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COMPARISON BETWEEN A STEADY-STATE FUSION REACTOR AND AN INDUCTIVELY DRIVEN PULSE REACTOR

—STUDY AS A POWER PLANT—

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In the present report, a comparison is made between tokamak reactors of steady state operation -SSTR- and pulse operation. The former design uses neutral beams as a current driver to realize steady state operation. The latter is inductively operated basic tokamak with burn time of one hour to a half day. This time is determined by dimensions of the central solenoid coil and these dimensions also determine the basic design concept of the pulse tokamak. The dimension includes effect of fatigue due to pulse operation. Performance as a power plant is evaluated with a schematic design of heat transport and power generation system. Heat accumulation in the primary coolant loop is studied in order to make up for a dwell time of a pulse reactor. It is shown that large heat accumulator is necessary to suppress a drop in output during the dwell time. The dwell time has an optimum length with respect to the dwell time. Comparison of fusion plant with other energy source reveals that reduction of the size is essential in order that the fusion is competitive with other sources.

Keywords: Pulse, Steady-state, Fusion, Reactor, Fatigue, Storage

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*3 On loan from Toshiba Corporation

誘導駆動パルス炉と定常核融合炉の特性比較
—パワープラントとしての比較—

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(1993年9月22日受理)

トカマクによる実用炉の設計には定常炉を目指す概念と，パルス炉で可とするものの二つがある。定常炉はＳＳＴＲとして原研にて概念設計がなされているが，パルス炉の設計例は稀有である。この差が原型炉の設計にどのような違いを生ずるかを比較検討し，今後どのように反映させるべきかを研究する目的で，ＳＳＴＲの設計をベースとしてパルス炉の概念を比較研究した。本報告では主にパルス炉の機械的な概念やエネルギー生産装置としての概念が定常炉と比較してどのようなものかを装置寸法とパワー出力の平坦化という２つの観点から検討した。その結果，パルス炉は中心ソレノイドコイルが大型になり，それに伴って装置全体が大型化することが示された。またパルスとパルスの間の停止時間中に出力が低下するのを防ぐために，１次冷却ループに蓄熱器が必要で，停止時間の関数として非常に大型の蓄熱器が必要とされることがわかった。定常炉の方がパルス炉より小型で経済的であることが示された。

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1. Introduction

Nuclear fusion research has now achieved a level of knowledge such that scientific and technological feasibility of the fusion can be addressed in an experimental reactor. Among discussions on the mission of the experimental reactor, the major issue is about the burn length of a demonstration reactor. That is, a plasma in the tokamak reactor is confined by the plasma current which is induced inductively in present devices. The non-inductive current drive is under development but does not seem to have very high current drive efficiency.

While several concepts were proposed for the demonstration reactor, many proposals discuss on a steady state reactor using non-inductive current drive [1-3] and a few concept on a pulse reactor [4]. The present report describes about the comparative study of the inductively operated pulse reactor and the steady state reactor, basing on an extrapolation from SSTR [1], ARIES [2] and ITER. The pulse reactor has a dwell period for recharging of the center solenoid (CS) coil with no energy output from a reactor. This period causes problems as an electricity generating power plant since the storage of electricity as it is very difficult [5] in addition to thermal and mechanical problems on the reactor structure.

In Chap.2, the operation regime of a pulse reactor and a steady state reactor is compared following our previous study [6]. In Chap.3, the effect of pulse operation on the structure is discussed from fatigue strength point of view. In Chap.4, the hardware required for regulating the output during the dwell period is designed and discussed from the steady state output point of view. Finally, the reactor dimensions are estimated and compared briefly showing that the steady state reactor will be smaller and more economical as a power plant.

2. Operation Region of Steady State and Pulse Reactors

2.1 Condition of Comparison

The pulse reactor of one hour burn and 12 hour burn were estimated basing on the concepts of SSTR, ARIES and ITER, where SSTR is a small steady state tokamak with neutral beam (NB) current drive. Since it is designed systematically, it served technical data bases for a pulse reactor. Two designs are considered for a pulse reactor. One has a burn time of one hour and the other 12 hour. Both are supposed to have the same plasma cross sectional shape as SSTR for comparison. Common features for both types of reactors are as follows;

a) Thermal out put : 3000 MW

b) Reactor life : 40 years

c) Plasma cross sectional shape

Minor radius : 1.75 m

Elongation : 1.8

Triangularity : 0.3

2.2 Characteristics of Plasmas of SSTR and Pulse Reactor

Comparison is shown in Table 1 and Fig.1 for major parameters of SSTR and pulse reactors. These were calculated with a system code using ITER power scaling law. Differences exist in safety factor q, discussed from the steady state output point of view. Finally, the reactor dimensions are estimated and compared briefly showing that the steady state reactor will be smaller and more economical as a power plant.

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a) Troyon coefficient $g = 3.0$
b) Safety factor $q > 3$
c) Confinement enhancement factor $H < 2$
d) Fusion output 3000 MW

After the operation region which satisfies above conditions is calculated, a parameter set of higher safety factor, longer burn time and lower divertor heat flux is selected and indicated in Table 1.

While the plasma density in SSTR is kept low in order to keep the current drive efficiency reasonably high, it is not a limit in the pulse reactor. Therefore, the pulse reactors are operated at higher density region of approximately 2×10^{20} m^{-3}, which is effective to decrease heat load at the divertor region. The toroidal field is stronger in SSTR in order to obtain high safety factor q, but it can be decreased in the pulse reactor. This value is determined by the estimation described in the next section. The flux swing capacity required for long burn makes the aspect ratio of the pulse reactor very large. The burn time of 10 m reactor decreases to 11.8 hour for the electron temperature of 8.0 keV. Therefore, the volt-second indicated will be a required minimum for a half day burn. The detail of these parameter study was reported previously [6].

3. Concept Comparison from Hard Ware

3.1 Operation Cycle

Operation cycle shows the characteristics of each tokamak. SSTR employs non-inductive current drive to induce the plasma current. It

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3. Concept Comparison from Hard Ware

3.1 Operation Cycle

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One hour reactor is assumed to burn 3400 seconds and cease 200 seconds to recharge CS coil. The repetition number with operation is approximately 300,000 times for the life of 40 years, and is 15,000 times for 12 hour reactor as indicated in Table 2. On the contrary, operation number for SSTR is very small. It will be less than 100 even if an annual inspection stop is included. However, the current LWR regulation requires the fatigue strength up to 1000 times of start and stop, the present estimation includes the fatigue cycle up to 1000 at SSTR. In both reactors, electric power was considered to be generated by a high pressure water loop which is similar to current PWR of 1000 MW_e. In the following sections, concept of the pulse reactor is extrapolated from the design basis of SSTR according to the fatigue strength of materials.

3.2 Toroidal Field Coil

TF coil in SSTR will be operated for a very long time as described above. The coil in the pulse reactor will be operated similar way to SSTR since there is no reason to stop it frequently. Toroidal magnetic field in SSTR is specified to produce 16.5 T at maximum. Since the super-conducting strand is so fragile that large electromagnetic forces arises in the coil are carried by the support structures made of stainless steels and coppers. The fatigue strength was estimated according to the crack propagation law for several stainless steels at the cryogenic temperature.

a) Life from crack propagation law

The fatigue life was estimated [7,8] with integration of Paris' law for the surface crack on a semi-infinite thick material under uniform stress. Namely, fatigue crack growth rate da/dN is given by

$$da/dN = C\,(\delta K_I)^{m},$$

where the stress intensity factor K_I is given by

$$K_I = \beta\,\sigma\sqrt{\pi a},$$

where $\beta = 1.1215$ and the other notations are standard. Integration of this equation gives a load repetition number N for a crack growth from initial size to critical size of break. This number as a function of stress value gives a similar dependence to usual S-N curves, as is shown in Fig.3 and in Ref.9.

b) Permissible load on the pulse reactor

The load in SSTR is low cycle load of electromagnetic forces. The load in the pulse reactor consists of the low cycle load due to the TF coil current and high cycle small amplitude load of the over turning force due to the poloidal magnetic field. These forces are shown in Table 3, and schematically in Fig.2 (a) where the horizontal axis denotes time and the vertical axis the stress level. While the level is low the high cycle load gives not negligible amount of fatigue damage. Therefore, the intensity of the toroidal field in a pulse reactor has to be lowered in order to give the same risk of the fatigue break at a steady state reactor.

The fatigue risk was estimated with the fatigue damage D,

$$D = \Sigma\,(n_i/N_i)\ ,$$

according to the Miner's law. The damage due to the over turning force on the self-electromagnetic force was estimated according to the fatigue limit diagram of the modified Goodman diagram. Calculation results are indicated in Table 4 where the stress values which give equal D values are indicated. This shows that JN1 [10] (new cryogenic material developed at JAERI) shows better result. From this calculation, the magnetic field intensity at 1hr pulse reactor has to be decreased by 15% from SSTR. Maximum toroidal field of 16.5 T at SSTR should be reduced to less than 14 T at the 1hr pulse reactor. Presently value of 13.8 T was selected because it gives the Troyon factor g=3.0 in the parameter region determined in Chap.2.

3.3 Center Solenoid Coil

a) Fatigue damage

The fatigue damage on center solenoid (CS) and poloidal field (PF) coils are much harder, because the electromagnetic force on CS coil is swung from 0 to 100% every time the plasma is turned on and off as shown in Fig.2 (b) and Table 5. In the steady state reactor, it is used solely at the ramp up of the plasma once or twice a year. But in the pulse reactor, it is used ten or twenty times a day, in addition to supplying much larger volt-second for inductive current drive.

The fatigue estimation described in the previous section was applied again. It indicates that the electromagnetic stress in CS coil should be less than 250 MPa for 1hr reactor and 550 MPa for 12hr reactor if the fatigue risk should be kept equal with that of 700 MPa at SSTR. This leads to very thick solenoids in the pulse reactor. From these estimations and parameter study, the poloidal cross-sectional dimensions of the reactors are determined as shown in Fig.1. The dimension of CS coil has large influence on the tokamak design. The major radius has to be 8 m for 1hr reactor and 10 m for 12hr, so as to accommodate large volt-second and to avoid fatigue damage for CS coil.

b) Dwell time and power supply

The dwell time has an impact on the capacity of both the heat accumulator described later and power supply for PF coil. If the dwell time is shorter the power supply is larger, and if the dwell time is longer the capacity of heat accumulator is larger. The operation of CS coil is estimated as indicated in Fig.4. The dwell time is sum of the plasma cool down, Ip ramp down, recharge time for CS coil, Ip ramp up and heating time. Additional time to adjust prefill might be required.

The power supply capacity was estimated from previous design results. The capacity could be related to the stored energy of the PF coil and typical ramp up or down time of the plasma current. Table 7 compares the stored energy in PF coil W^*_{PF}, typical plasma current ramp time T and the designed power supply capacities for JT-60U, ITER [9] and SSTR [3]. The capacities of the power supply are examined so as to minimize their capacity and load to the power network. The values for ITER indicate switched unipolar supply and bipolar supply. The stored energy for JT-60U is the design value of OH coil. It is reasonable to consider that the capacity of the supply is scaled approximately in proportion to W^*_{PF}/T, and from this table the proportional constant is seen to be approximately 10.

The supply is required to work with full power at three phases. That is the time for recharge of CS coil, Ip ramp up/down, and plasma heating/cooling. If the dwell time should be shortened as least as possible, these time will converge to the equal value of $W^*_{PF}/\langle P \rangle$, where $\langle P \rangle$ denotes nominal power of the supply which gives the shortest time under a given capacity. If we neglect the time required for plasma heating/cooling, the dwell time T_D can be related by

$$T_D = 3\, W^*_{PF}/\langle P \rangle.$$

3.4 Plasma Facing Components

Thermal stress on the plasma facing components is also a problem in the case of pulse reactor. The stress limits which give the same risk of fatigue damage as SSTR are derived from the S-N curves of molybdenum and tungsten, which may be primary candidate materials for PF components at the demonstration reactor. Figure 2 (c) indicates schematically applied stress and heat load. Thermal stress applied on them varies from zero to 100% during a single plasma operation. Allowed stress in the pulse reactor is smaller by 1/4 with Mo and by 1/10 with W as can be seen from Figs.5 and 6 [11,12]. Although the divertor heat loading in the pulse reactor is smaller owing to higher density operation, the allowed fatigue stress is much smaller in the 1hr reactor which is derived from the fatigue characteristics of those metals due to larger number of thermal stress repetition. The dimension of the divertor will be larger and its design will be more difficult in the pulse reactor (Table 6).

4. Power Generation System

In this chapter, problems of supplying the generated electricity to the commercial power grid are discussed. Largest problem in the pulse reactor is compensation of power output during the dwell time. This includes a problem not only of output but also of thermal fatigue in the coolant loop and the power generation system which are not developed to be used in pulse operation. Combination of a heat accumulator in the primary coolant loop and steam accumulators in the secondary loop is considered in this report.

4.1 Heat Accumulator

The cooling loop with the heat accumulator and steam accumulator is illustrated schematically in Fig.7. The upper shows the diagram and the lower variation of power output at the reactor exit (A), the SG exit (B), and the electric terminal (C).

a) Tubes as an accumulator

Smoothing the drop of the reactor output ((A) in Fig.7) requires large heat accumulator. The heat accumulator can be made from various materials of such as stainless steel, copper and molten salt with good thermal conductivity and large heat capacity. In the smaller owing to higher density operation, the allowed fatigue stress is much smaller in the 1hr reactor which is derived from the fatigue characteristics of those metals due to larger number of thermal stress repetition. The dimension of the divertor will be larger and its design will be more difficult in the pulse reactor (Table 6).

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Thin tubes enable quick temperature diffusion during the dwell time. Tubes are easier in the design of thermal response time and coolant conditions than other shapes of a ball and a block. The accumulator designed is indicated in Fig.8 where the upper shows the whole construction and the lower the cross-sectional view of a single unit. The vessel with inner diameter of 3 m contains tubes with 2 cm inner diameter and 20 m long and tolerate 150 atm of pressure.

b) Numerical model

The temperature response of the coolant components was calculated using two dimensional non-steady state program. In the program, the blanket, steam generator, coolant tubes and heat accumulator are simulated by multi-layered tubes with a several meshes of thickness and 10 to 20 meshes of length. The core plasma was assumed to change like a step function from 3000 MWth to zero, and come back to 3000 MWth after the dwell time.

The result is indicated in Fig.9, where the ordinate shows the required accumulator unit number as is shown in Fig.8 and the abscissa the dwell time, taking the minimum output during dwell time (height of dips of (B) in Fig.7) as a parameter. In the calculation the tube number was fixed to keep constant coolant conditions, instead tube thickness was increased to have a longer time constant with the dwell time. The number of tube in a unit is changing with the dwell time. It is seen that the unit number increases very rapidly with the dwell time. The heat accumulator of approximately 50,000 ton is necessary to smooth the drop to 70% height (dashed line, 700 MW) of the rated output during the dwell time of 200s. For longer dwell time, the accumulator mass increases enormously as shown in the figure.

If the power fluctuation increases, various problem will occur in delicate components such as steam generator and turbine which are designed in marginal condition even under very flat output of the present power plant.

4.2 Vapor Accumulator

For further flattening of output, an additional system of vapor accumulator is necessary in the secondary loop. Two vapor accumulators store pulsing portion of vapor ((C) in Fig.7) turn by turn. Saturated accumulator discharges vapor to generate power, while the other stores the vapor from the steam generator.

Since a 300 MW class turbine generator requires start-up time of approximately an hour, it would be not practical to consider that the steam accumulators could be switched within an hour. It would be necessary to operate them for five to eight hours. The vapor accumulator of five to eight hours discharge is very close to the present day vapor storage power plant being developed for a replacement of pump-up type hydraulic power plant [14].

4.3 Boiler System

It is plausible to make up the dwell time with an externally fired boiler [4, 5]. This system is better if the failure of the plasma break down is anticipated. However this scheme can not suppress the temperature fluctuation in the primary coolant loop. The boiler takes a half to an hour to start from waiting condition to full output due to the large heat mass and always has to be kept hot condition. Therefore, it would require a many control and maintenance jobs in addition to the capital cost.

4.4 Requirement from Power Line

The tolerance of power line could be supposed from the regulation on the power line. Table 8 lists the regulations in various countries on the frequency and voltage [15]. Very precise regulation is required and most of these come from the utility users. Mechanically allowable deviation for components such as generator and pump is larger than these values. The pulse reactor without smoothing the output would not be acceptable as a source of electricity.

5. Cost Estimation

a) SSTR and Pulse reactor

On the basis of concept definition described in above, the cost of the pulse reactors was estimated from SSTR costing data base as listed in Table 9. Major differences come from the size of tokamak as well as size of CS coil and capacities of the power supply and refrigerator. Pulse tokamaks are more expensive because all major components are larger.

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The cost of tokamak includes that for current drive or heating system. The power ratings of these systems are not very different from the present day heating systems such as 40 MW NBI for JT-60U and 75 MW NBI for ITER-CDA. We should note that these are much cheaper than CS or TF coil. The difference between SSTR and these pulse reactors far outweighs the cost (and labors) required for upgrade of CD system from pulse to steady state application.

Additional cost due to the heat accumulator and the steam accumulator system is accounted separately and is summed in the columns in Table 10.

b) Cost related to the dwell time

Here we mention about the relation between the dwell time and the cost for the power supply and the heat accumulator. Following the estimation of power supply illustrated in Sec.3.3, the cost for the supply can be related as a function of the dwell time. Figure 10 illustrates this as well as that for the heat accumulator. The abscissa means the dwell time and the ordinate scale or cost of the supply and accumulator. Meanings of curves are as follows;

1) Heat accumulator of 95% compensation
2) Heat accumulator of 70% compensation
3) Vapor accumulator system + 2
4) Power supply
5) 3 + 4

Curves 1 and 3 mean that for the dwell time of more than 70s, combination of vapor accumulator and heat accumulator is more economical than heat accumulator only, and less than 30-40s no accumulation system is necessary. Curve 5 is the result of the present estimation and shows that there is some optimum length of the dwell time and it lies between 100 to 200s. This is because too short time requires large supply and too long time large accumulator. In the case of AC operation [16], curve 4 is reduced only by 33% with a sacrifice of double sized CS coil.

c) Cost of electricity

Table 10 shows the list of the capital cost and the cost of electricity (COE) for power plants. The listed are flow of river type hydraulic power plant, pump-up type plant, petroleum plant, coal plant, LNG plant, atomic power plant, SSTR, pulse reactor of one hour burn and that of 12 hour burn. The cost of the heat accumulator and vapor system for the dwell time of 200s is included in Pulse 1hr, and no such cost in pulse 12hr. COE in pulse 12hr may be doubled when it is operated for a half day only. The right hand side column shows percentage of fuel fee in cost of electricity.

This table indicates that the power plant can be classified into two groups. One consists of plants with high capital cost but low fuel cost such as river type hydraulic and atomic plants. The other consists of plants with relatively low capital cost but high fuel fee such as petrol, coal and LNG. Because the fuel of the latter plants is not very economical for longer period of operation, they are mainly used as dairy start and stop operation as is indicated in Fig.11. On the other hand, the former plants feature high capital costs so that longer operation time and longer repay period are essential in order to decrease the cost of electricity. The fusion plant is featured by highest capital cost and lowest fuel fee among them. Therefore, this plant has to be operated with highest availability. It is also apparent that this plant has to be reduced in capital cost to less than two thirds of SSTR in order to be competitive in economy.

d) Circulation power

Circulation power inside of a plant is important to estimate the net power gain and is compared in Table 11. The value for LWR is typical for present PWR or BWR. The power in SSTR consists of powers for cooling pumps, refrigerator for coils and current driver. That in the pulse reactor consists of powers for cooling pumps, refrigerator and joule loss in the power supply. The last loss originates from frequent operation of the power supply and varies between 1 to 2% of the total volt-amperes depending on current density of transformers and rectifiers. It should be noted that the circulation power in the pulse reactor is fairly large and this decreases net power gain of the pulse reactor.

6. Conclusion

The fusion reactors of steady state and pulse operations were compared from engineering view point. The results indicate,

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requirement of longer inductive burn. This forces the reactor very large.

2. A pulse reactor permits operations at higher density regions. This results in lower divertor heat flux together with higher aspect ratio characteristics. However, this advantage is invalidated by fatigue damages due to pulse operation.
3. The scale of the power supply for PF coil was studied and found to be proportional with $10W^{*}_{PF}/T$.
4. The dwell time of pulse reactor was studied. During this time the reactor out put falls down and huge mass of heat accumulator is required to make up the fall down. This accumulator is also needed to reduce thermal fatigue in the primary coolant loop, steam generator and turbines which are still marginal and critical components even in the present day power plants of steady state operation. The accumulator system was studied with numerical program, whose mass is found to increase very steeply with the ratio of smoothing and dwell time. A stainless steel of 50,000 ton is necessary to keep generation of 700 MWe at minimum during the dwell time of 200s.
5. For the dwell time longer than 70s, it is more economical to add vapor accumulators with a small power generator in the secondary loop.
6. Though shorter dwell time reduces mass of the heat accumulator, it requires larger power supply for the CS coil magnetization. Thus the dwell time has a optimum value with respect to the capital cost of the power supply and the accumulator.

7. The capital cost for a construction of pulse tokamak reactor is 60 and 80% higher for 1hr and 12hr burn reactors, respectively. This cost growth comes from the size of tokamak due to larger CS coil, refrigerator and power supply. This far outweighs the cost and labor required for upgrade of CD system from pulse to steady state application.
8. Circulation power inside of the plant and hence the net efficiency differs slightly with the fusion gain Q. This is because larger power is necessary for P/S and refrigerator in the pulse reactor.
9. Although no estimation was made so far about reliability problem due to frequent start and stop of the pulse plant, this can be the most important problem for the actual application of the fusion reactor, because failure of the restart of the pulse plant will exert severe damage to the power grid operation.

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7. The capital cost for a construction of pulse tokamak reactor is 60 and 80% higher for 1hr and 12hr burn reactors, respectively. This cost growth comes from the size of tokamak due to larger CS coil, refrigerator and power supply. This far outweighs the cost and labor required for upgrade of CD system from pulse to steady state application.
8. Circulation power inside of the plant and hence the net efficiency differs slightly with the fusion gain Q. This is because larger power is necessary for P/S and refrigerator in the pulse reactor.
9. Although no estimation was made so far about reliability problem due to frequent start and stop of the pulse plant, this can be the most important problem for the actual application of the fusion reactor, because failure of the restart of the pulse plant will exert severe damage to the power grid operation.

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Table 1 Comparison of plasma parameters of SSTR and the pulse reactors of one hour burn and a half day (16hr) burn.

	Pulse 1hr	Pulse 12hr	SSTR
Major radius (m)	8	10	7
Minor radius (m)	1.75	←	←
Elongation κ_{95}	1.8	←	←
Triangularity δ_{95}	0.3	←	←
Plasma current (MA)	12	10	12
MHD safety factor q	3.4	3.9	4.5
Electron temp. (keV)	10	10	17
Electron dens. ($\times 10^{20} m^{-3}$)	2.2	1.9	1.5
Troyon g	3.0	3.0	3.3
Poloidal beta	2.4	3.5	2.0
H-factor H_{IP}	1.8	1.9	2.2
Fusion power (GW)	3	3	3
Wall load (MW/m^2)	2.6	1.9	3.0
Power to SOL (MW)	397	381	511
Divertor heat load (MW/m^2)	23	11	42
Toroidal field on axis (T)	8.3	9.3	9.0
Max toroidal field (T)	13.8	13.8	16.5
TFC stored energy (GJ)	74	117	137
Position of OH coils(m)	2.2	4.9	2.2
Max poloidal field (T)	13.4	13.4	7.0
Thickness of OH coils (m)	1.4	1.4	0.4
PFC stored energy (GJ)	22	113	7
OH coil stress (MPa)	250	540	670
Total Flux (Vs)	510	2200	295
Burn time (hr)	1	16	∞
Operation number(10^4)	30	1.5	<0.1
Weight ($\times 10^4$ton)	4	5	3

Table 2 Design conditions for SSTR and pulse reactor.

	SSTR	Pulse 1hr	Pulse 12hr
Burn Time	Months	3400s	12hr
Dwell Time	-	200s	200s or 12hr
Operation Number	200 to1000	300,000	15,000
LIFE	40 y	40 y	40y

Table 3 The comparison of TF coils in SSTR and pulse reactor.

	SSTR	Pulse 1hr	Pulse 12hr
TF	200 cycle	200 cycle + 300,000 ripples	200 cycle+ 15000 ripples
BT (MAX)	16.5 T	13.8 T	←
Stress Limit in JN1	850 MPa	610 MPa	810 MPa

Table 4 The stress and the maximum magnetic field at the equal risk of fatigue break.

	SSTR	Pulse 1hr	Pulse 12hr
JN1		610	810
SS316LN	850 MPa	490	740
SS316		380	640

Table 5 Comparison of CS of SSTR and pulse reactor.

	SSTR	Pulse 1hr	Pulse 12hr
CS	1000 cycle	300,000 cycle	15000 cycles
Stress Limit in SS	700 MPa	250 MPa	540 MPa
Volt sec	295	510	1900
	SLIM	THICKER	←

Table 6 Comparison of the divertor thermal loadings.

	SSTR	Pulse 1hr	Pulse 12hr
Divertor	1000 cycle	300,000 cycle	15000 cycles
Heat Load	HARD	x 1/2	x 1/4
Stress Limit in Mo,W	HIGH	x 1/4 - 1/10	x 1/2 - 1/4

Table 7 Stored energy, typical Ip ramp time and power supply capacities for JT60U, ITER and SSTR.

	W^*_{PF}	T	P/S
JT60U	90 MJ	1s	750 MVA
ITER	12/16 GJ	70s	1600/2200 MVA
SSTR	7 GJ	100s	880 MVA
Pulse 1hr	20 GJ	?	?

Table 8 Regulations on the power net in several countries.

	FREQUENCY	VOLTAGE
U.K.	± 0.1 Hz	240 V ± 6%
FRANCE	± 2%	220 V ± 5% (Paris) ± 10% (Others)
GERMANY		± 3% (Cities) ± 10% (Countries) ± 5% (Others)
SWEDEN	± 0.1 Hz	
USA		
CONSOLIDATED EDISON Co.	± 0.01 Hz	
CONNECTICUT VALLEY POW.	± 0.02 Hz	
NIAGARA MO HAWK	± 0.02 Hz	
PENNSYLVANIA NEW JERSEY	± 0.2 Hz	120 V ± 5%
NEWYORK		120 V + 5% - 1.7%
CLEVELAND POWER	± 0.01 Hz	
DETROIT EDISON	± 0.01 Hz	120 V + 4.2% - 6.7%
TVA	± 0.01 Hz	
NORTHWEST POWER	± 0.05 Hz	
PACIFIC GAS ELECTRIC	± 0.02 Hz	
JAPAN	± 0.1 Hz	101 V ± 6 V, 202 V ± 20 V

Table 9 Capital cost comparison between the steady state and pulse reactors.

	SSTR	Pulse 1hr	Pulse 12hr
Center Solenoid	(SLIM)	(x3.5 LARGER)	(x8 LARGER)
Divertor Stress	(HARD)	(HARD)	(HARD)
Current Drive/Heating	NB 60 MW CW (400 M)	NB 40 MW Pulse (200 M)	←
TOKAMAK	5500 M	7200 M	10000 M
Heat Accumulator	NO	50,000 ton >700 M	NO
Steam Accumulator	NO	200,000 m^3 400 M x 2	NO

Table 10 Cost of electricity for power plants.

	Capital cost	Cost of E.	Fuel ratio %
Hydro.	4900	10	0
Pump hyd	640	12*	↑
Petrol.	1500	8.5	75
Coal	1800	7.7	40
LNG	1500	7.7	60
Atomic	2400	6.9	25
SSTR	5500	12	10
Pulse 1hr	8700	17	↑
Pulse 12hr	10000	19 (x 2)	↑

* = 6.9/0.7+2.5

Table 11 Circulation power.

	Power	
LWR	50 MW	pump (& aux)
SSTR	50 +2 0 + 120 MW	pump, Refrigerator, NB
Pulse	60 + 50 + 10 MW	pump, Refrigerator, P/S

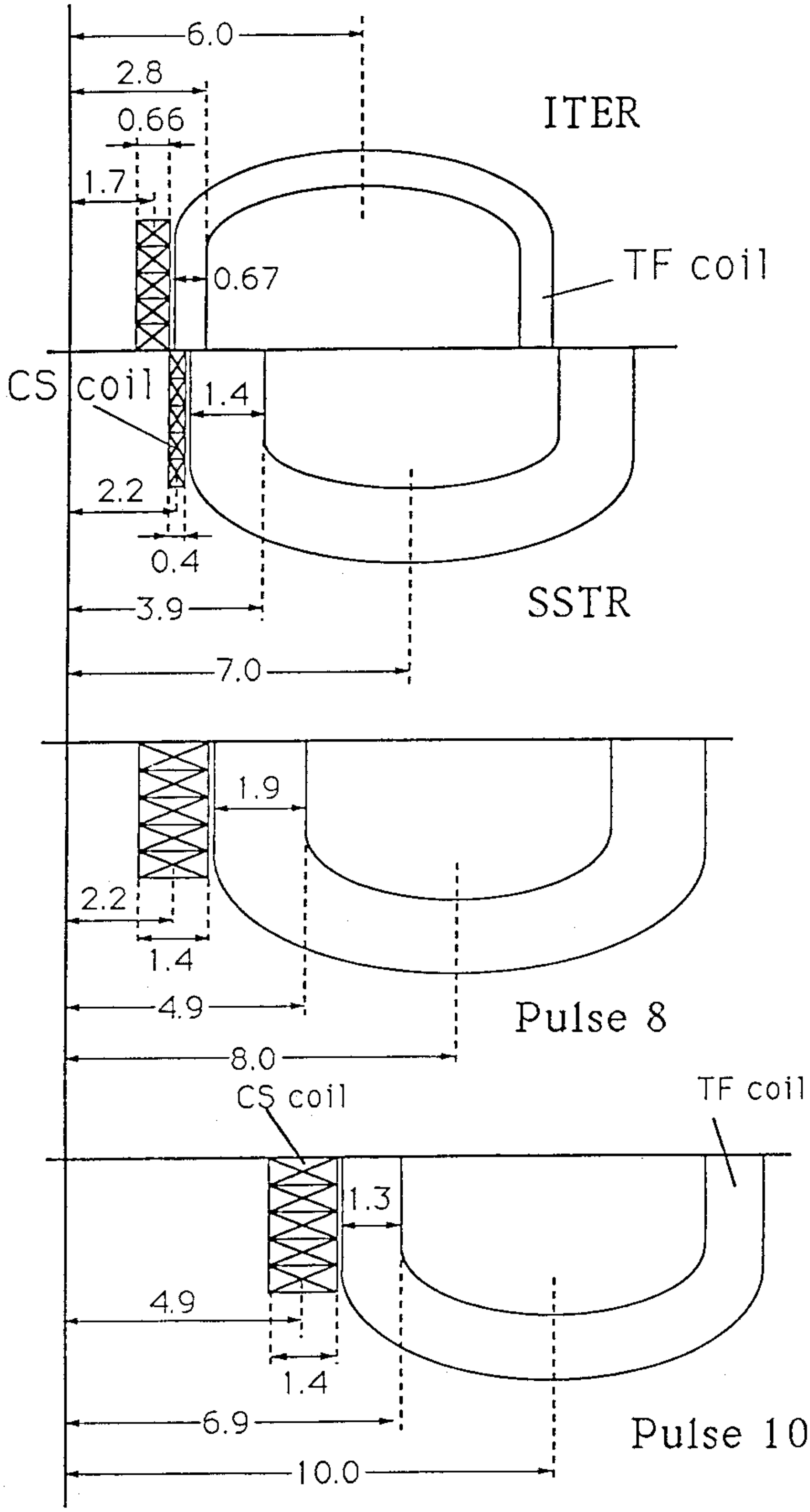


Fig. 1 Cross sectional views of ITER, SSTR and pulse reactors of 1hr burn (Pulse 8) and a half day burn (Pulse 10).

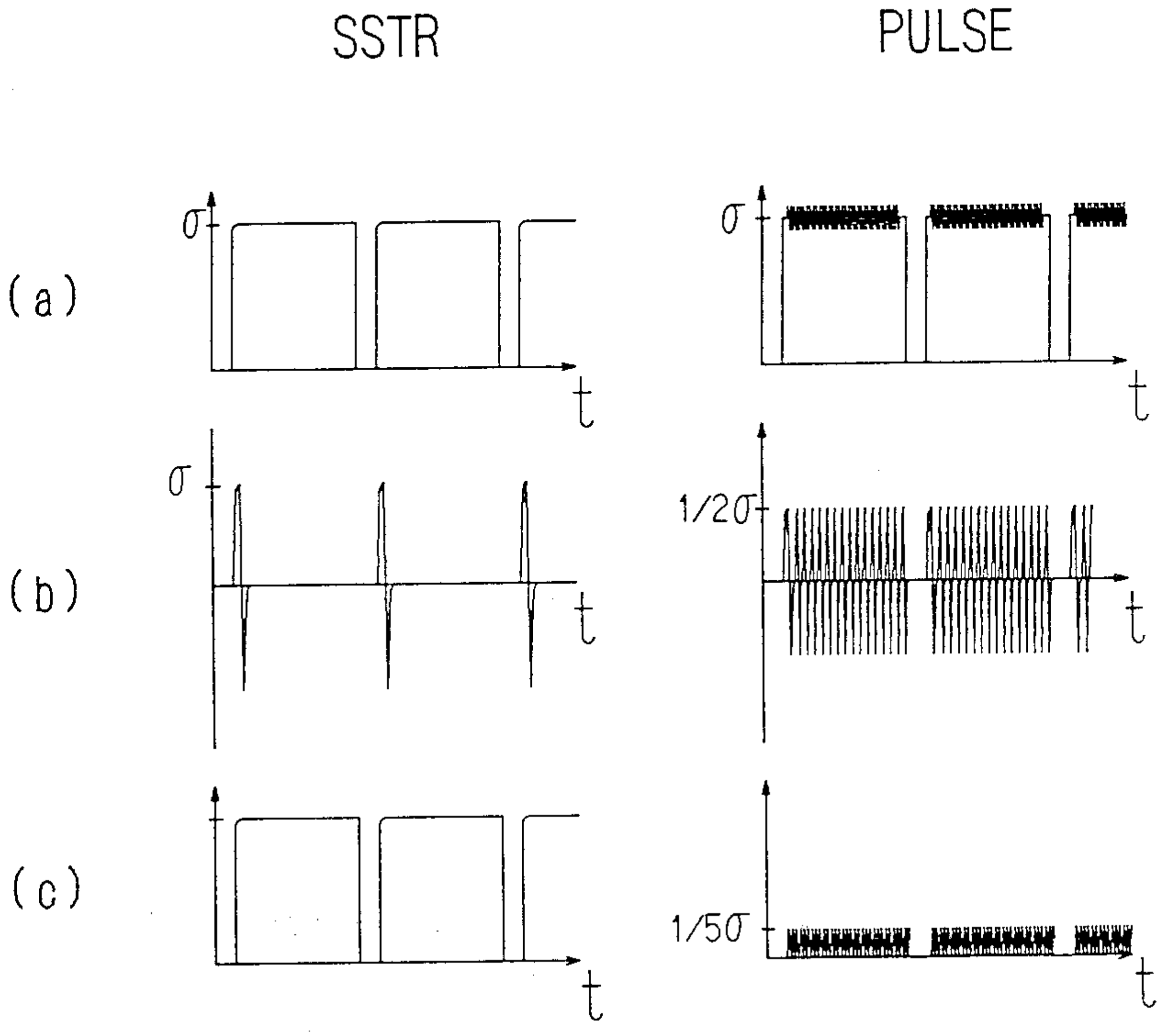


Fig. 2 Comparison of stress wave form on the steady state and pulse reactors. a) shows those on TF coils, b) on CS and c) on divertors.

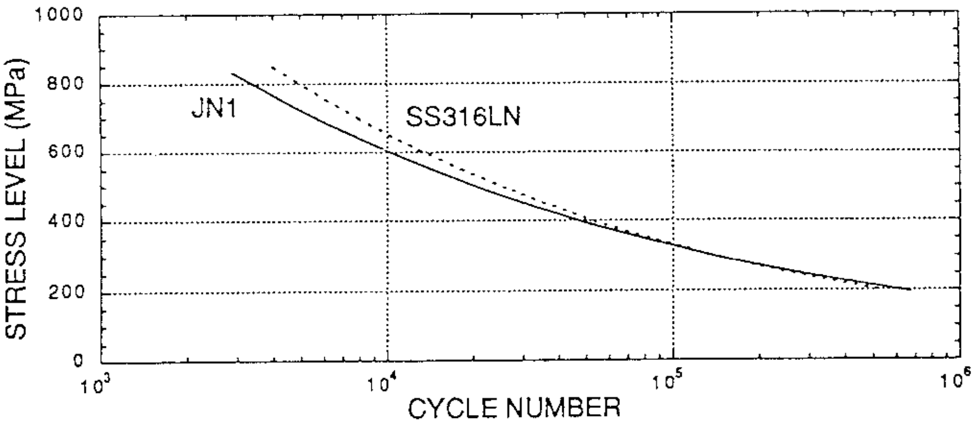


Fig. 3 Estimated crack propagation life of JN1 and SS316LN.

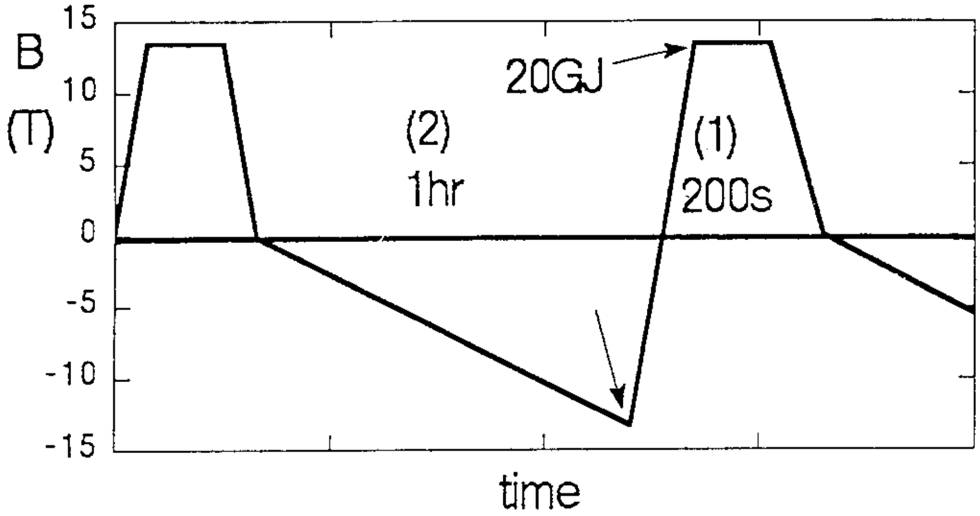


Fig. 4 Schematic operating scenario of pulse reactor. The vertical axis shows the magnetic field in CS and the horizontal time. The burn stops in every one hour followed by immediate ignition of plasma. The dwell time is shown by (1). CS is swung from -13.4T to +13.4T every time.

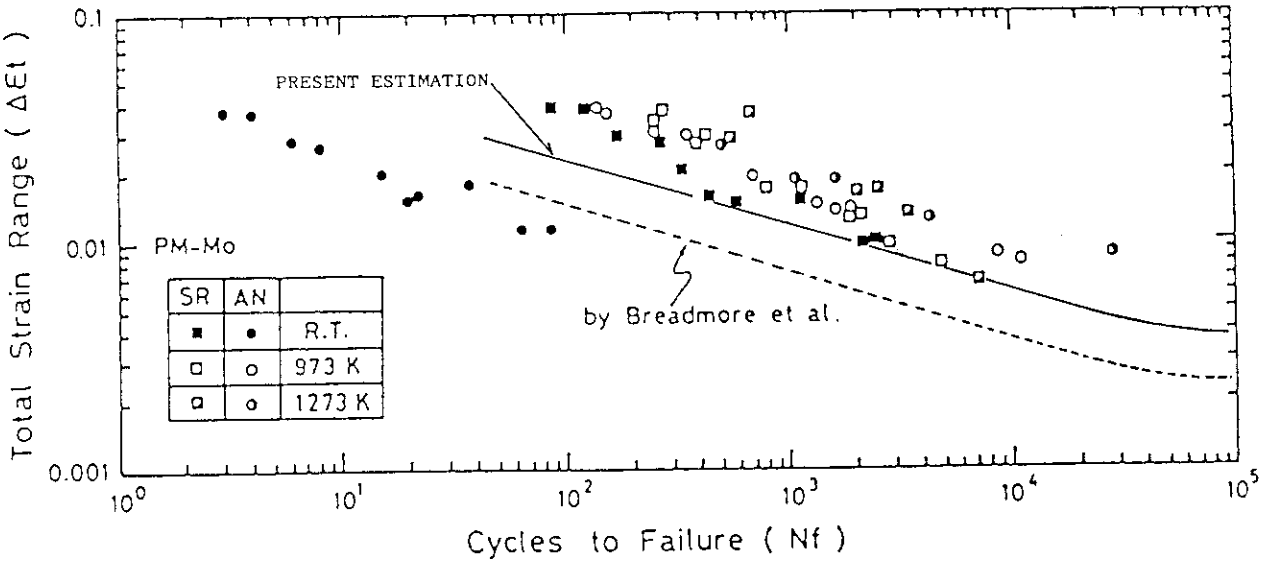


Fig. 5 Fatigue curve of Pm-Mo.

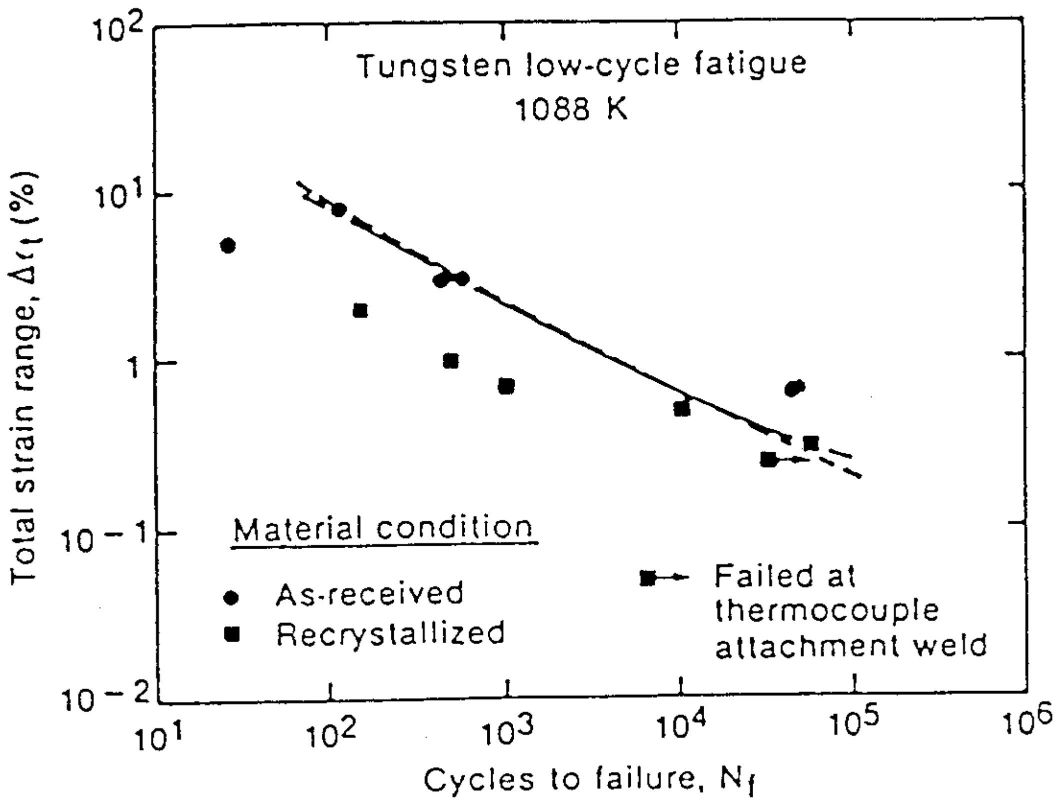


Fig. 6 Fatigue curve of Tungsten.

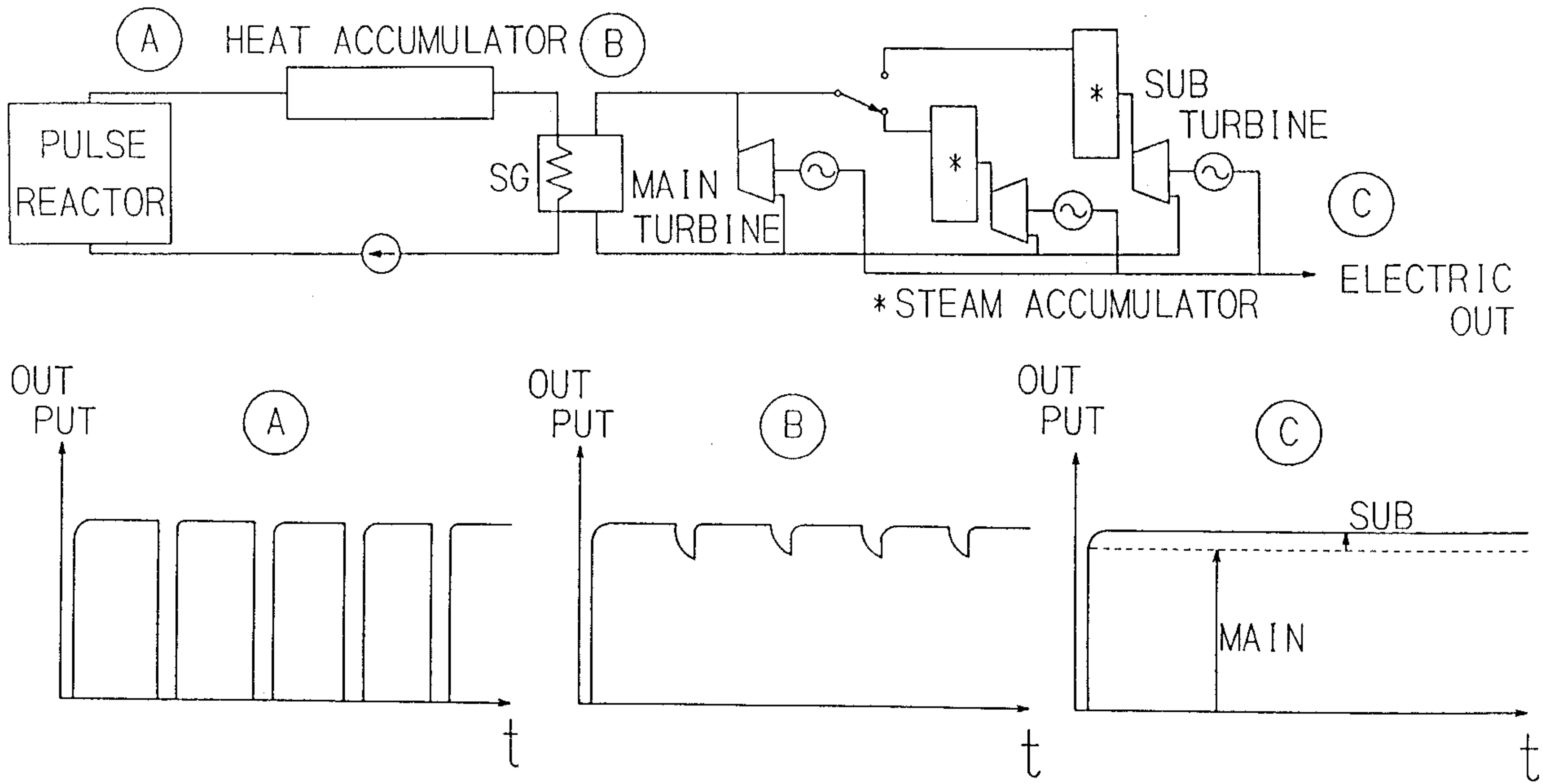


Fig. 7 How to smooth deep drops in the output of pulse reactor. The upper shows the schematic diagram of the coolant loop and electric generator, and the lower the wave form of the power.

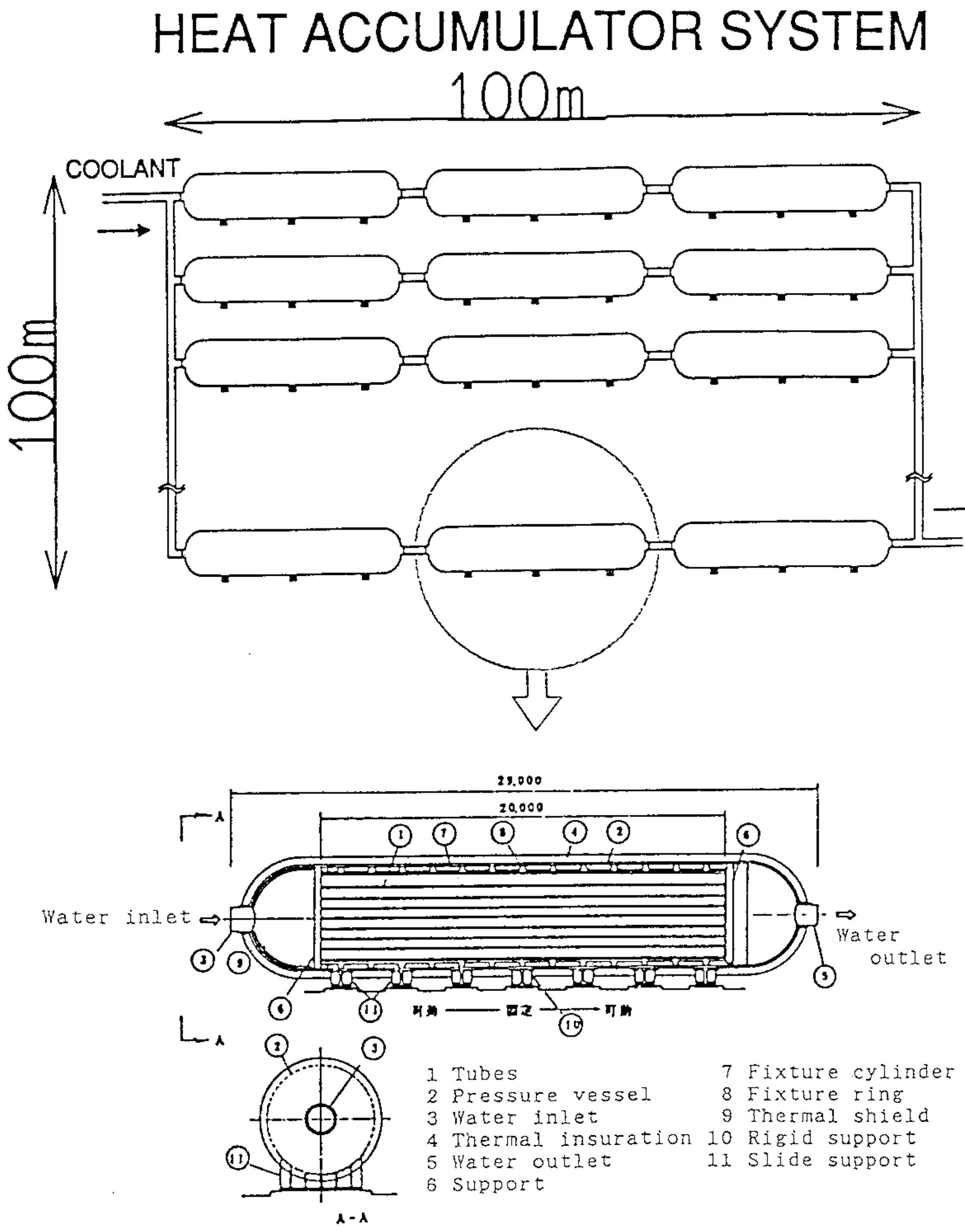


Fig. 8 Schematics of the heat accumulator. The upper figure indicates whole structure, and the lower cross sectional view of an accumulator unit. This unit is made of piled stainless steel tubes of 20m long in the high pressure vessel of 150atm. In order to recover 70% of 3000MWt drop for 200s, 27 accumulator units are required.

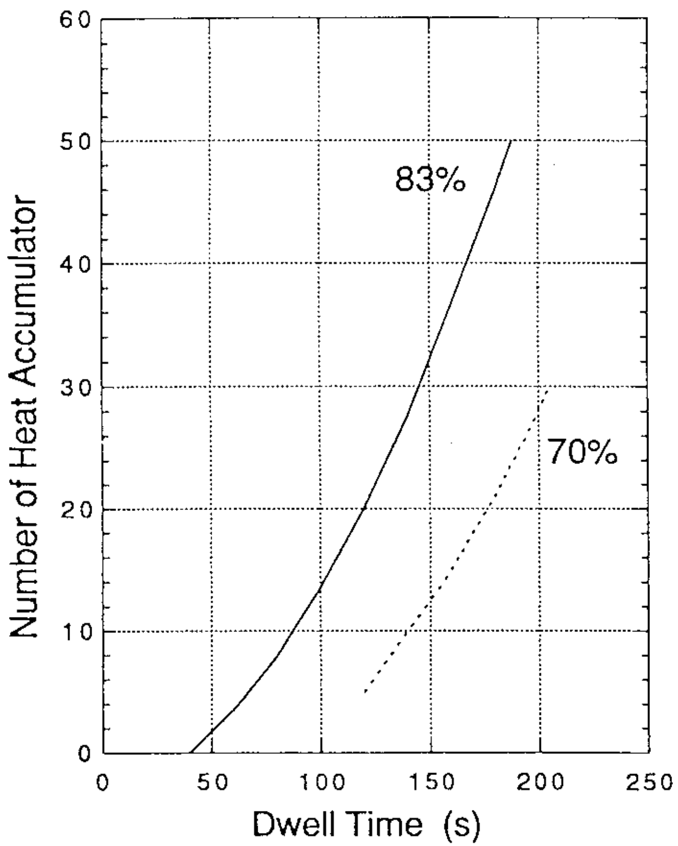


Fig. 9 Number of heat accumulator as a function of the dwell time and minimum output during the dwell time.

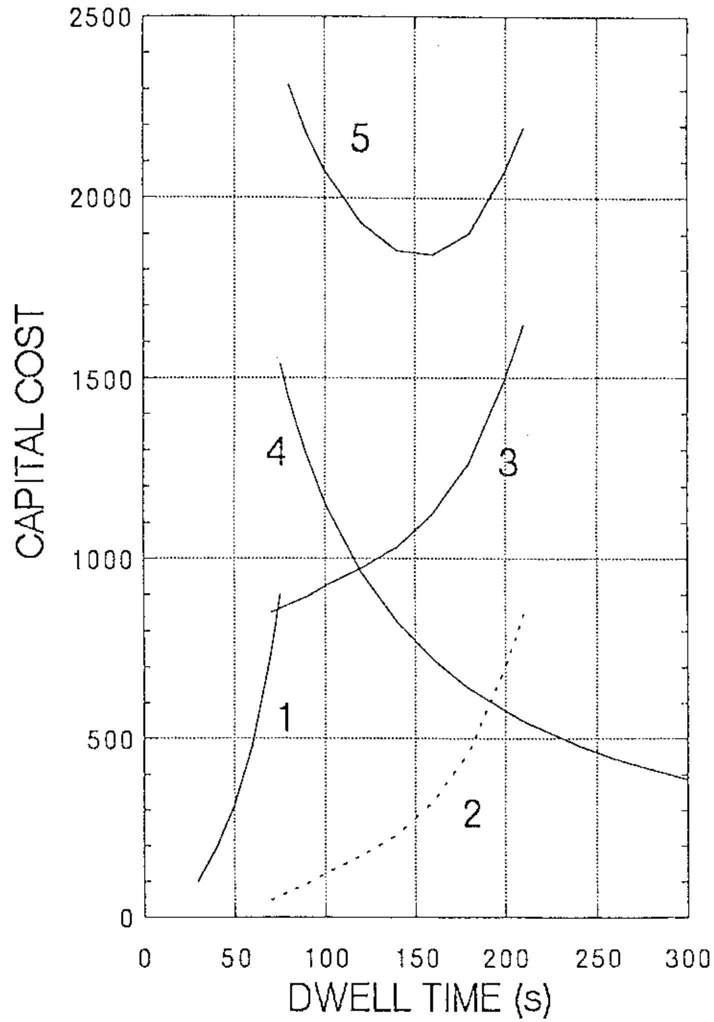
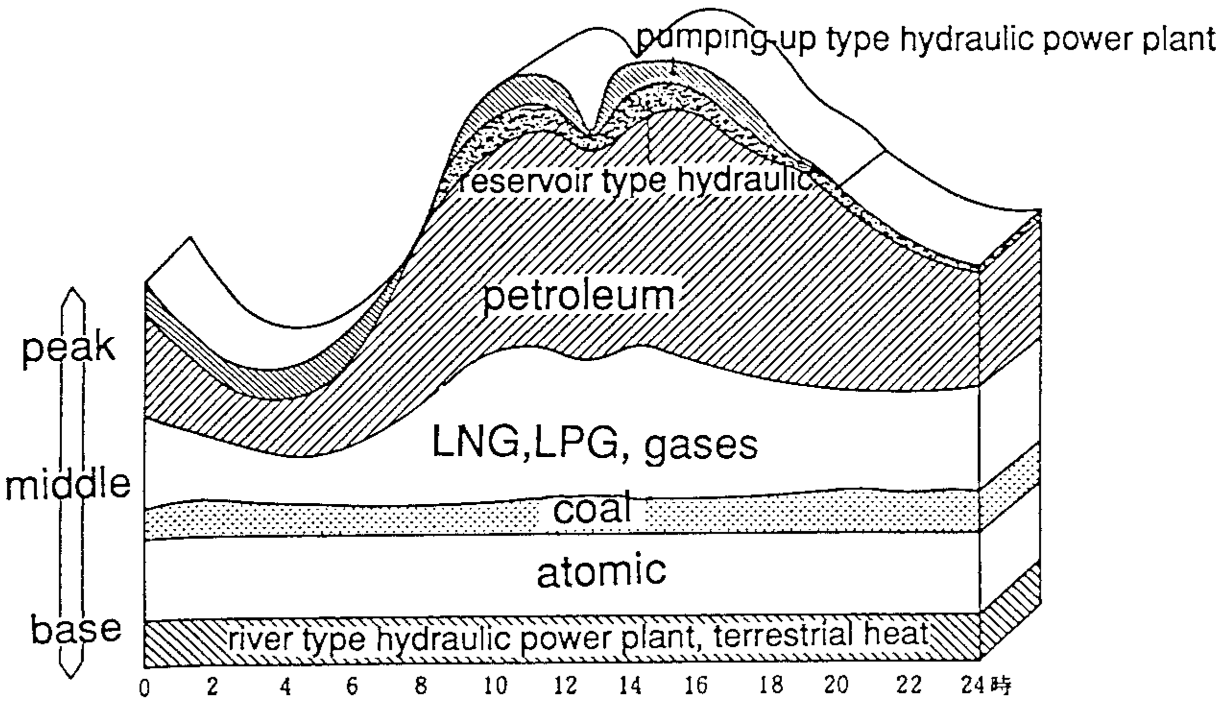


Fig. 10 Relation of the dwell time and scale or cost of the power supply and accumulator.
Curve 1 -- Heat accumulator of 95% compensation
2 -- Heat accumulator of 70% compensation
3 -- Vapor accumulator system +2
4 -- Power supply for PF coil
5 -- Total cost of 3+4



peak: Petroleum,pumping and reservoir power plants which are better in follow-up of the load variation.
middle: Coal and LNG plants which are good in both the running cost and follow-up of the load variation.
base: Atomic and run of river plants which are lowest in running cost and highest in capital cost.

Fig. 11 Schematic of power source constitution in Japan. The vertical axis indicate consumed electric power and ratio of power source. The horizontal axis shows the time of one day. The left hand side and the right hand side denote midnight, 0 o'clock and the center midday.