SOME THOUGHTS ON THE DESIGN OF A THERMONUCLEAR SPACE POWER SYSTEM*

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INTRODUCTION

Since the dawn of the nuclear era the Air Force has shown interest, both officially (ANP-Project) and unofficially (various publications by its members) in the exploitation of nuclear energy. As I am not the official Air Force historian I shall mention only some of the early events with which I have been intimately involved.

To the best of my memory the earliest nuclear plasma engine configuration considered was after thepublication of Alfvén's book[1]. This book showed the usefulness of magnetic fields as confinement walls for a plasma medium. The plasma was then assumed to be of fission origin as it was discussed in detail by the author[5]. The first electric thrust generators were mentioned in Alexander's book[2].

The first performance analysis of a nuclear (fission) electric space propulsion system was done and reported in 1952[3]. When in 1954 it was found that a thermonuclear plasma is not in thermodynamic equilibrium and the bremsstrahlung losses ($\propto T^{1/2}$ rather than $\propto T^4$) are predominant the first performance analysis of a thermonuclear power plant was made (19[illegible]). It was a crude analysis because it employed low accuracy thermonuclear cross-sections published in the Physical Review between 1951 and 1954. In these calculations only bremsstrahlung losses were considered.

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*The views and opinions expressed by the author do not necessarily represent those of the AFOSR or the USA.

DISCLAIMER

After the publication of more accurate cross-sections these calculations were drastically revised and extended. A more drastic revision and extension followed the first Geneva Atoms for Peace Conference (1953).

In 1956 an electric plasma thrust generator was designed and built by my associate and student (OSU Graduate Center) Dr. Kenneth Kissell. It was subsequently tested successfully. A copper thrust chamber was used as anode and a coaxial tungsten electrode as cathode. The electric power supply was a rotary arc welder. Argon and helium gas were employed as working media.

In 1957 Col. Paul Atkinson started the present AFOSR Electric Propulsion Program. The first project scientist was Milton Slawsky. This program stressed low temperature plasmas, electrostatic thrust generators, colloids and MHD power generators.

In 1962 when Samaras took over the project (9752) a change from low to high temperature plasmas was initiated.

Whereas the AEC work on thermonuclear power was based on microscopic approaches and Plasma Physics, the early Air Force work[5] was mostly based on macroscopic approaches and Plasma Engineering. It is not surprising that little overlapping occurred and the information from both may be considered as complementary.

It should be well understood that a thermonculear space power plant, although based on the same fundamental plasma physics as a stationary terrestrial power plant, is vastly different from a stationary one. There are many fundamental differences between the aforementioned:

a. A space power plant requires extremely high thermodynamic efficiency in order to minimize the weight of the radiator and increase the payload.

b. It demands a direct transformation of thermonuclear into electrical energy.

c. It should have a very wide range of efficient operation, e.g., the ratio of maximum to cruising power may be 10^2 to 10^3.

d. A very advanced and reliable control system is mandatory.

THE APPROACH TO DESIGN STUDIES

The philosophy of early investigations was based on zero order effects and the experience gained from Jet Propulsion in World War II. This approach is based upon a given (rather general) configuration and a thermodynamic cycle. In most cases the configuration does not have to be very detailed although it may be more specific than a system consisting of black boxes.

A typical example of a black box configuration is shown in Fig. 1 taken from Ref. 5, p.453. While this may be suitable for early design investigations a more detailed one is required even for a preliminary design study.

The thermodynamic cycle is shown in Fig. 2. In the most general case, the thermodynamic cycle will represent the following processes:

a. Polytropic compression (energy addition from external sources, e.g., turbulent heating).

b. Energy release caused by the nuclear reaction

c. Polytropic expansion (energy extraction and transformation).

The thermodynamic medium in which the thermodynamic changes occur is usually a plasma flow.

It is well known that the thermodynamic cycle represents mean values of the parameters and one-dimensional flows. Again it is understood that the thermodynamic diagram varies little from steady functioning to cyclic operating machines.

The thermodynamic cycle is plotted in two coordinates: total enthalpy (including both kinetic and electromagnetic) χ and entropy S. Any other suitable coordinates may be used, for example, kinetic temperature, pressure and others; experience with jet propulsion systems, however, suggests that the former are extremely useful for cycle performance analysis.

In Fig.2 line 1-2 indicates a diabatic compression, namely, a compression accompanied by energy (heat) addition. The ignition point lies on this line and is not far away from point 2.

Line 2-3 corresponds to a rapid energy release process which, most of the time, may be considered as isobaric.

Line 3-5 represents adiabatic expansion which under certain conditions may approach an adiabatic one.

Sometimes both the compression and expansion processes of the plasma may approach adiabatic conditions. For comparison, the ideal case of an isentropic variation may be invoked in all cases.

As the cycles under consideration are not markedly different from those of other power-producing devices, similar efficiencies may be defined. On the other hand, the losses occurring in each part of the cycle are different; consequently, they require a detailed analysis and appraisal.

Generally speaking, the losses appear as energy losses and as particle losses. The energy losses are either associated with radiation or with energy carried away by mass. The most important radiation losses are:

- a. Bremsstrahlung
- b. Gyromagnetic radiation
- c. Excitation radiation
- d. Cherenkov radiation.

The energy losses associated with mass are:

- a. Heat conduction and convection
- b. Energy carried by runaway particles
- c. Energy lost by charge exchange collisions.

The loss of mass is caused by:

- a. Diffusion
- b. Runaway particles
- c. Neutral particles which cannot be confined by the magnetic field.

The preceding losses may cause a number of effects on the plasma and the surrounding solid walls. These are contamination of the plasma resulting from thermal evaporation of solid walls and sputtering.

The compression and expansion processes have been discussed in detail before[5], however, a few fundamentals on the direct transformation of nuclear into electrical energy may be given. Before this it is advisable to compare thermonuclear with chemical power plants.

In today's chemical power plants, such as gasoline and diesel engines, gasturbines and rockets, the time of confinement of the reacting medium (time of flame propagation) is about one (1) millisecond. The corresponding temperatures are 0.12 - 0.5 ev (1200-6000° K). In thermonuclear power plants the temperatures are expected to be 10 to 100 kev, i.e., five (5) orders of magnitude higher. From this it may be concluded that plasma confinement times larger than the aforementioned (millisecond) cannot be seriously supported. To explain this contention, in the following the time required for energy release and the time available from diffusion will be calculated.

1. The time of energy release

In 1957 Lawson's rule was announced: the plasma density multiplied by the time of confinement is constant

$$n\tau = \text{constant} \qquad (1)$$

Immediately after (1958) it was shown by Samaras[5] (p.326 and Fig. 4.43) that $n\tau$ is not constant but varies enormously with initial θ_2 and final θ_3 temperatures (substitute time of energy release t_{23} for τ) as follows:

$$nt_{23} = f(\theta_2, \theta_3) \qquad (2)$$

Figures 3 and 4 (taken from Ref. 6) show the energy release time as a function of the initial θ_2 and final θ_3 temperatures for D-T and D-He^3 reactors.

2. The time of confinement

To obtain the time of confinement the plasma diffusion coefficients should be known. This is easily done by non-dimensionalizing the laminar and turbulent diffusion coefficients as a diffusion parameter:

$$\text{laminar} \qquad C_d = \frac{q_e \, BD_\ell}{k_3 T} = (\omega\tau)^{-1} \qquad (3)$$

turbulent $$C_d = \frac{q_e\, BD_t}{k_B T} = K \qquad (4)$$

where:

q_e = charge of the electron

B = magnetic field intensity

D_ℓ, D_t = laminar and turbulent diffusion coefficient, respectively

k_B = Boltzmann's constant

T = temperature

$\omega\tau$ = Hall's parameter

The experimental results of various diffusion experiments are shown in Fig. 5. This picture is similar to that of the friction coefficient in the flow through a circular pipe with walls of various degrees of roughness. The laminar and turbulent regions are obvious and the roughness coefficient has an analog in the type of boundary layer existing between the plasma and the confining magnetic field.

The diffusion coefficient $D_\perp$ may be correlated with a characteristic length L of the power plant and a diffusion time which for convenience may be called as t'_{23} as follows:

$$D_\perp = f \frac{L^2}{t'_{23}} \qquad (5)$$

where:

f = constant

Another important parameter is the kinetic over magnetic pressure ratio.

$$\beta = \frac{2n\, k_B\, \theta}{B^2} \cdot \mu_m \qquad (6)$$

From the foregoing assuming a reference ion density $n_r = 10^{20}\ m^{-3}$ the following results:

$$t'_{23}(n \times 10^{-20}) = 24.65 \left(\frac{f\beta L^2}{C_d}\right) \left(\frac{B_2}{10}\right)^3 \cdot \theta_2^{-2} \qquad (7)$$

The most pessimistic case, namely, of Bohm diffusion is considered ($C_d = 1/16$). For simplicity the following values of the parameters may be assumed: $f = 1$, $\beta = 1$, $L = 1$ meter. Then Eq. (7) may be plotted as broken line in Figs. 3 and 4 for various values of the magnetic field B.

Examination of these figures suggests that for magnetic fields realizable in the future (B = 40 Tesla) and final temperatures $\theta_3 = 100$ kv, the confinement time is larger than the energy release time $t'_{23} \gg t_{23}$.

Taking as an example $\theta_2 = 20$ kv, $\theta_3 = 50$ kv and an ion density $n = 10^{23}$ m^{-3} the required time for energy release is $t_{23} = 1.3$ msec. The corresponding diffusion time for a magnetic field B = 15 Tesla is $t'_{23} = 3.3$ msec.

Assuming a diffusion coefficient one order of magnitude lower than Bohm (see Fig. 5) the corresponding diffusion time is $t'_{23} = 33$ msec.

Increasing the magnetic field to B = 30 Tesla the diffusion time becomes $t'_{23} = 27$ msec and for B = 40 Tesla is $t'_{23} = 64$ msec.

The foregoing magnetic fields are not fictitious. Existing superconductors produce magnetic fields of 20 Tesla, whereas those in the experimental stage (see Dallas Meeting of the APS) are around 40 Tesla. The high magnetic field intensity superconductive magnets will need a force-free design as it was discussed by M. Levine of AFCRL sometime ago. One of the most important components of the system is the radiator which radiates the losses. Preliminary calculations indicate reasonable sizes at temperatures of 1100 to 1200° K. While these temperatures seem excessive for maximum power they are considerably decreased for cruising conditions which may correspond to 10^{-2} to 10^{-3} of the maximum power. Then corresponding temperatures may be calculated

$$\text{Rel } T = 10^{-2/4} \text{ to } 10^{-3/4} = 0.316 - 0.178$$

and for $T_m = 1200^\circ K$, $T_{cr} = 379$ to 213.5° K which are acceptable.

The high temperatures of maximum power will appear in the flight corridor where aerodynamic cooling may have a significant effect. Some early calculations (Fig. 6) indicate the altitude speed characteristics of the spacecrafts with large, medium, and small engines.

DIRECT TRANSFORMATION OF NUCLEAR INTO ELECTRICAL ENERGY

The energy transformation between the plasma and its surroundings may be easily understood by examination of the energy equation.

The mechanism of energy transformation may be examined in various ways, and the methods of approach used depend upon the investigator's viewpoint.

A plasma in a magnetic field behaves as a diamagnetic medium $k_m < 1$; this diamagneticity of course depends upon its conductivity. Each charged particle of the plasma rotates around a magnetic line of force and thus possesses a magnetic momet M_d. The sum of these magnetic moments is the total magnetic moment of the plasma in the magnetic field. It is well known also that an electric current loop possesses a magnetic moment M_d. From the foregoing, the similarity between a plasma in a magnetic field and an electric current is obvious. Taking as an example a cylindrical plasma in a magnetic field, it is seen that the plasma may be represented by a current layer, i, whose magnetic moment per unit length is the same as that of the plasma. With increasing plasma temperature which may be caused by the energy release process, the magnetic moment M_d of the plasma increases and with it the current, i. The rising current induces electromotive forces in the electromagnetic circuits which surround the plasma. This process continues until the maximum temperature of the cycle is attained. Further transformation of plasma mechanical enthalpy may occur by an expansion of the plasma. This may be effected by a reduction of the external magnetic field.

The system of plasma and external magnet coils may also be considered as a transformer. The primary of the transformer is the plasma and the secondary is the magnet coils. This is shown in Fig. 7 both schematically and in a circuit form.

The external magnetic field interacts with the plasma and this interaction is shown as the magnetic pressure upon the plasma caused by the external magnetic field $p_m = B^2/(2\mu_m)$. It is known that an increase of the external magnetic field B compresses the plasma, that is, transfers energy from the external coils to the plasma. Again an expansion of the plasma transfers electric energy to the external coils.

Some typical results of calculations are shown in Figs. 8 and 9.

POWER EQUILIBRIUM, STARTING AND STARTERS

The power equilibrium in a fusion reactor is not markedly different from that of any other heat engine. Thus the power equilibrium equation for a continuous reactor will be similar to that of a gas turbine and the power equilibrium of an impulsive reactor will be similar to a reciprocating engine. It should be stressed, however, that the losses will be different in each case.

For a continuous reactor in a steady state of operation, the power generated by the reaction and the power of the starter (external power introduced into the system) will be equal to the excess power and the losses; In an unsteady state of operation, the energy required for the acceleration or deceleration should also be considered. Then the power equilibrium equation may be written

$$\mathbf{P}_f + \mathbf{P}_{st} = \mathbf{P}_{ex} + \mathbf{P}_{ac} + \sum(\mathbf{P}_L) + \mathbf{P}_{aux} \qquad (8)$$

where $\mathbf{P}_f$ = power produced by the fusion reaction
$\mathbf{P}_{st}$ = power of the starter,
$\mathbf{P}_{ex}$ = excess power,
$\mathbf{P}_{ac}$ = power of acceleration (negative in the case of deceleration),
$\sum(\mathbf{P}_L)$ = sum of the power losses,
$\mathbf{P}_{aux}$ = power required for the auxiliaries.

The power losses may be analyzed into

a. Radiation losses (bremsstrahlung and gyromagnetic)

b. Leakage power losses

c. Joulean losses

d. Heat conduction losses

and other losses peculiar to the system under consideration.

For an impulsive reactor in an unsteady state of operation, the energy balance per cycle may be written

$$\int_0^{t_{cy}} (\mathbf{P}_f + \mathbf{P}_{st})\, dt = \int_0^{t_{cy}} \left[\mathbf{P}_{ex} + \mathbf{P}_{ac} + \sum(\mathbf{P}_L) + \mathbf{P}_{aux}\right] dt \quad \text{(joules)} \qquad (9)$$

where t_{cy} = duration of the cycle in seconds

and the other symbols have their usual meaning.

Depending upon the cycle of operation, a number of simplified assumptions may be made and simple zero order effects may be obtained.

A starting process is necessary to put a nuclear energy release system into operation. This is not a peculiar requirement of nuclear systems because a similar process is also necessary in chemical energy release systems, such as gas turbines and reciprocating internal combustion engines.

In the special case of nuclear energy release systems installed in a spacecraft, there may be two main types of starting: (1) starting at ground level; (b) starting in space. In ground level starting, large power external starters may be available most of the time. In space starting, the low density of the surrounding space helps considerably in creating the desirable vacuum conditions in the system.

Depending upon the type of the system, the power required by the starter is given by Eq. (8) or by Eq. (9).

A large number of starting systems for fusion energy release engines may be proposed; because of the extreme requirement upon power, however, the solid fuel MHD generator seems to have certain merits.

Depending upon the starting system selected and the type of the engine, various methods of starting may be developed.

WATCHING AND CONTROL

Nuclear energy release systems may be divided into two basic types: (a) those which can be analyzed into individual components; (b) those which cannot be analyzed into individual components. The first type may be considered as comparable to a gas turbine system; the second, to a reciprocating engine.

The main advantage of the first type over the second is its capability of being analyzed into individual components which can be investigated and tested separately. Generally speaking, each one of these components performs a discrete function and is represented by a separate line in the thermodynamic cycle. As always, this great advantage of component separation and testing is accompanied by the disadvantage of the necessity of matching the various components during the synthesis stage of the energy release system. This situation may be aggravated by the appearance of narrow operational characteristics of the different components and the incompatibility of different requirements, such as easy starting, low weight, high efficiency, and high reliability.

Past experience with terrestrial jet propulsion engines indicates that some of the greatest operational difficulties may be attributed to unsatisfactory matching of the components.

To perform the matching of the components during the synthesis process, a satisfactory understanding of the component characteristics is necessary. Again, to satisfy the performance requirements, certain rules for changing the performance characteristics are needed.

To a certain degree, existing information may be considered sufficient to allow us to calculate the performance of each of the components at the design point and its vicinity; today, however, there is little knowledge about the theoretical evaluation of the instabilities and performance away from the design point. In this case, experimental data should be provided, if possible.

By using similarity and non-dimensional analysis methods, steady state performance characteristics may be developed. It is anticipated that the characteristics during unsteady operation will be different from those of steady operation.

During the development of the performance characteristics, considerable help and inspiration may be obtained by employing information available from terrestrial jet propulsion engines. Then instead of time, such as cycle time, t_{cy}, its inverse may be used, namely, the number of cycles per unit time which corresponds, to a certain degree, to the rotational speed N.

The equation for the excess power may be written in a functional form

$$P_{ex}/(n_2\theta_3 N) = f_2\{\theta_2/\theta_3,\ \theta_1/\theta_2,\ \theta_0/\theta_2,\ \eta_{cx},\ a\} \qquad (10)$$

Taking into consideration the linearity characteristics (of Fig.4.43 of Ref. 5) the following results

$$P_{ex}/(n_2\theta_3 N) = f_3\{(N/n_2),\ (\theta_1/\theta_2),\ (\theta_0/\theta_2),\ \eta_{cx},\ a\} \qquad (11)$$

Equation (11) represents the non-dimensional excess power of an engine as a function of five parameters. Fortunately, only some of these can be varied independently; thus, the compression-expansion efficiency is a function of the other parameters. As the injection temperature θ_0 is usually fixed and the relative mass addition parameter α can be kept constant, only two parameters may be varied and the performance of the engine may be plotted as

$$P_{ex}/(n_2\theta_3 N) = F[(N/n_2),\ (\theta_1/\theta_2)] \qquad (12)$$

In a similar way, the fuel consumption and the specific fuel consumption may be expressed in terms of the parameters just cited.

When an engine is functioning, the operator must always be able to control it to the desired conditions. Thus a control system should be incorporated with the energy release system.

The control system should be designed for both steady and unsteady (accelerating, decelerating) conditions.

Experience has shown that the energy release system and its controls should not be examined separately but always as a system. The main reason for this requirement is that one of the main functions of the controls is to protect the engine at any marginal operational condition. Experience with nuclear reactors suggests that the protection afforded by automatic control considerably increases the life and reliability of the system.

Control systems may be classified according to the level of intelligence available in the loop. Thus the lowest level of intelligence is held by the open-loop control system. The next is the closed-loop control system. Above this is the adaptive control system.

The next three steps are held by artificial intelligence control systems, namely, automata with various degrees of sophistication which are adept at learning and pattern recognition.

For the sake of convenience human intelligence was also subdivided into three (3) levels. Animal intelligence may be considered as overlapping between artificial and human intelligence.

From the preceding, it is obvious that artificial intelligence automatic controls and protecting devices should be incorporated in all thermonuclear energy release systems. The protecting devices should be incorporated in complete electronic control systems and they should contain electronic temperature limiters, pressure limiters, and others.

The control system may be subdivided into two parts: controls for steady operation and controls for acceleration.

The variables to be controlled may be subdivided into two groups: dependent and independent variables. These are shown in the following table

DEPENDENT AND INDEPENDENT VARIABLES OF A NUCLEAR ENERGY RELEASE SYSTEM

Independent Variables	*Dependent Variables*
Time of the reaction or rps	Power extraction
Plasma density $(n_D + n_T)$	Specific fuel consumption
Fuel mixture ratio $n_T/(n_D + n_T)$	
Temperature	

For a simple system, all four independent variables shown in the table may be varied independently; in many cases, however, it is advisable to reduce the number to one or two. Such a system will employ a single lever and the variation of the other variables will be such as to guarantee optimum power or minimum specific fuel consumption.

The measuring instruments of the controlled quantities are numerous and have been discussed elsewhere[2].

For design of the control system, methods similar to those discussed before[2] may be employed. The equations to be used for these are

a. The energy conservation equation

b. The mass conservation equations.

Depending upon the type of the control system, these equations may be simplified considerably. This is true for the mass conservation equations which may be reduced to a single one.

An increase in engine power is effected by increasing the fuel injection rate beyond and above that required for steady state operation.

Assuming constant reaction time t_{23} or its inverse N, the maximum temperature θ_3 increases. Under difficult cooling conditions, the increased maximum temperature may affect the engine life adversely; consequently, due consideration must be given to limiting the maximum temperature θ_3 below a certain level during the acceleration. At the same time, the rate of acceleration must be fast enough to give satisfactory system operation. This may be accomplished by limiting the top temperature to a reasonable maximum and making the period of acceleration short enough to satisfy the engine operation requirements.

The automatic acceleration control which satisfies the conditions just mentioned should be an integral part of the automatic fuel injection system.

AUXILIARIES

The energy release system requires extra power to drive a large number of components collectively called auxiliaries. The auxiliaries may be subdivided into two main groups:

a. Those directly connected with the operation of the engine, such as fuel pumps, vacuum pumps, and others.

b. Those which may be required in the immediate environment of the engine.

The various installations in a spacecraft are serviced by auxiliaries:

a. Electric requirements, such as generators, transformers, control panels, lighting, radar, and others.

b. Navigation equipment

c. Heating and airconditioning.

Various methods of extracting power from the engine may be devised. These may fall within either of the following categories; direct extraction and utilization and indirect extraction.

The direct methods utilize the electric energy in the form produced by the engine, whereas the indirect use transformers and other intermediate equipment.

In conclusion it is felt that the time is ripe to train the designers who will be able to initiate design studies leading to the final design for the development of a successful prototype thermonuclear power plant.

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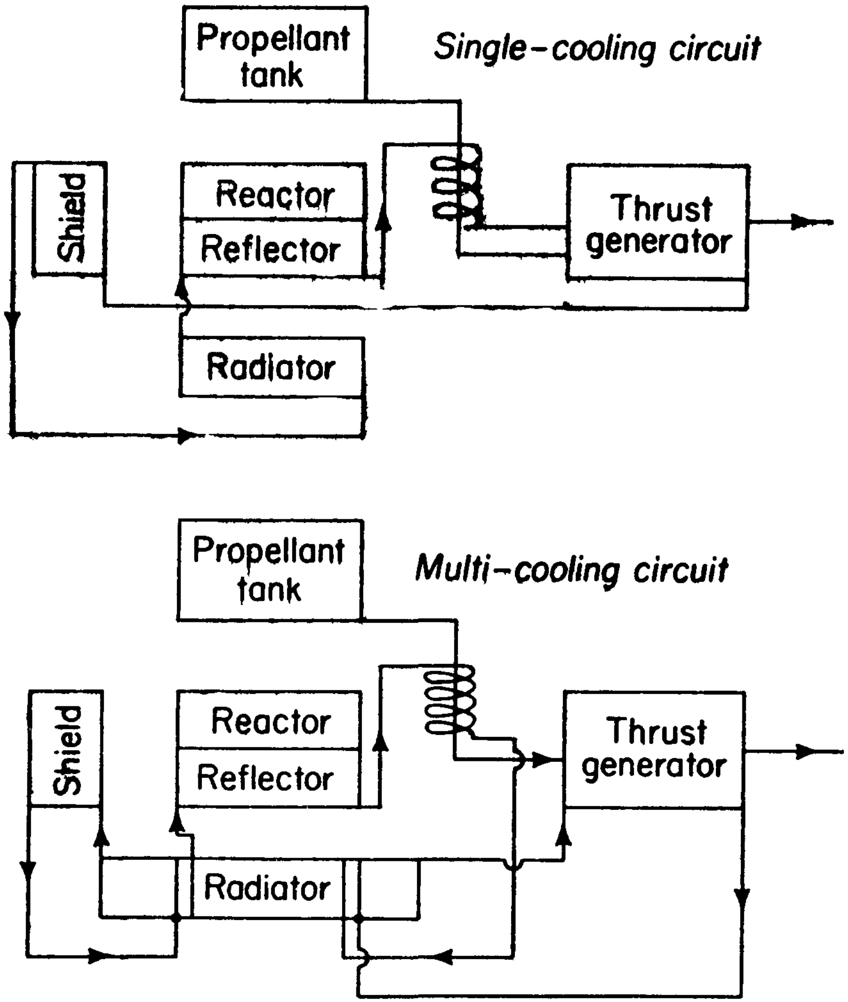

Fig. 1 Single and Multi-cooling Circuits of a Nuclear Space Propulsion System

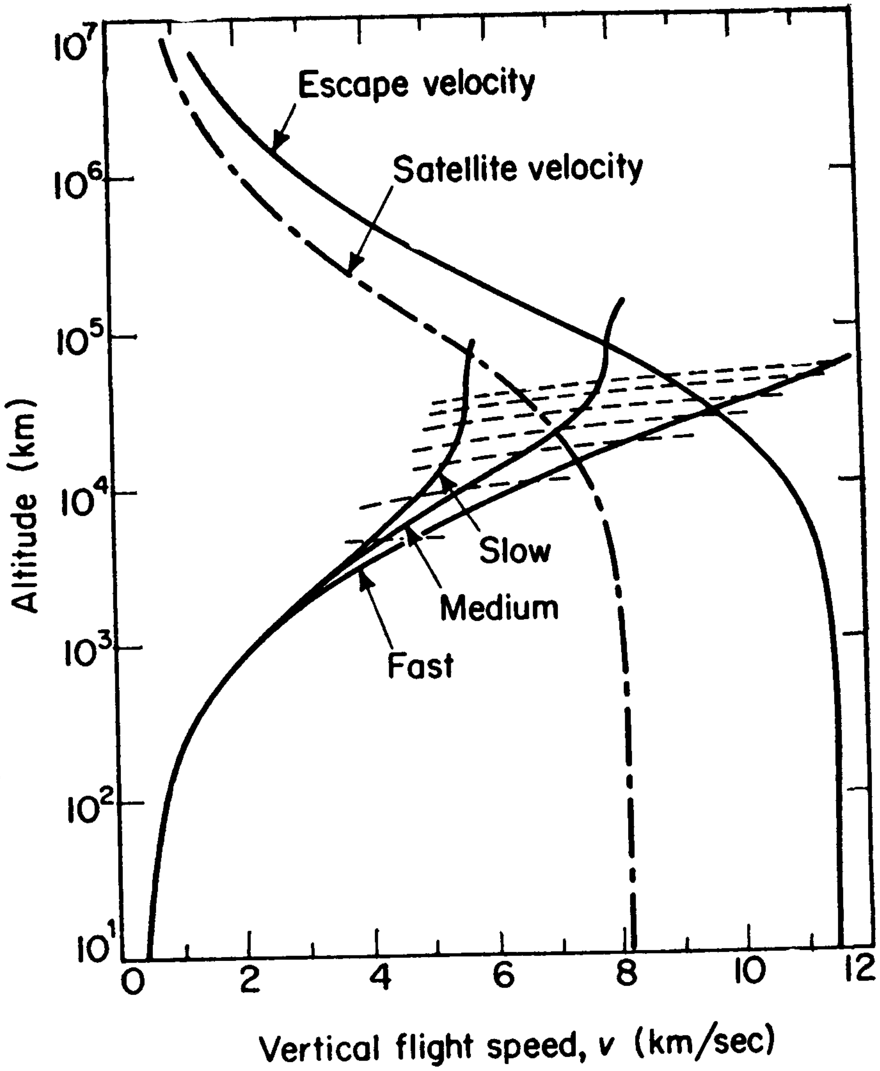

Fig. 6 Variation of Altitude with Vertical Flight Speed of Three Thermonuclearly Driven Spacecraft

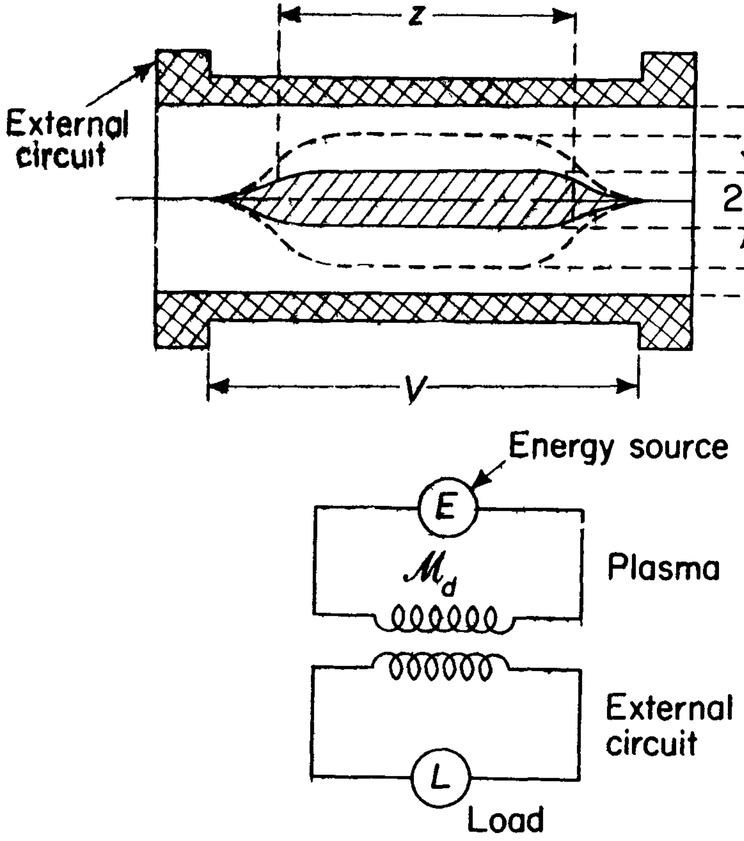

Fig. 7 Schematic Diagram Circuit Equivalent of Energy Transfer from a Plasma to Surrounding Coil

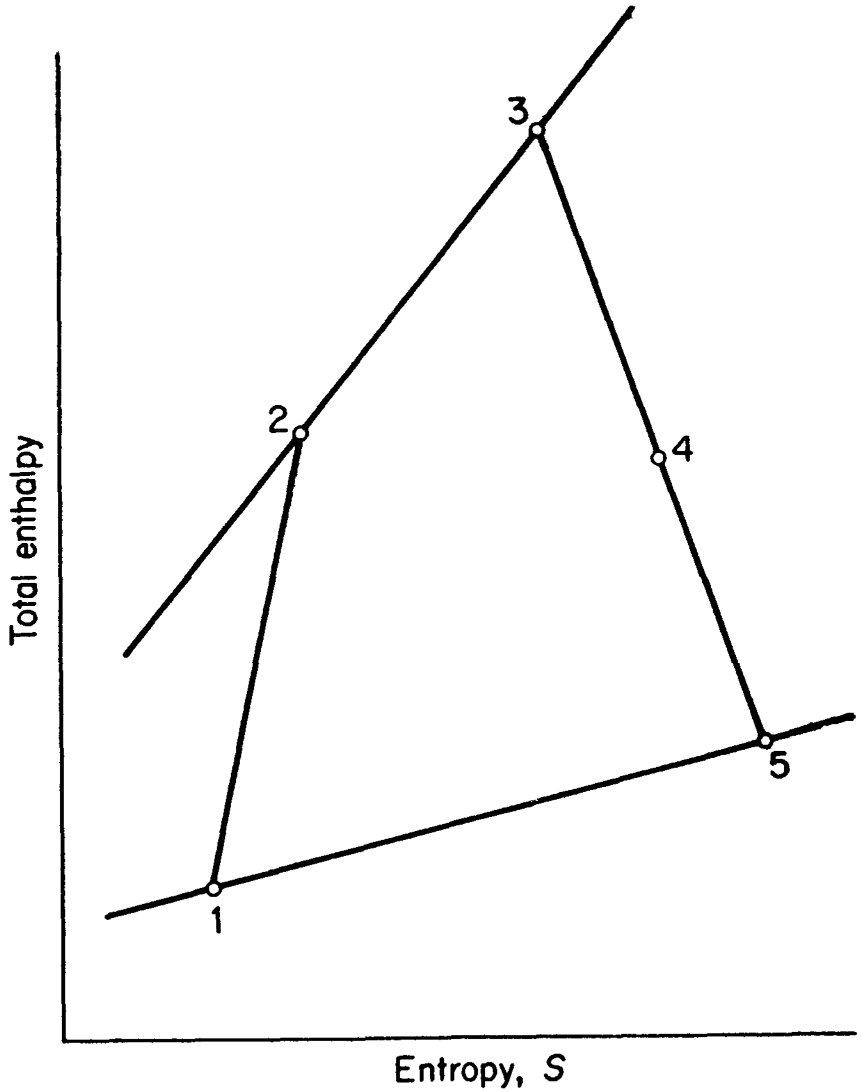

Fig.2 Thermodynamic Cycle of a Nuclear Energy Release System

D-T

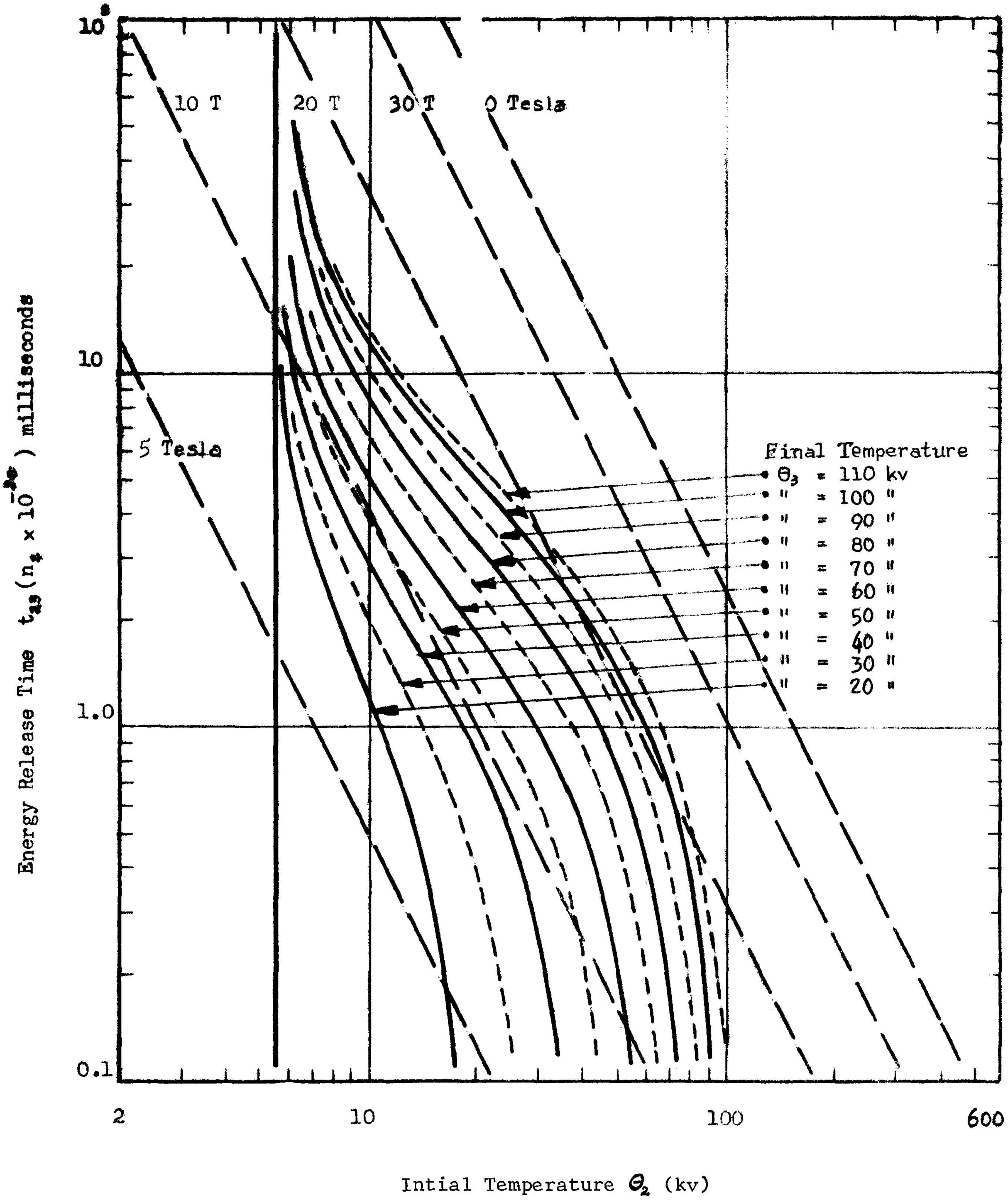

Fig.3 Variation of the Energy Release and Confinement Times with the Initial and Final Temperature and Magnetic Field for D-T

D-He^3

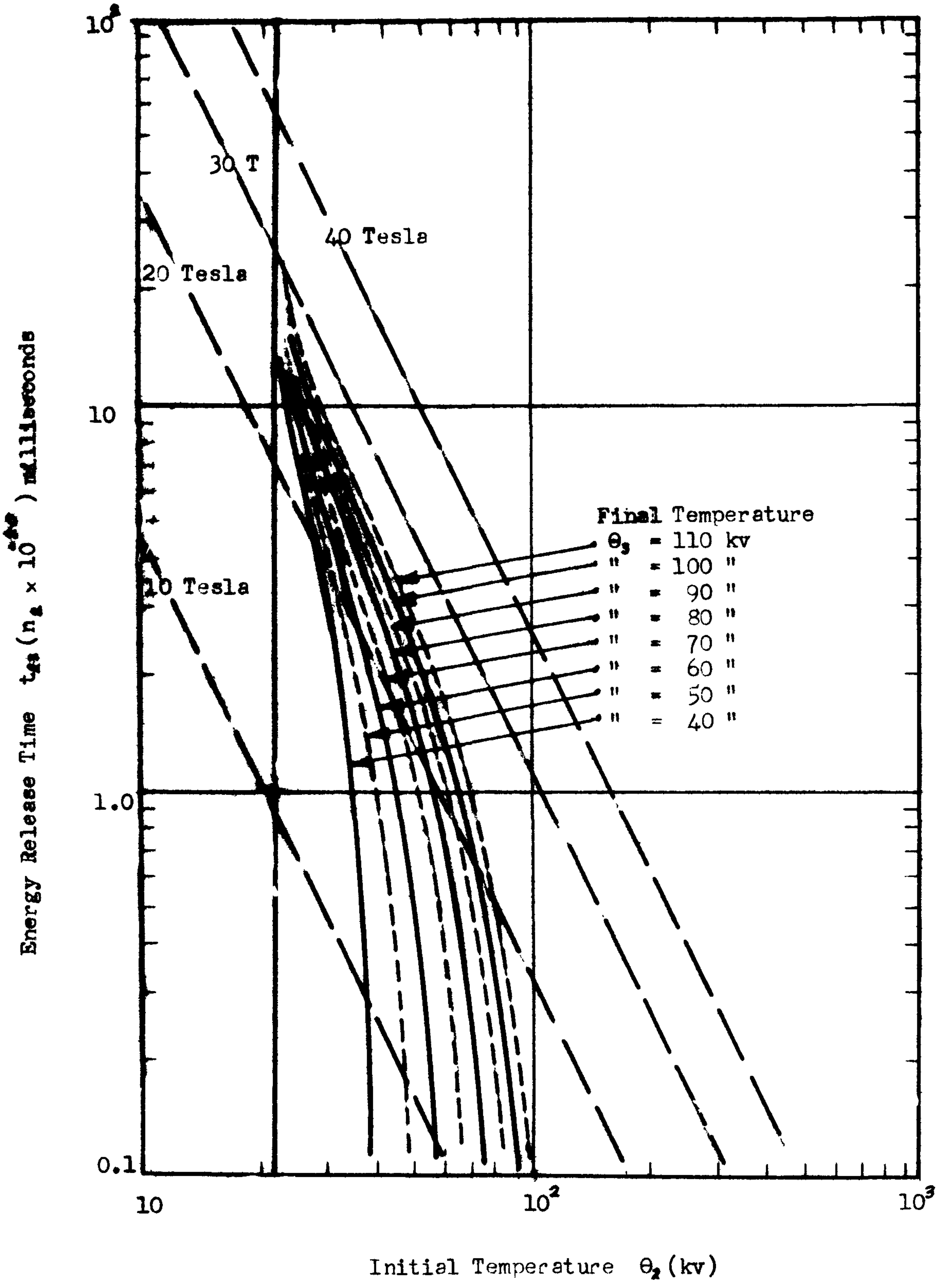

Fig.4 Variation of the Energy Release and Confinement Times with the Initial and Final Temperature and Magnetic Field for D-He^3

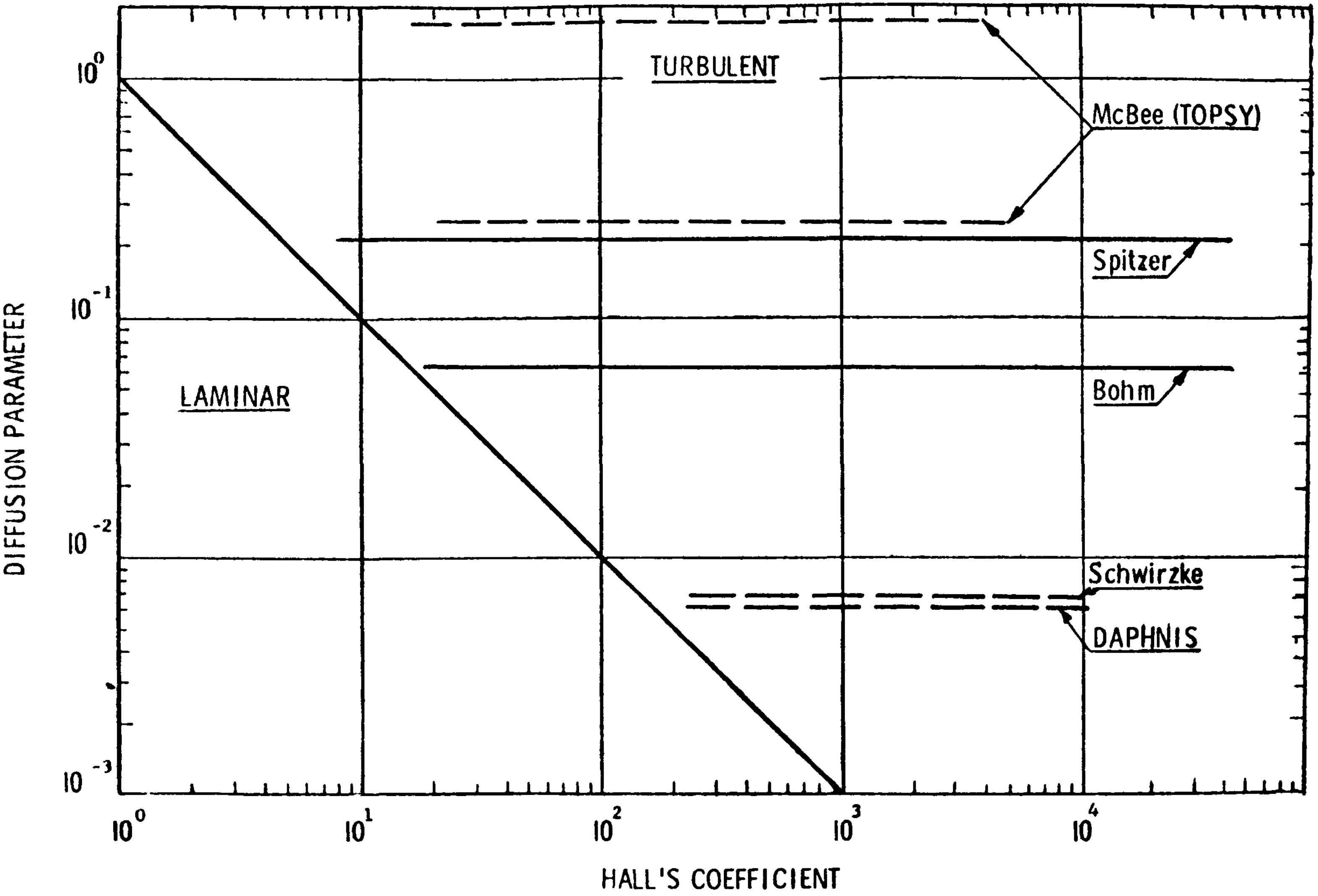

Fig. 5 Plasma diffusion through a magnetic field

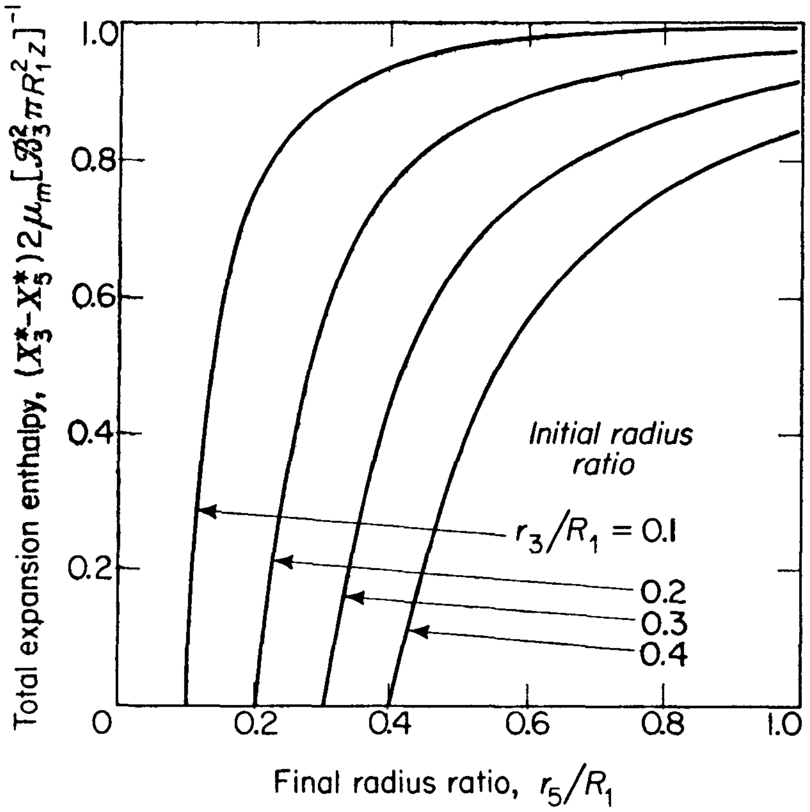

Fig. 8 Variation of the Total Two-dimensional Enthalpy During Adiabatic Radial Expansion

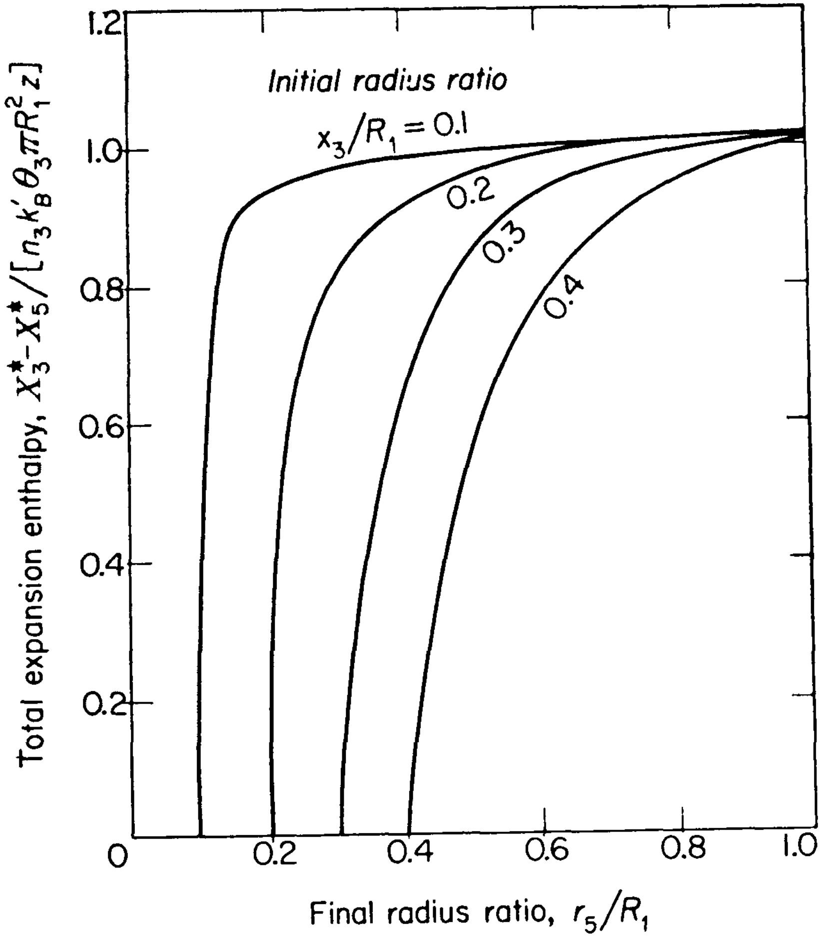

Fig. 9 Variation of the Total Three-Dimensional Enthalpy During Adiabatic Radial Expansion

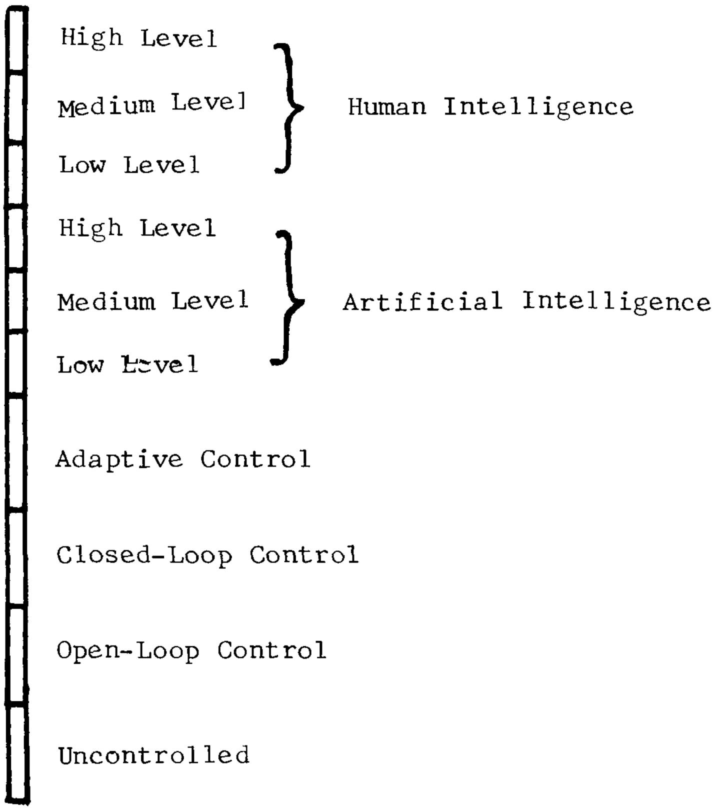

Fig.10 Classification of Control Systems. According to the Level of Intelligence in the Loop