The Energy Reserves of D-T Fusion

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Abstract

The total quantities of energy releasable in fusion reactors based on the D-T reaction are governed by the specific fuel requirements and the amounts of lithium available. The specific fuel requirements are given for three concepts for deriving tritium from lithium. The lithium resources in the earth are classified in a McKelvey diagram according to the reliability of the quantities stated and the size of the recovery costs. Here differences are made between proved and probable reserves (now economically recoverable), possible reserves or resources, the costs of recovering which would exceed today's, and predicted and speculative resources even at higher recovery costs. Lithium resources in sea water are considered, the recovery costs possibly being not so much above today's owing to the conventional extraction technique. The amounts of energy releasable and the amounts of power installable corresponding to these lithium resources are classified in the same way. The contributions of fuel consumption and fuel inventory to the power production costs are calculated, including the case of additional utilization of beryllium. It is not only the vast amounts of fuel and low fuel costs that afford a high element of reliability in fuel supply, but also the fact that the lithium reserves and resources in the earth are widely scattered, the technology of recovering lithium from rocks and salt lakes is conventional, and the costs will probably also be small when lithium is extracted from sea water. Neither world-wide nor local shortages are anticipated.

CONTENTS

1. Introduction

The relative advantages and disadvantages of different types of power plants, including fusion power plants, are essentially governed by power costs, environmental impact and availability of fuel. Extrapolation of the lines of research now being pursued, tokamak experiments being the main activity, to fusion reactors shows that the radioactive hazard to the environment is likely to be one to two orders of magnitude less than that caused by fission reactors and their fuel cycles. It is believed that power costs will presumably be on the same level as those of nuclear fission power plants. The amount of energy releasable in the nuclear fusion process is so large that the possible duration of this energy source exceeds the human imagination. Any statement about the availability of fuel and hence about the reliability of supply calls, however, for detailed consideration of the specific fuel requirements of fusion power plants, i.e. fuel consumption in relation to energy released and fuel inventory in relation to power installed, together with an analysis of the fuel resources on earth as far as recoverable amounts, costs and geographical distribution are concerned.

2. Specific fuel requirements of fusion power plants

2.1 Fuel cycle and tritium production

Of the many reactions involving fusion of light atomic nuclei, e.g. those presented in [1], the D-D reactions given in Table 1, followed by the D-^{3}He and D-T reactions (eqs. (1) to (4) in the top box), appeared to be particularly interesting at first because the energy yield per D atom is sufficiently high and the amount of deuterium available on earth in water is very large, as will be discussed later. The maximum probability of D-T reactions is, however, much higher than that of D-D reactions and, in addition, the energy required of the collision partners is more than an order of magnitude lower. This is shown in Fig. 1 (in accordance with [1]), in which the D-D and D-T reaction cross-sections are plotted versus the energy of the collision partners (in their centre-of-mass system). To achieve the D-T reaction alone, it is, however, necessary to produce T, which is practically not present in nature. This can be done by making the neutrons produced in the reaction react with lithium (see eqs. (5) and (6) in Table 1). The reaction space of a D-T reactor thus has to be enclosed by a blanket containing lithium.

The reactions listed in the bottom box in Table 1 lead to the fuel flowchart shown in Fig. 2. In the fuel cycle (upper dashed box) the amounts coming from the deuterium storage system and tritium storage system, which contains a starting quantity of tritium, are mixed and conveyed to the reaction space, where a few per cent of the fuel mixture reacts in accordance with eq. (4). The rest of the fuel with the ^{4}He produced in the fusion reaction is transferred from the reaction space via the vacuum system to the gas separating system, where the helium is separated and taken out, while the fuel flow remaining in the mixer is replenished from the storage systems. In the tritium production process, shown in the lower dashed box, the blanket is first provided with a certain amount of lithium, in which the neutrons coming from the reaction space produce tritium in accordance with eqs. (5) and (6). This tritium and the helium also produced are largely separated from the lithium. The tritium is conveyed to the storage system in the fuel cycle,the helium taken out and the lithium flow is again transferred to the blanket, where the quantity of lithium consumed in the reactions according to eqs. (5) and (6) is replenished from the storage system. Apart from the starting quantity of tritium, only deuterium and lithium have to be introduced to the fusion reactor, helium being taken out.

To achieve this scheme, particularly the tritium production process, there are a number of possibilities since the breeding material lithium can be used as coolant as well and one can use as breeding material not only pure lithium but also mixtures, e.g. LiF and BeF_2 (called flibe) or solid lithium aluminium compounds. In addition, it is possible to change the isotopic ratio of natural lithium (7.42 % ^{6}Li and 92.58 % ^{7}Li) by enriching the one isotope or the other. This is important because the dependences of the cross-sections of the reactions according to eqs. (5) and (6) on the neutron energy are very different (see Fig. 3 according to [2]). Whereas the ^{6}Li reaction has a very large cross-section at low neutron energies as well, ^{7}Li reactions take place only beyond a neutron energy threshold of approx. 2.5 MeV and also the maximum of the ^{7}Li cross-section is only about 1/3 of the maximum of the ^{6}Li cross-section. As the neutrons coming from the plasma with an energy of 14 MeV (see eq. (4)) are thermalized in the blanket, the neutron energy is locally variable, and hence the abundance of ^{6}Li and ^{7}Li reactions as well. The neutron energy distribution is also affected by the type and arrangement of structure materials in the blanket. The tritium yield of a blanket, and hence ultimately the fuel consumption per unit energy released as well, thus strongly depends on the basic concept, the breeder and structure materials used and the design layout.

In order nevertheless to obtain data on the specific fuel requirements, a few characteristic tritium production concepts are considered in the following.

2.2 Specific fuel requirements for the various tritium production concepts

This aspect is studied on the basis of three different concepts already designed for proposed fusion power plants:

- the use of liquid lithium as breeding material and coolant simultaneously (e.g. UWMAK I design [3])
- the use of a eutectic lithium salt mixture as breeding material and blanket cooling with helium (e.g. the PPPL design of Princeton Plasma Physics Laboratory [4])
- the use of a solid lithium compound as breeding material and blanket cooling with helium (e.g. the UWMAK II design [6] based on the work of Brookhaven National Laboratory [5]).

In determining the fuel requirements a basic distinction has to be made between the actual fuel consumption resulting from the release of energy and the fuel inventory, which has to be present in the reactor for operational reasons. The fuel consumption in relation to the unit of energy released, together with the fuel reserves, determines the total amount of energy releasable; the fuel inventory in relation to the unit of installed power, together with the quantities of fuel available at a given time, yield the maximum power that can be installed at this time.

2.2.1 Liquid lithium as breeding material and coolant

In this concept it is assumed that at the start of operation the reactor is provided with lithium in its natural isotopic ratio (7.42 % ^{6}Li, 92.58 % ^{7}Li). The lithium consumed in the reactions according to eqs. (5) and (6) is replaced accordingly by natural lithium. The specific fuel consumption or its reciprocal, the magnitude of the energy released per unit quantity of fuel, is first determined for a special case that is only theoretically conceivable. It is here assumed that the isotopic ratio of the lithium is not changed by irradiation with neutrons (which actually is not true since the ^{6}Li and ^{7}Li reactions have different cross-sections as has already been explained in Fig. 3). This special case gives a fuel consumption which may be regarded as the theoretical lower limit.

To determine this limiting value, the quantities used and their relation to one another are first discussed. This is done by considering the example shown in Fig. 4 for an energy flow diagram of a fusion power plant whose reactor is fitted with a divertor (= device for extracting unused fuel, burn-up and impurities). The greatest part of the fuel energy E_{fuel} is released as fusion energy E_f together with the energy E_h for heating the plasma, this process creating the reaction conditions. The fusion energy is (according to eq. (4)) composed of the energy of the neutrons E_{neutr} and that of the α-particles E_α. The fusion energy, together with the heating energy input, gets into the blanket and into the divertor and first wall ($E_{D,W}$). The reactions occurring in the blanket are exothermic on the whole, yielding the energy E_{RM}. The size of this energy yield depends, however, on design features, e.g. the thickness of the first wall, i.e. the one facing the plasma, and the amount of structure material in the blanket. The ratio of the energy in the blanket E_M to the neutron energy E_{neutr} is normally expressed by the multiplication factor

$$M_{tot} = \frac{E_M}{E_{neutr}} \qquad (7)$$

or, if the energy loss E_1 to the shielding and magnets is taken into account (see Fig. 4), by

$$M = \frac{E_{Bl}}{E_{neutr}} \cdot \qquad (8)$$

If it is now assumed that the power plant, once it has been provided with an initial quantity of tritium, is neither supplied with further tritium nor deprived of tritium (the power plant then supplies itself with tritium), then according to eqs. (4), (5) and (6) one obtains per Li atom one T atom, which then reacts with a D atom. Altogether then an energy of

$$e_{th} = (M \cdot 14.06 + 3.52)\ \frac{\text{MeV}}{\text{atom}} \cdot 1.602\ \ 10^{16}\ \frac{\text{kJ}}{\text{MeV}} \cdot 6.023 \cdot 10^{26}\ \frac{\text{atoms}}{\text{kmol}} \cdot \qquad (9)$$

is liberated. According to existing designs of fusion reactors one can take $M \approx 1.2$ (e.g. in [3] one has $M = 1.17$). This value yields $e_{th} = 1.968 \cdot 10^{12}$ kJ/kmol. With reference to the mass of 1 kmol of lithium (of natural composition), i.e. 6.939 kg, the energy that can be released per unit quantity is

$$e_{th} = 0.28 \cdot 10^{12}\ \text{kJ/kg}_{Li} = 3.28\ \text{MW}_{th}\text{d/g}_{Li\ nat}.$$

These values indicate the "heating value" or "burn-up" of the lithium fuel, i.e. the specific energy that can be released. The specific consumption of natural lithium is accordingly

$$b = 0.3\ \frac{g_{Li\ nat}}{\text{MW}_{th}\text{d}}.$$

This is a theoretical lower limit according to the assumption that the isotope ratio of the lithium is constant. In reality, however, the difference in the cross-sections of the two lithium reactions (Fig. 3) leads to a higher specific consumption since the ^{6}Li burns up faster than the ^{7}Li, so that the tritium production is finally no longer sufficient to cover the tritium consumption. To determine these processes, one has to make extensive neutronics calculations which, in addition to the different Li reaction cross-sections, also take into account the neutron energy spectrum, the geometry of the blanket as well as the type and quantity of structure material in the blanket.

Detailed studies of this kind were first reported in [2]. Of the cases treated there the following comes closest to the special case considered above. At the start of operation natural lithium is put into the reactor. During operation the sum of the burnt-up quantities of ^{6}Li and ^{7}Li is replaced by natural lithium until the tritium breeding rate has dropped to the value "1"; this is the case when the ^{6}Li component in the coolant is down to ≈ 0.3 % [2]. In subsequent operation this value is kept constant by replacing a certain amount of coolant by natural lithium. For this case an energy yield of 1.05 $MW_{th}d/g_{Li\ nat}$ is given in [2] and so the specific fuel consumption is

$$b_{nat} = 0,95 \ \frac{g_{Li\ nat}}{MW_{th}d} .$$

Since the work on which [2] is based was carried out knowledge of the data used for the neutronics calculations involved has improved, and more detailed ideas on the design of blankets cooled with liquid lithium are also available. Systematic studies for designing tokamak power plants are therefore now reappraising the fuel system and the resulting values for the specific consumption. This will be reported at length in [7]. Data on the fuel inventory can only be obtained from reactor designs since design features have a major influence. In the UWMAK I design already mentioned [3] the lithium inventory is 1700 t (natural composition), i.e. with reference to the thermal reactor power of about 5000 MW_{th}

$$i_{nat} = 340 \ \frac{kg_{Li\ nat}}{MW_{th}} \ .$$

After decommissioning of a reactor this inventory can be used in a new reactor. In keeping with the breeding rate then required, however, an appropriate amount has to be replaced by natural lithium.

2.2.2 Flibe as breeding material

In this concept a eutectic mixture of LiF and BeF_2 is used as breeding material, while helium serves as coolant. It is incorporated in the PPPL reactor design of Princeton Plasma Physics Laboratory [4]. The material, called flibe, is composed of 46.9 % LiF and 53.1 % BeF_2. The ^6Li content of the lithium used is enriched to 12 % relative to the natural content of 7.42 % (at the start of operation). The beryllium contained in the other component serves as neutron multiplier in accordance with the reaction

$$^9Be + n \rightarrow 2\ ^4He + 2n' - 1.57\ MeV \ . \qquad (10)$$

According to [4] the consumption of ^6Li is 1 kg/d, which at a thermal power of 5305 MW_{th} corresponds to a specific consumption of

$$b_6 = 0.189 \ \frac{g\ ^6Li}{MW_{th} d}$$

so that the amount of natural lithium required is

$$b_{nat} = 2.55 \frac{g_{Li\ nat}}{MW_{th} d} .$$

The isotope ^{7}Li is scarcely used at all in this concept.

Besides lithium, beryllium is also consumed in tritium production, the amount being 0.352 kg/d; this corresponds to a specific value of

$$b_{Be} = 0{,}066 \frac{g_{Be}}{MW_{th} d} .$$

The total flibe inventory of the reactor is 6.8×10^{3} t, of which 1.86×10^{3} t is contained in the blanket, while 4.94×10^{3} t serves as heat storage for bridging the idle time of the reactor. Of this total quantity 3189 t is LiF, of which 848 t is Li (with 12 % ^{6}Li); the amount of BeF_2 is 3611 t, of which 692 t is Be. The natural lithium requirements for the inventory, in relation to the thermal power installed, are then found to be

$$i_{nat} = 258 \frac{kg_{Li\ nat}}{MW_{th}} ,$$

and the specific beryllium inventory is

$$i_{Be} = 130 \frac{kg_{Be}}{MW_{th}} .$$

The authors of [4] stress that this fuel system is not optimized. The use of flibe as heat storage medium need not be optimum either. If flibe were to be used for tritium production only and a medium not containing Li were used for heat storage, the inventory required would be reduced by a factor of 0.274 to 71 $kg_{Li\ nat}/MW_{th}$ and 36 kg_{Be}/MW_{th}.

2.2.3 Solid lithium compounds as breeding material

An example of this concept is the UWMAK II [6] design, in which $LiAlO_2$ is chosen as breeding material, Be as neutron multiplier and helium as coolant. Here the amount of the isotope ^6Li in the lithium is 90 %. In 30 years of service a total of 680 t of this lithium will be required since the quantities of $LiAlO_2$ replaced at certain intervals are not intended to be re-used although the lithium will actually have been only partly consumed. The amount stated corresponds to a natural lithium requirement of 8248 $t_{Li\ nat}$, which for a thermal reactor power of 5000 MW_{th} yields a specific requirement of

$$b_{nat} = 151 \frac{g_{Li\ nat}}{MW_{th}d} .$$

The amount of beryllium required for 30 years is given as 985 t, and so the specific requirement is

$$b_{Be} = 18 \frac{g_{Be}}{MW_{th}d} .$$

As the quantities of $LiAlO_2$ and Be removed from the modules are not intended to be replaced for cost reasons only, the consumption figures stated do not represent the real consumption and are thus not comparable with the values given in the previous sections. To obtain comparable values, that consumption is estimated which would be obtained if the amounts of fuel removed were to be replaced in so far as the concept allows.

As the lithium used contains 90 % ^6Li, the tritium production, and hence the energy release, in this concept is governed to such an extent by the amount of ^6Li that the amount of ^7Li can be neglected in determining the specific fuel requirement. According to [6] the energy yield is 21.59 MeV per ^6Li atom or

$$e_{th} = 21.59 \frac{\text{MeV}}{\text{atom}} \cdot 1.602 \cdot 10^{-16} \frac{\text{kJ}}{\text{MeV}} \cdot 6.023 \cdot 10^{23} \frac{\text{atoms}}{\text{mol}} \cdot$$

$$\cdot \frac{\text{mol}}{6.015\ \text{g}\ {}^{6}\text{Li}} \cdot \frac{\text{MW}}{\text{kJ}\ 10^{3}} \frac{\text{d}}{3600 \cdot 24}$$

$$e_{th} = 4 \frac{\text{MW}_{th}\text{d}}{\text{g}\ {}^{6}\text{Li}} \ .$$

This is equivalent to a specific consumption of natural lithium of

$$b_{nat} = 3.37 \frac{\text{g}_{\text{Li nat}}}{\text{MW}_{th}\text{d}} \ .$$

The actual consumption of beryllium is given in [6] as 10.9 t for 30 years; one thus has

$$b_{Be} = 0.2 \frac{\text{g}_{Be}}{\text{MW}_{th}\text{d}} \ .$$

The size of the fuel inventory is also taken from [6]; it is 50 t of lithium enriched to 90 % ^{6}Li and 300 t of natural lithium for the divertor. For a thermal power of 5000 MW_{th} this yields a specific value of

$$i_{nat} = 180 \frac{\text{kg}_{\text{Li nat}}}{\text{MW}_{th}}$$

for the natural lithium requirement. The design [6] requires that about 2/3 of this quantity should be available every two years for replacement of the fuel modules. The beryllium inventory is 433 t, i.e.

$$i_{Be} = 87 \frac{\text{kg}_{Be}}{\text{MW}_{th}} \ .$$

About 9 % of this quantity is required every two years for replacement.

2.2.4 List of consumption and inventory values

The values discussed in the last three sections are listed in Table 2. It is found that in the most favourable case the specific consumption of natural lithium is a factor of about 3 above the theoretical minimum, and in the most unfavourable case about an order of magnitude above. As none of today's concepts seems to afford any particular advantage, there are two alternative values on which to base later determination of the energy equivalent of lithium reserves: 0.95 $g_{Li\ nat}/MW_{th}d$ as the lowest value actually attainable according to present-day views and 3.37 $g_{Li\ nat}/MW_{th}d$ as the maximum value.

3. Fuel reserves and costs

In determining the mineral resources available in the earth there is a great deal of uncertainty about what quantities could be recovered at what costs. The degree of uncertainty is the greater the smaller the scale of previous prospecting, i.e. the smaller demand has been. It has therefore long been customary to classify information on resources of raw materials according to various geological categories graded according to the reliability of the data available on the quantities concerned. Increasing recognition of the crucial role of raw materials in recent years has prompted efforts to make the classification schemes used in the different industrial countries comparable and uniform [8, 9] in order to provide an overall picture of world resources. The best prospects of being used world-wide are afforded at present by the scheme proposed in 1972 by McKelvey [10] and adopted already in 1974 by the World Energy Conference in its documentation of world energy resources [11].

This scheme, the McKelvey diagram as it is called, is shown in Fig. 5. In the horizontal direction the reliability of the data decreases from left to right, while in the vertical direction the recovery costs increase from top to bottom. In addition to the terminology originally used by McKelvey [10], this chart also includes that previously in standard use at U.S. Geological Survey [9, 11] and that customary in Germany [8] because both German and American data are enlisted later in considering lithium resources. The assignment of the various terms was done according to [8].

3.1 Lithium

At present lithium can only be extracted from the earth, either from pegmatite rocks or from the brine of salt lakes. It could also be extracted from geothermal and mineral springs as well as from the water pumped from oil fields. It could also be derived from sea water. As the reserves definitely known at present exceed the annual world requirement of 6400 t (1972) by more than two orders of magnitude, only the most favourable deposits, from the economic point of view, are now being exploited and no systematic prospecting is being done. Interest in lithium has, however, increased in view of possible applications in energy technology (in addition to fusion power plants, lithium sulphur batteries) and recently led in the U.S. to an appraisal of the lithium supply situation [12].

The most comprehensive collections of data on world resources of lithium in the earth were made in 1973. The data provided by Bundesanstalt für Geowissenschaften und Rohstoffe [13] and those taken from [14] are presented in Fig. 6 according to the respective classifications in Fig. 5. In [13] the proved and probable reserves ("sicher" and "wahrscheinlich") are put at 1.4×10^6 t, the possible ("möglich") reserves at 5.2 x 10^6 t, and the predicted ("prognostisch") resources at 4.3 x 10^6 t, while in [14] the proved and probable reserves are put at 1.2 x 10^6 t, the possible reserves and conditional resources (i.e. including what exceeds the range of "economically recoverable") at 3.3 x 10^6 t, and the hypothetical resources at 6.5 x 10^6 t. While the data from the two sources on the proved and probable reserves almost agree, the other figures show more pronounced differences, this being due to the poorer reliability of the data in these cases. Noteworthy, however, is the fact that the respective sums of the quantities stated are almost equal: 1.09 x 10^7 t [13] and 1.1 x 10^7 t [14]. This is exactly the order of magnitude, from 0.9 x 10^7 to "a few" times 10^7 t, that is given in [15, 16] and [17].

Estimates are also available for the total recoverable resources of lithium (including speculative resources) and up to high recovery costs. It is assumed in [14] in this connection that the geographical distribution of lithium is probably just as uniform as in the U.S. Since the U.S. covers about 1/16 of the earth's land surface, total world resources are deduced from those of the U.S. to be 1.2 x 10^8t. The U.S. resources taken as a basis have been confirmed in a recent publication [18]. Metallgesellschaft AG, Frankfurt, also estimates total recoverable lithium resources at 1.5 x 10^8 t [19], while USAEC gives a figure of 1.1 x 10^8 t [20], as also does [21].

The present world market price for (99,9 % pure) lithium is about 62 DM/kg_{Li} [22].

These figures adequately document lithium reserves and resources. As no marked increase in lithium requirements in the near future is anticipated either, there is still little incentive for extensive prospecting. As [12] shows, however, further thought is being given to recovering lithium from geothermal and mineral springs [23, 24, 25] and from the water pumped from oil fields [26]. In addition, an extensive study on lithium extraction from sea water is reported in [27].

The mean lithium content of sea water is variously put at 0.1 ppm (the range being between 0.07 and 0.17 ppm) [28], at 0.17 ppm [29], and 0.192 ppm [30]. The lithium content of the world's oceans is thus (1.37 - 2.63) x 10^{11} t. With conditions in the lithium market as they are now, it is not an economic proposition to exploit these reserves although no special technological problems are anticipated because the experience gained in recovering lithium from salt lakes can be enlisted for the purpose. The present economy limit for producing lithium from salt lake water is a lithium concentration of 60 - 70 ppm [13, 19]. Li producers give no cost figures for extracting lithium from sea water [19, 31, 32] because the large resources relative to demand do not warrant such considerations. An estimate [31] nevertheless shows that in water desalination plants it would be quite possible to extract from the residue water not only potassium and magnesium (which is already planned) but also about 80 % of the lithium also contained. One may thus consider 80 % of the total lithium present in sea water to be technically recoverable, i.e. (1.1 - 2.1) x 10^{11} t. As little as 1 % of this quantity exceeds the maximum estimates for the quantities of lithium in the earth. The above-mentioned first detailed investigation of methods of extracting lithium from sea water [27] shows that the costs for recovering lithium in this way will probably not be much above present-day lithium costs.

3.2 Deuterium

Deuterium is at present obtained mainly from natural water via heavy water (D_2O) although, in principle, it could be extracted, but presumably at greater expense, from the earth, in which hydrogen is present with a mean abundance of 1400 ppm [33]. The deuterium content of 0.01492 % in natural hydrogen corresponds to a deuterium concentration in hydrogen of 33.36×10^{-4} % by wt. This means that the total volume of the world's oceans of 1.37×10^{9} km^3 [15] contains a total mass of about 4.6×10^{13} t deuterium.

The price for heavy water was fixed at 121 \$/kg in April 1974 by USAEC [34], while Atomic Energy of Canada Ltd. (AECL) was selling it at 75 \$/kg in June 1974 [35]. If these costs are referred to only the deuterium content in heavy water, one obtains 930 - 1500 DM/kg_D +). The costs for splitting D_2O and for sufficient purification of the deuterium are relatively low by comparison. One can take as a guideline the price of 2.6 DM/kg_{H2} now quoted for electrolytically obtained hydrogen [36]. One can thus take 930 - 1500 DM/kg_D as the price for deuterium suitable for direct use in the fusion reactor.

3.3 Beryllium

Knowledge of beryllium reserves is extremely scant (see also [6]). At present it is a by-product of lithium extraction from pegmatite rock. Lack of demand so far has made intensive prospecting unnecessary. Its mean abundance in the earth of 6 ppm is a factor of 10.8 lower than that of lithium, yet still 50 % higher than that of uranium [33]. The present price of beryllium is about 80 DM/kg [37]. ++)

+) 1 \$ ≙ 2.50 DM; 1 DM ≙ 0,4 \$

++) New information on beryllium price increases is highly inconsistent. The impact of these changes can be assessed from Tables 3 and 4 .

4. Amounts and costs of the total releasable energy

4.1 Amounts of releasable energy

As more lithium than deuterium is required and, furthermore, the amounts of lithium available are smaller than those of deuterium, the lithium governs the total amount of energy releasable. It is not possible to state anything definite about limitations of the amount of energy on the basis of concepts using beryllium, as the preceding section has shown. The fact, however, that the specific beryllium consumption in both concepts considered (Table 2) is less than 1/11 of the respective specific lithium consumption, but that the mean abundance of beryllium is about 1/11 of that of lithium allows the conclusion that in these concepts, too, the amount of lithium is decisive for the total amount of energy releasable. This conclusion will, however, have to be checked when more detailed information on beryllium resources is available.

The Li reserves in the earth totalling 1.1×10^7 t correspond to a total energy of 267 - 948 Q [+)], of which 35 - 123 Q (≙ 13 %) is proved and probable, 128 - 455 Q (≙ 48 %) possible, and 104 - 270 Q (≙ 39 %) predicted ("prognostisch" according to [13]). The maximum value of the estimated amounts of recoverable lithium of 1.5×10^8 t [19] corresponds to a total energy of $(0.36 - 1.3) \times 10^4$ Q. These values together with the energies from [14] are presented in Fig. 7, which is also arranged according to the scheme in Fig. 5. This reveals the correlation between the energies and the classification of the respective quantities of lithium.

[+)] 1 Q ≙ 1.055×10^{18} kJ

The use of these figures for comparison with the amounts of energy that can be released in fission of uranium is, however, not realistic since systematic prospecting for uranium has been in progress for many years, but not for lithium. If it is assumed that the amounts of recoverable lithium and recoverable uranium are in the same ratio as the mean abundances of these substances in the earth (uranium 4 ppm, lithium 65 ppm), and if it is also taken into account that the specific energy release from uranium in the most favourable case (the fast breeder reactor) is about 0.8 $MW_{th}d/g_U$[+)] and from lithium between 0.3 and 1.05 $MW_{th}d/g_{Li\ nat}$, the total energy released in fusion is a factor of 6 - 20 greater than in fission. If such an estimate is based on the recovery of fuels from sea water (U content 0.00334 ppm, Li content 0.1 - 0.192 ppm), this factor attains values of 11 and 76 respectively.

The quantity already stated for lithium derived from sea water, $(1.1 - 2.1) \times 10^{11}$ t, corresponds to an energy of $(2.7 - 5.1) \times 10^6$ (concept 3) or $(0.95 - 1.8) \times 10^7$ Q (concept 1). Only 10 % of the minimum value or 6,6 % of the maximum value would be sufficient to cover ten times the present world energy requirements of approximately 0.23 Q for about 10^5 years. The energy reserves of fusion may therefore be regarded as unlimited.

4.2 Specific fuel costs

The fact that there is a practically unlimited quantity of fuels on earth for fusion reactors is not sufficient alone

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[+)] Corresponding to 90 % of the 190 MeV released per fission.

to characterise the reserve situation. One also requires additional information on the costs for fuels now and in the future. The present costs for lithium have already been quoted as 62 DM/kg_{Li} and for deuterium as 930 - 1500 DM/kg_D. As deuterium consumption is about 0.07 $g_D/MW_{th}d$ ([4, 6]), the specific price for the fuel for concept 1 (Table 2) is 122 - 161 DM/kg_{fuel} (specific consumption 1.02 $g_{fuel}/MW_{th}d$), while for concept 3 one obtains values of 80 - 91 DM/kg_{fuel} (specific consumption 3.64 $g_{fuel}/MW_{th}d$). This yields heat prices of 12.4 - 16.4 Pf/$MW_{th}d$ +) (concept 1) and 29 - 33 Pf/$MW_{th}d$ (concept 3).

If a net efficiency of η_{net} = 38 % is taken as a basis for converting heat into electric energy, one obtains for the fuel costs in relation to the electric energy extreme values of 1.4 - 3.6 x 10^{-3} Pf/kW_eh.

In predicting the future cost development for lithium and deuterium, only real costs (i.e. without inflation) being considered, it is important that both fuels be recoverable, even in large quantities, with present-day technology. At present prices 35 - 123 Q of lithium is available and according to [14] it is likely that with more intensive prospecting a substantial share of possible and predicted ("prognostisch") reserves can be transferred to this category. Deuterium production can be based on a constant deuterium component in water. According to [27], the derivation of lithium from sea water will presumably entail costs exceeding the present level by only a small amount. As the lithium concentration in sea water remains nearly constant for a long time, the real extraction costs may be regarded as constant.

+) 1 Pf = 4 mills; 100 Pf = 1 DM = 0,4 $

5. Theoretical maximum installable powers and costs of fuel inventory

5.1 Installable powers

In keeping with what was said at the beginning of Sec. 4.1 lithium is also regarded here as the limiting substance. The lithium resources stated in Fig. 6 are converted into thermal powers with the maximum and minimum values for the specific inventory of lithium, 340 and 180 kg/MW_{th} (Table 2). These power values represent the thermal reactor powers that could be installed with the quantity of lithium involved; they are thus theoretical maximum values of the installable power since the lithium consumption is not taken into account.

The total lithium reserves in the earth, 1.1×10^7 t, represent installable powers of 32 - 61 TW_{th}. Of this 4.1 to 7.8 MW_{th} (≙ 13 %) is based on proved and probable ("sicher") and "wahrscheinlich") resources, 15.3 - 28.9 TW_{th} (≙ 48 %) on possible ("möglich") resources, and 12.7 - 23.9 TW_{th} (≙ 39 %) on predicted ("prognostisch") resources (quantities of lithium according to [13]). For the maximum value of the estimated quantity of lithium recoverable, 1.5×10^8 t [19], one obtains 441 to 833 TW_{th}. These values are plotted in Fig. 8 together with the values resulting from the lithium quantities in [14](Fig. 6). This figure also gives the installable powers of 0.32 - 1.2×10^6 TW_{th} relating to the lithium resources in sea water.

These data can be assessed by comparing them with the total power plant capacity now installed on earth: according to [38] about 25 % of the world's primary energy consumption is converted into electric energy, i.e. about 0.06 Q/a. Taking 4,400 hours of full-load operation per annum as a basis, this is equivalent to an installed (thermal) power plant capacity of about 3.8 TW_{th}. If this figure is compared with the above values for the maximum installable powers on the basis of lithium, no limitation at all is to be expected, not even if the (thermal) power plant capacity to be installed were to increase to ten times today's value.

5.2 Specific costs of the fuel inventory

These costs, listed in Table 4, are governed by the inventory of lithium and, where present, of beryllium since the deuterium inventory can be neglected (e.g. approx. 3 - 5 kg/MW_{th} [4]). A lithium price of 62 DM/kg_{Li} yields for concept 1 specific lithium (= fuel) inventory costs of 55 DM/kW_e if the net efficiency of the power plant is again put at 38 %. In concept 2 the costs of the lithium inventory are 42 DM/kW_e, those of the beryllium inventory 27 DM/kW_e (with 80 DM/kg_{Be}), i.e. together 69 DM/kW_e. Concept 3 involves 29 DM/kW_e for lithium, 18 DM/kW_e for beryllium, i.e. a total of 47 DM/kW_e. In relation to the installation costs (cash value, without additional costs during construction) of, for example, the UWMAK-I power plant, 2,067 DM/kW_e [3], the lithium inventory represents a percentage of between 1.4 and 2.7 %, the beryllium inventory between 0 and 1.3 %, and the total fuel inventory between 2.2 and 3.3 %.

These values yield the specific contributions of the fuel inventory to the power costs (Table 3, column II), based on an annuity of 13.15 % (rate of interest 10 %, depreciation in 15 years), an extra 35 % for additional costs during construction and 75 % load factor of the power plant. The specific power costs due to the lithium inventory are 0.08 - 0.15 Pf/kW_eh [+)], those due to the beryllium inventory 0 - 0.07 Pf/kW_eh, the total values being between 0.13 and 0.18 Pf/kW_eh. According to the resource situation described in Sec. 3 major increases in costs are not expected.

[+)] 1 Pf = 0,01 DM; 1 DM ≙ 0,4 $, 1 Pf ≙ 4 mills

6. Reliability of fuel supply

Lithium reserves in the earth are widely scattered. Besides presenting the production data for 1972, Fig. 9 shows the geographical distribution of deposits at present known according to [13]. With reliability of supply in mind, it is also important to note that there are many mineral springs on earth which have a considerable lithium content. This aspect is exhaustively covered in [28]. Even though the extraction of this lithium is not an economic proposition at present, the contents of, for example, 62 ppm max. (in Northern Italy) and 22 ppm (in the Federal Republic of Germany) are not so very much lower than those of the salt lakes now being exploited in the U.S. In view of the low specific fuel costs such reserves may also be regarded as a contribution to ensuring supplies. The technologies for recovering lithium from rocks and salt lakes are conventional tools of mining and process engineering and are thus available to practically all countries. This also applies to the technology required for extracting lithium from sea water, which will not differ essentially from that for deriving lithium from salt lakes. The technology for deuterium extraction is less simple but nevertheless transferable, as the example of a D production plant built in Argentina shows. Both fuels are thus available from the earth and from the oceans, as regards quantity and technology, and so neither world-wide nor local shortages with all their implications for the market situation are to be expected.

The handling and storing of these substances are standard techniques. The stockpiling of reserves in individual countries, by supply companies and in individual power plants, can be achieved with little outlay. According to the data already stated, the fuel consumption per 1000 MW_e of net electric power for a fusion power plant utilized 80 % in a lifetime of 30 years is, in the minimum case given for concept 1 (Table 2), 22 t of natural lithium and 1.6 t of deuterium, making a total value of 2.9×10^6 DM, and, in the maximum case for concept 3, 78 t of natural lithium, 1.6 t of deuterium and 4.6 t of beryllium with a total value of 7.7×10^6 DM.

The fact that a fusion power plant will have only a reactor-internal fuel cycle also helps to ensure supply. The fuel supply cannot be impaired by external influences to which, for example, the entire fuel cycle for fission reactors is exposed.

7. Summary

The total quantities of energy releasable in fusion reactors based on the D-T reaction are governed by the specific fuel requirements, i.e. in relation to the unit of energy, and the amounts of fuel available. Lithium was found to be the fuel mainly responsible for the total amount of energy releasable.

Depending on the concepts adopted for deriving tritium from lithium, the specific fuel requirements are between 0.95 and 3.37 $g_{Li\ nat}/MW_{th}d$.

The lithium resources in the earth (Fig. 6) are classified according to the reliability of the quantities stated and the size of the recovery costs. Proved and probable reserves (now economically recoverable) were found to be 1.2 - 1.4 x 10^6 t, possible reserves or resources, the costs of recovering which exceed today's, to be 3.3 - 5.2 x 10^6 t, and predicted ("prognostische") resources to be 4.3 - 6.5 x 10^6 t, making a total of 1.1 x 10^7 t of natural lithium. If speculative resources and even higher recovery costs are included in the estimate, the total resources come to 1.2 - 1.5 x 10^8 t. One can regard 1.1 - 2.1 x 10^{11} t as being recoverable from sea water, the costs possibly being not so very much above today's recovery costs owing to the conventional extraction technique.

The energy resources (Fig. 7) corresponding to these lithium resources are in the ranges 30 - 123 Q (proved and probable reserves) and 104 - 408 Q (predicted ("prognostisch") resources), making a total of 267 - 948 Q. The total energy resources in the earth are 0.29 - 1.3 x 10^4 Q. The lithium resources in sea water correspond to an energy of 1 - 2 x 10^7 Q. The world's present annual primary energy consumption is about 0.23 Q.

The corresponding maximum powers that might be installed are 3.5 - 7.8 TW_{th} (proved and probable reserves), 9.7 - 28.9 TW_{th} (possible reserves and more expensive resources), and 12.7 - 36.1 TW_{th} (predicted resources). With the total amount of lithium in the earth 353 - 833 TW_{th} could be installed, and with the lithium from sea water 0.32 - 1.2 x 10^6 TW_{th}. The world's total amount of installed power plant capacity is 3.8 TW_{th} (in 1975).

On the basis of today's fuel costs the heat price is 12.4 - 33.0 Pf/MW_{th}d +), which for a conversion efficiency of 38 % yields specific fuel costs of 1.4 - 3.6 x 10^{-3} Pf/kW_eh. The lithium inventory makes a contribution of 29 - 55 DM/kW_e to the specific installation costs; this corresponds to a contribution of 0.08 - 0.15 Pf/kW_eh to the power production costs. If it is taken into account that beryllium is used in some concepts, the total specific costs for the fuel inventory are 47 - 69 DM/kW_e and the corresponding contribution to the power production costs is 0.13 - 0.18 Pf/kW_eh.

A high element of reliability in fuel supply is afforded by the fact that the lithium reserves and resources in the earth are widely scattered, the technology of recovering lithium from rocks and salt lakes is conventional, and the costs will probably also be small when lithium is extracted from sea water. Neither world-wide nor local shortages are anticipated. For an investment of 2.9 - 7.7 x 10^6 DM per 1000 MW_e a fusion power plant can be provided with fuels for 30 years; this makes it independent with respect to its entire fuel supply because it has only a reactor-internal fuel system.

+) 1 DM ≙ 0,4 $; 1 Pf = 0,01 DM = 1 mills

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Table 1 Reaction equations

$$D + D \longrightarrow T\ (1{,}01\ \mathrm{MeV}) + p\ (3{,}03\ \mathrm{MeV}) \quad (1)$$

$$D + D \longrightarrow {}^{3}He\ (0{,}82\ \mathrm{MeV}) + n\ (2{,}45\ \mathrm{MeV}) \quad (2)$$

$$D + {}^{3}He \longrightarrow {}^{4}He\ (3{,}67\ \mathrm{MeV}) + p\ (14{,}67\ \mathrm{MeV}) \quad (3)$$

$$D + T \longrightarrow {}^{4}He\ (3{,}52\ \mathrm{MeV}) + n\ (14{,}06\ \mathrm{MeV}). \quad (4)$$

$${}^{6}Li + n \longrightarrow {}^{4}He + T + 4{,}78\ \mathrm{MeV} \quad (5)$$

$${}^{7}Li + n \longrightarrow {}^{4}He + T + n' - 2{,}47\ \mathrm{MeV}. \quad (6)$$

$1\ \mathrm{MeV} \mathrel{\hat{=}} 1{,}602\ 10^{-13}\mathrm{J}.$

Table 2 Specific data for fuel consumption and inventory

Concept	spec. consumption [g/MW_{th}d]		spec. requirement for first inventory [kg/MW_{th}]	
	Li_{nat}	Be	Li_{nat}	Be
1. Liquid lithium as breeding material and coolant (acc. to [3])	0.3 (theor.) 0.95	—	340	—
2. Flibe as breeding material (acc. to [4])	2.55	0.066	258	130
3. Solid Li compounds as breeding material (acc. to [6])	3.37	0.2	180	87

Table 3 Contribution of fuel consumption and inventory to the specific power production costs

Concept	I. Spec. power production costs for consumption [Pf/kW_eh]	II. Spec. power production costs for inventory [Pf/kW_eh] +)		
		Li_{nat}	Be	Total
1. Liquid lithium as breeding material and coolant (acc. to [3])	(1.4 - 1.8) · 10^{-3}	0.15	0	0.15
2. Flibe as breeding material (acc. to [4])	(2.5 - 2.9) · 10^{-3}	0.11	0.07	0.18
3. Solid Li compounds as breeding material (acc. to [6])	(3.2 - 3.6) · 10^{-3}	0.08	0.05	0.13

+) 1 Pf ≙ 4 mills

Table 4 Contribution of fuel inventory to specific installation costs

Concept	Spec.costs of inventory [DM/kW_e] ++)			Contribution to power plant installation costs [%] +)		
	Li_{nat}	Be	Total	Li_{nat}	Be	Total
1. Liquid lithium as breeding material and coolant (acc. to [3])	55	0	55	2.7	0	2.7
2. Flibe as breeding material (acc. to [4])	42	27	69	2.0	1.3	3.3
3. Solid Li compounds as breeding material (acc. to [6])	29	18	47	1.4	0.9	2.3

+) Referece value for UWMAK-I [3]: 2067 DM/kW_e

++) 1 DM = 0,4 $

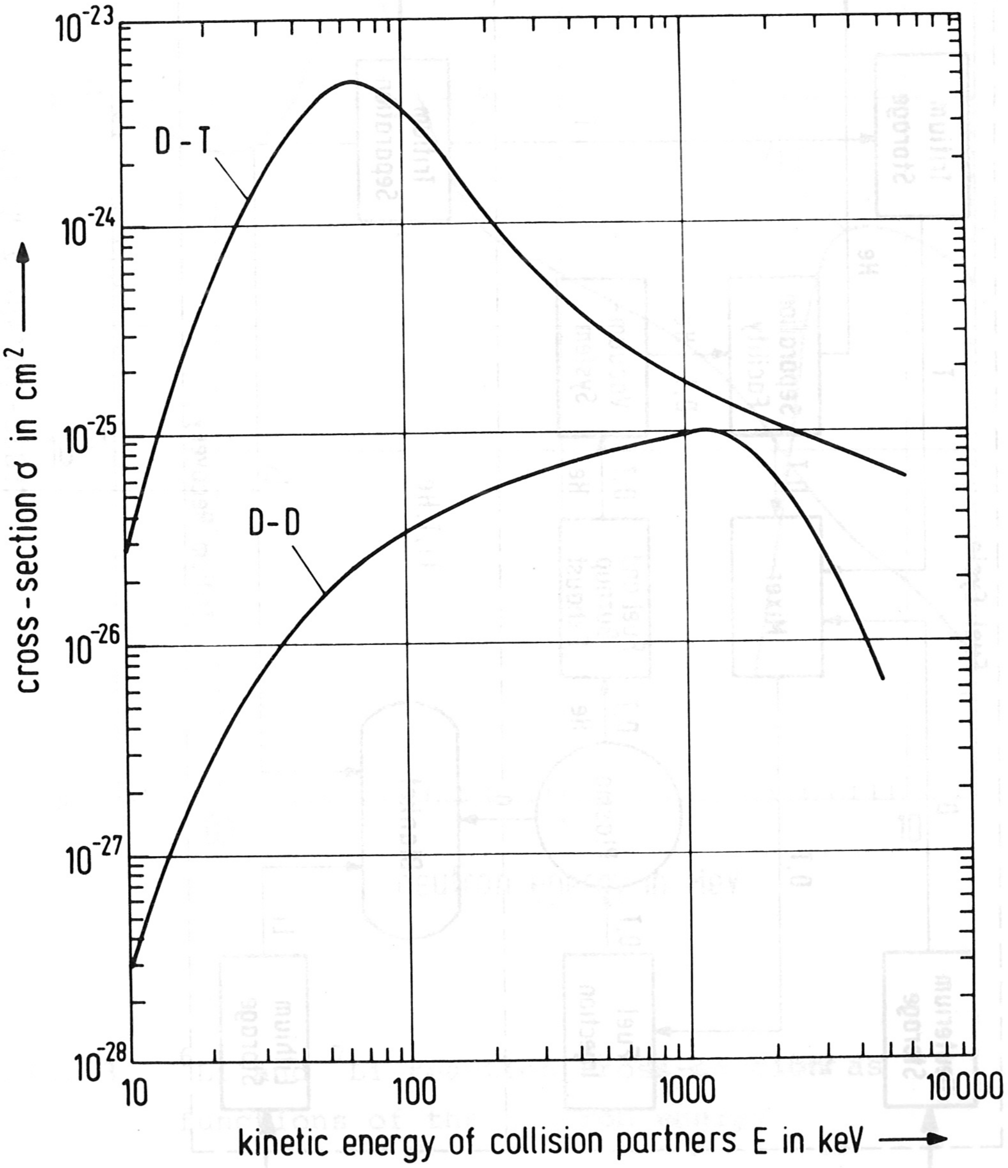


Fig. 1 D-T and D-D reactions cross-sections as functions of the kinetic energy in the centre-of-mass system of the collision partners

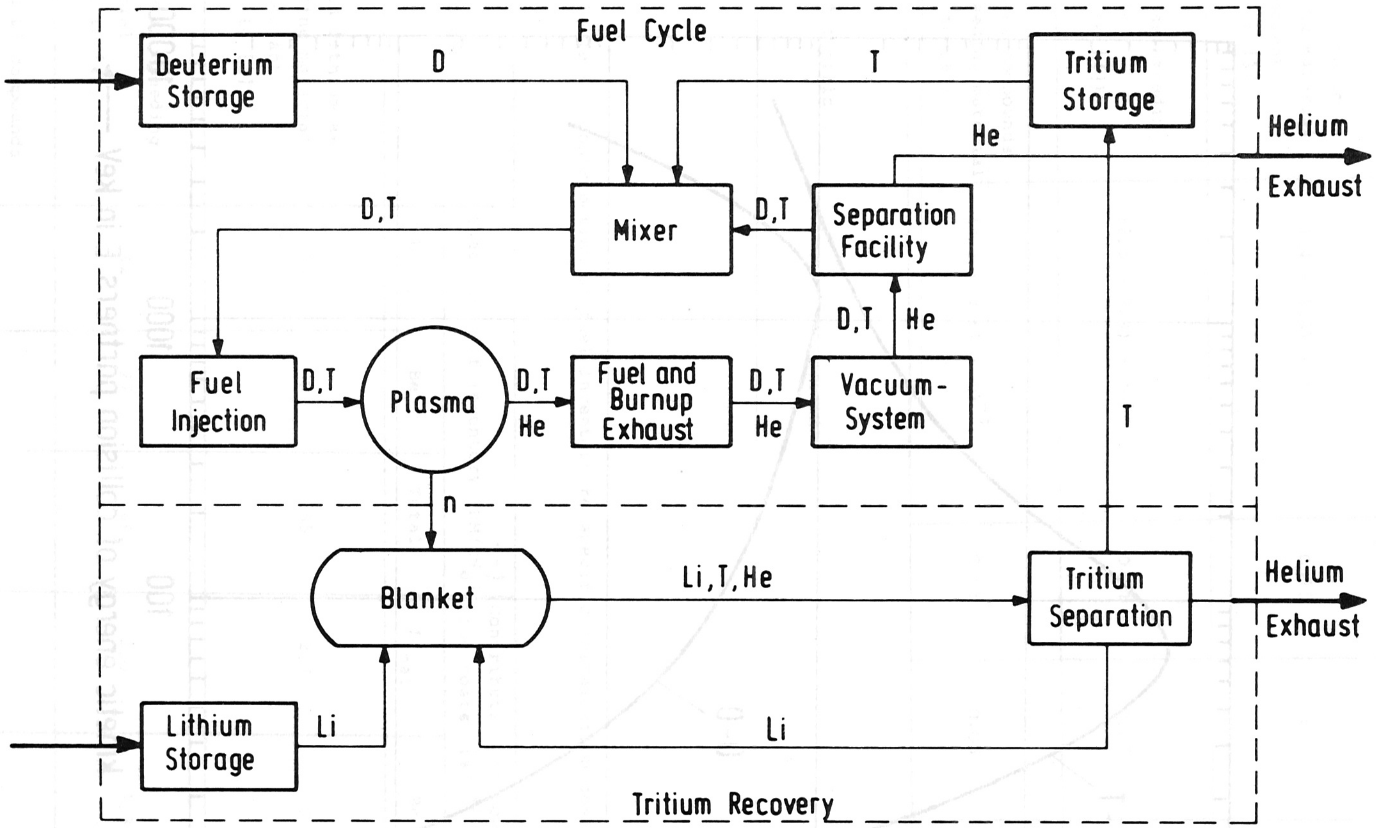


Fig. 2 Fuel flow chart of a D-T fusion reactor

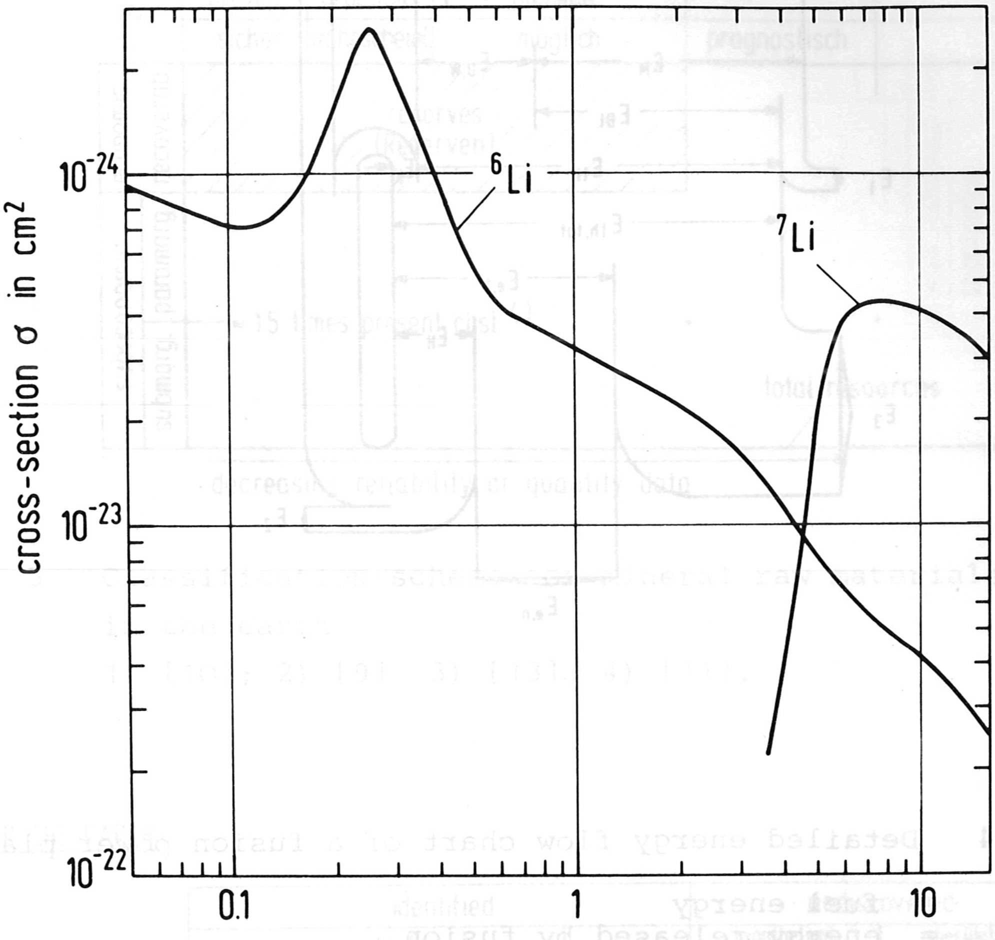


Fig. 3 ^{6}Li and ^{7}Li reaction cross-sections as functions of the neutron energy

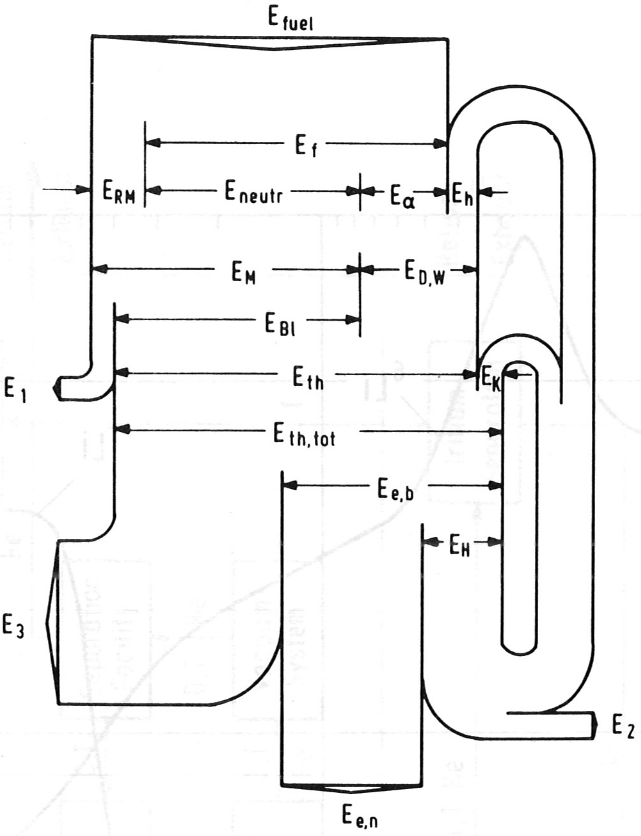


Fig. 4 Detailed energy flow chart of a fusion power plant

E_{fuel} = fuel energy
E_f = energy released by fusion
E_{neutr} = energy of the neutrons
E_α = energy of the α-particles
E_h = energy for heating
E_{RM} = thermal energy from reactions in blanket
E_M = thermal and neutron energies in the blanket
$E_{D,W}$ = energy input to divertor and first wall
E_{Bl} = thermal energy available from the blanket
E_1 = energy loss to shielding and magnets
E_{th} = thermal energy output of the reactor
E_K = thermal energy in the coolant
$E_{th,tot}$ = total thermal energy input to energy conversion process
$E_{e,b}$ = gross electric energy
E_H = energy demand of auxiliary systems
E_2 = energy losses of auxiliary systems
E_3 = waste heat
$E_{e,n}$ = net electric energy

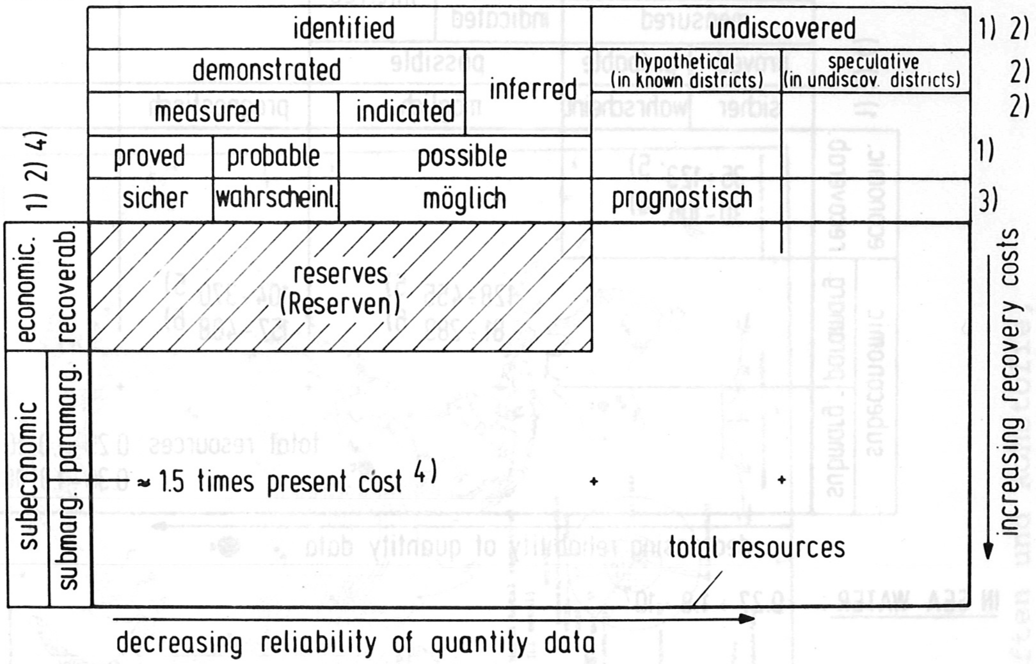


Fig. 5 Classification scheme for mineral raw materials in the earth
1) [10]; 2) [9]; 3) [13]; 4) [11].

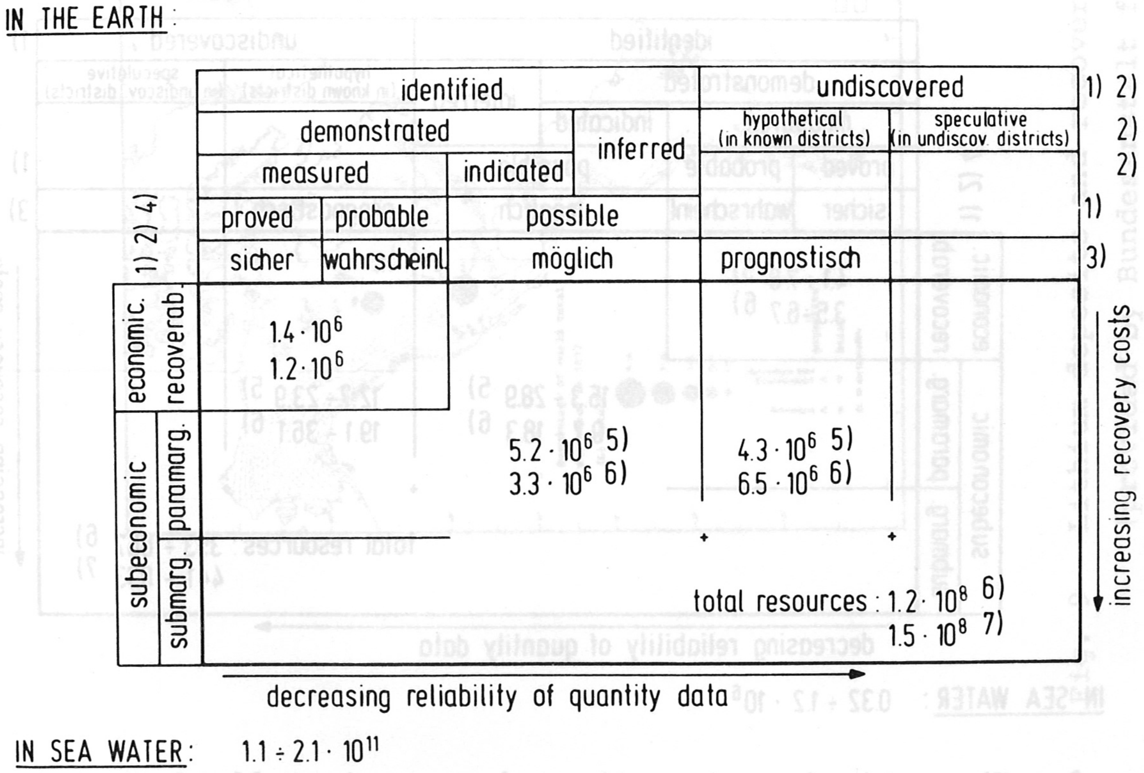
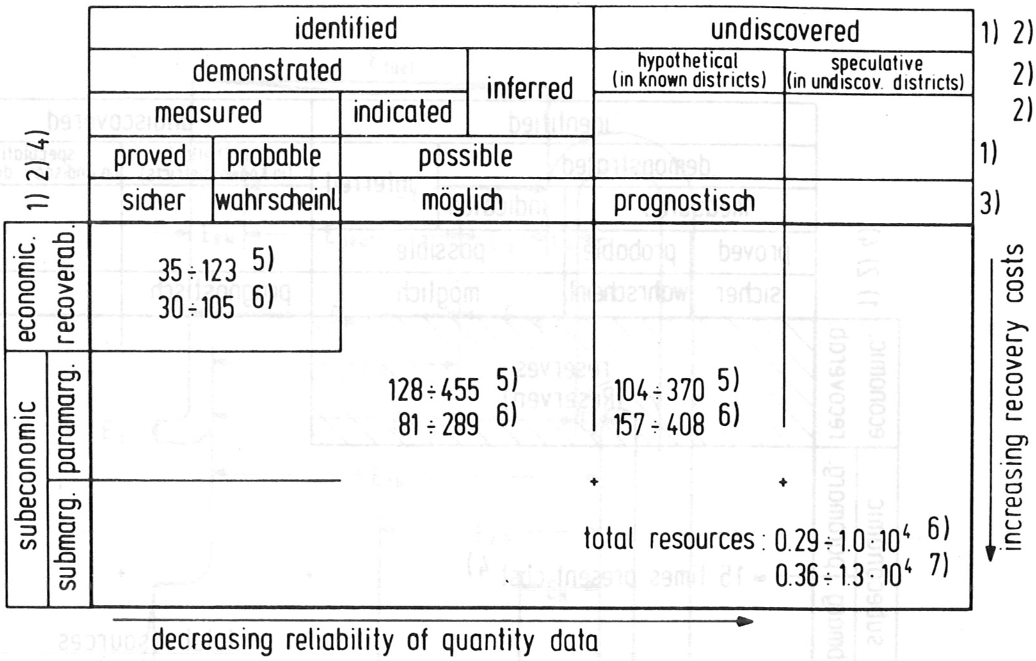


Fig. 6 Lithium reserves and resources (values in t).
For key see Fig. 5.

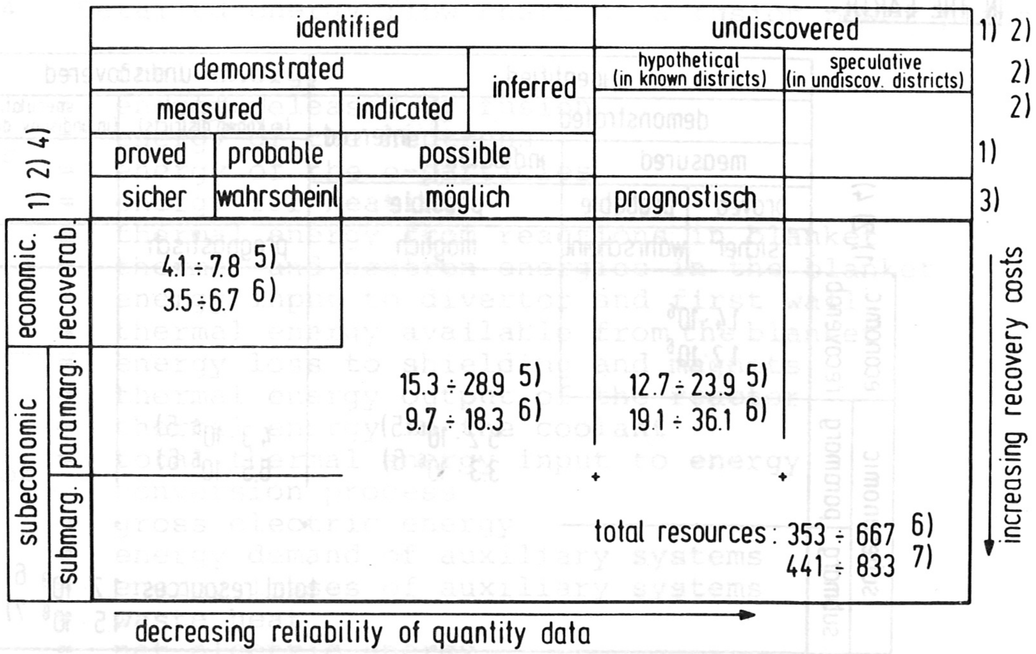
IN THE EARTH:



IN SEA WATER: $0.27 \div 1.8 \cdot 10^7$

Fig. 7 Energy equivalent of lithium reserves and resources (values in Q; 1 Q ≙ 1.055×10^{18} kJ; world energy consumption 1976: ≈ 0.23 Q). For key see Fig. 5.

IN THE EARTH:



IN SEA WATER: $0.32 \div 1.2 \cdot 10^6$

Fig. 8 Theoretical maximum thermal power installable with the lithium reserves and resources. (values in TW_{th}).
5) [13]; 6) [14]; 7) [19]. For key see Fig. 5.

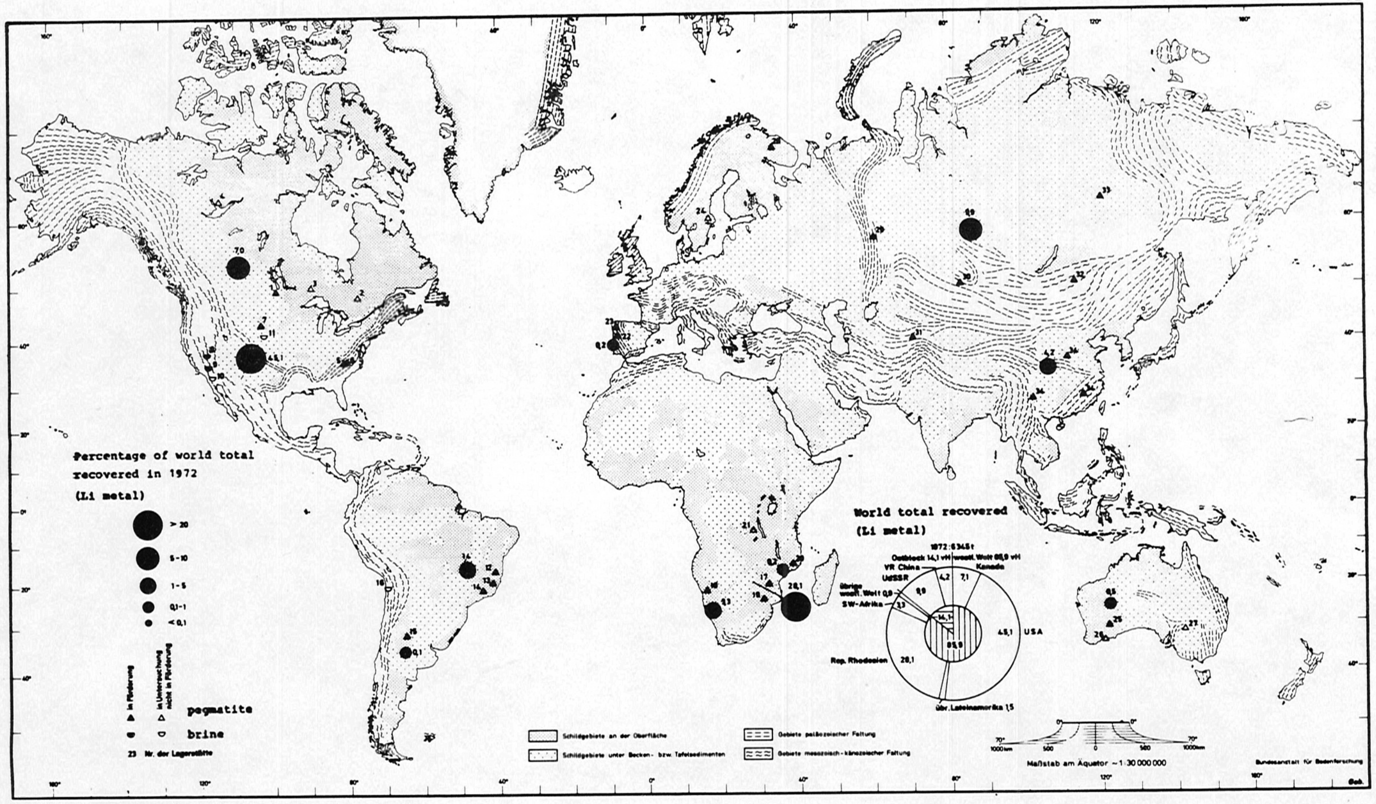


Fig. 9 Lithium deposits and recovery 1972
(provided by Bundesanstalt für Geowissenschaften und Rohstoffe,
formerly Bundesanstalt für Bodenforschung, Hannover, 1973)