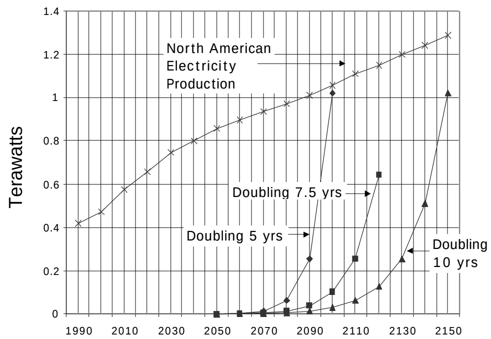

Fig. 4. Fusion contributions to North American electricity production if we assume an exponential implementation.

There is a basis for a more linear growth assumption that is related to the poor fit of fission power implementation to exponential characteristics as noted before. Figures 5 and 6 show the growth of fission power production in France and Canada (CANDU Reactors). The Canadian implementation is primarily an Ontario activity. The total power consumption for France and Canada are in the 80 GW range. As a normalization factor for the growth of the Canadian power production it may be better to use the Ontario level of a little above 20 GW. Bases on this data the linear growth rate for fission power in these two countries falls in the 1-7%/year range with France at the top and Canada normalized by total Canadian production at the 1% level and Canadian grow normalized by Ontario power production at the 3-4% level.

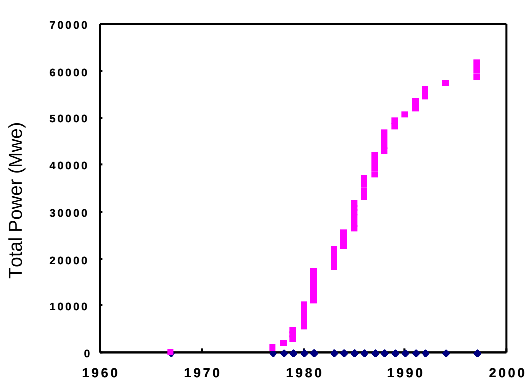

Fig. 5. France Fission Power Implementation

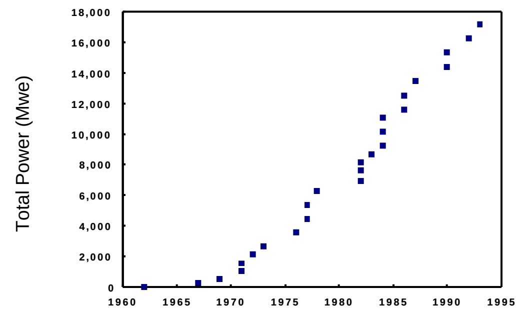

Fig. 6. Canadian Fission Power Implementation

Based on the French and Canadian experience we have chosen to consider 1% and 2% for fusion growth relative to the total U. S. power production. The other determinant for the implementation scenario is the starting date for aggressive implementation. Based on the French and Canadian fission experience, which is consistent with the assumption of a few cycles of development between DEMO and the launching of an aggressive linear growth phase for fusion, we assume linear growth begins in 2070. Figure 7 shows the implementation scenarios that follow from these assumptions. These implementation scenarios show a significant fusion contribution to the U.S. electrical energy production before the end of this century.

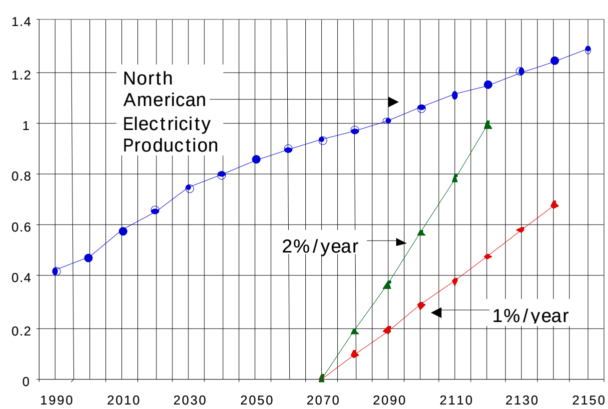

Fig. 7. Fusion contributions to North American electricity production assuming a linear growth of 1 and 2% per year.

IV. WASTE PRODUCTION AND DISPOSAL

The fusion program has developed a legacy of detailed reactor studies that form the basis for proceeding with the development of broader fusion implementation scenarios. The most recent reactor studies were the ARIES series. The well executed and documented ARIES RS study [5] was used as the primary source of detailed information for this activity. Vanadium was a key structural material choice for ARIES RS to minimize the activation. In the future we will look at the waste classification and volume for other materials choices such as ferritic steels. The waste production and construction materials needs were developed as part of this study from the detailed ARIES information by summing the specific elements from each of the subsystems.

Using the ARIES studies, the waste production, amortized over the operating and decommissioning periods of a reactor life, is about 200 cubic meters per gigawatt-year of full energy production. This waste has been determined to be class C or below for the ARIES RS configuration. Figure 8 shows the total waste production per year for the fusion scenarios discussed above. As one measure of the magnitude of this waste production we can compare it to the present licensed U.S. shallow burial waste repositories. The present licensed U.S. shallow burial capacity is over one million cubic meters. This is not meant to indicate knowledge of the expected waste disposal capacity during the last half of next century; it is used only as an indicator of the significance of the volume of the waste produced. The significance of the magnitude of the waste produce by fusion should not be overlooked; however, the waste disposal should be a manageable problem.

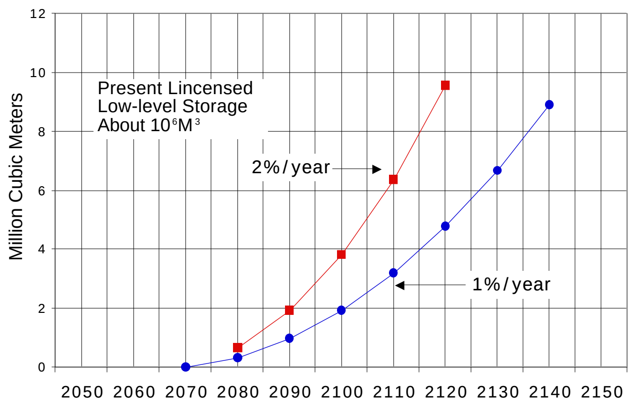

Fig. 8. Fusion waste production form implementation scenarios shown in figure 7.

V. RESOURCE NEEDS

The construction of fusion reactors will require the use of a number of materials that may be in short supply. The specific materials for ARIES RS that may fall into this category are Vanadium, Niobium, and Tungsten. Figure 9 shows the integrated requirements for vanadium for the fusion scenarios considered. As one measure of the significance of the magnitudes of material requirements they can be compared to present yearly production rates and identified reserves. The present world production rate of vanadium is roughly 50 kt/yr with an identified reserve of roughly 30 mt. For an aggressive fusion implementation scenario the yearly demand for vanadium would quickly surpass the present world production rate. However, the present production rate is dictated by the present demand and there should be no special problems increasing production. Of more importance is the reserves. The identified reserves for vanadium indicate an ample supply for fusion implementation.

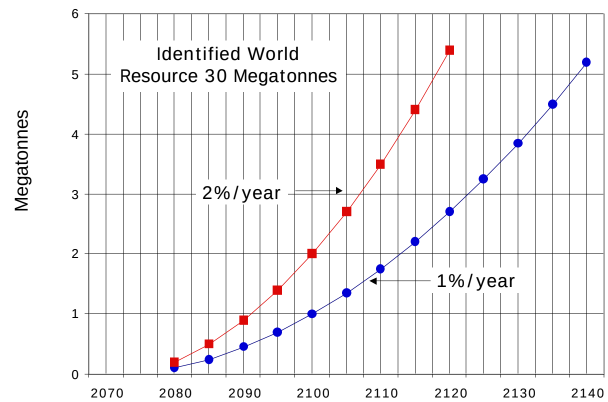

Fig. 9. Vanadium requirements for implementation scenarios shown in figure 7.

The development phase of fusion will rely mainly on external supplies of tritium [7]. However, when fusion reactors are deployed commercially, they must be self-sufficient in tritium from the outset, because of the large quantities consumed. Moreover, the tritium breeding ratio (TBR) in each reactor must exceed unity in order to:

(i) supply inventory for start-up of other reactors;
(ii) maintain the equilibrium hold-up inventory;
(iii) provide reserve storage inventory;
(iv) compensate for losses and leakage (although this must be essentially negligible in practice);
(v) compensate for radioactive decay of all inventories (with a 12.3-year half-life).

It is shown in this report (for ARIES-RS tokamak reactors) that an achieved TBR of only 1.01 would be sufficient for these purposes.

Blanket designs for fusion reactors such as ARIES-RS generally aim at a substantially larger design TBR. For a particular choice of breeder and first-wall and blanket structural materials, the TBR is obtained from neutronics calculations, which generally employ approximations to the actual geometry. It has long been recognized that there are substantial uncertainties in these calculations [8]. For the case of ARIES-RS, the uncertainties are estimated to be [9]:

(i) uncertainties of order 6% in the basic nuclear data;
(ii) uncertainties of order 3% in geometrical approximations used in the calculations.

Accordingly, the design value of the TBR in ARIES-RS is 1.1; for the uncertainties given above, the actual value would be in the range 1.01 - 1.2 and would fulfill the requirement even in the "worst" case.

For a TBR of 1.01 and a 3-kg tritium hold-up/inventory, each reactor would produce enough excess tritium to begin operation of another reactor in 3.6 years. Correcting for a 53-year reactor lifetime, the overall time-average "doubling time" for fusion power is only 3.9 years.

Table 1 gives the doubling time for other values of TBR and other values for the tritium hold-up/inventory. It is seen that the doubling time exceeds about 5 years only if the TBR falls below 1.01 or the hold-up/inventory is more than about 4 kg. Thus, for conventional (even moderately conservative) assumptions, tritium supply should not be a serious limitation on exponential fusion power growth once a breeding ratio even just slightly in excess of unity has been routinely achieved. The onset to a linear power growth will need to be tailored to accommodate tritium supply requirements. This accommodation should not present a serious limitation.

	Tritium Hold-up/Inventory (kg)				
TBR	2	3	4	5	6
1.005	5.5	9.6	15.3	24.3	41.0
1.01	2.4	3.9	5.5	7.4	9.6
1.02	1.2	1.8	2.4	3.1	3.9
1.03	0.8	1.2	1.6	2.0	2.4

Table 1. Fusion power doubling times in years for various values of the tritium breeding ratio (TBR) and the tritium hold-up/inventory in each reactor.

VI. CONCLUSIONS

If we use the French and Canadian fission experience as a historical basis for fusion implementation we will have a reasonable expectation for producing significant fusion power during this century. The resource needs associated with this power production should not present a significant problem. The waste production should not be overlooked; however, this problem should be manageable.

ACKNOWLEDGMENTS

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