Start-Up of UWMAK-II

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Abstract

Ohmic heating coils have been designed for UWMAK-II. The current, energy storage and power wave forms have been calculated for each operation cycle. The plasma was considered as inductive lead during start-up. Spitzer resistivity with neoclassical and effective Z correction was used during the burn.

At the start of each burn cycle, the plasma current required for Tokamak operation is generated by having the plasma act as a single turn secondary of a transformer. Energizing the primary side produces an electric field that causes gas breakdown and plasma formation in the torus (the plasma could be pre-ionized by other means) and drives the plasma current. Once the desired operation condition is attained, the diffusion-driven current (bootstrap current) is sufficient, according to neoclassical theory(1,2) and no electric field is required. Operation could then be truly steady-state unless other factors, such as impurity buildup, limit the burn time. However, as discussed in section II-A-2,(3) there is no experimental evidence as yet that the bootstrap current exists. Therefore, in UWMAK-II, we generate the necessary electric field to maintain the plasma current by a slowly rising primary current in the transformer. Thus, the Tokamak reactor is a pulsed device but the burn time per pulse can conceivably be quite long. The reactor can be considered steady-state during the burn and for UWMAK-II the burn time is taken as 5400 sec or 90 minutes.

Here we discuss the design and operation of the transformer. The primary is assumed to be superconducting and the coupling to the plasma is via an air-core. The transformer currents are assumed to vary from some positive value to some negative value giving a total change in the transformer current of ΔI_T. This procedure gives the smallest core size. The exact limits for the transformer currents are determined by minimizing the required poloidal magnetic field energy. This then minimizes the maximum required power. The determination of these values is discussed shortly. Alternatives to the above approach include using a normal conducting primary programmed to vary from some maximum current to 0 with an air-core or using a superconducting primary programmed the same way with an iron core. Both these possibilities were studied and were found to require larger core sizes than the design chosen.(4) The smallest possible core size is required to allow the smallest possible aspect ratio.

During the burn, the plasma current $I_\phi(t)$ is constant at the design value, I_ϕ. For simplicity, we assume that $I_\phi(t)$ rises linearly in time during the startup. The time, T_1, has been chosen as 10 seconds to keep the maximum power requirements during startup to about 1000 MW_e and to keep the heat load in the superconductor coils due to eddy current loss within acceptable limits.

The plasma resistance is shown in Table I for various values of the electron temperature. The inductance can be calculated approximately from

$$L = \mu_o R_o (\ln 8 \frac{R_o}{a} - 1.75)$$

where R_o and a are major and minor radii respectively. For UWMAK-II, we have

$$L = 2.41 \times 10^{-5} h$$

The voltage transient equation of the plasma during the startup and shutdown phase can be written as

$$L \frac{dI_p}{dt} + R_p I_p = V_{external},$$

where R_p is the resistance and equals $\frac{2\pi R_o}{\pi a^2} \eta$. The plasma is inductive if

$$R_p I_p < L \frac{dI_p}{dt} .$$

For a 10 second startup and assuming a linear current rise, we have

$$R_p < 2 \times 10^{-6} \text{ ohm},$$

so that

$$\eta = \frac{\pi a^2}{2\pi R_o} R_p = 2 \times 10^{-4} \text{ ohm-cm}$$

which corresponds to $T_e \cong 128$ ev for Spitzer resistivity with the neoclassical correction. Therefore, for $T_e < 128$ ev, the plasma acts like a resistive load where as for $T_e > 128$ ev, the plasma is an inductive load. To a first approximation, we will neglect the resistive mode and assume that over the entire startup phase, the plasma acts as an inductive load.

The blanket of UWMAK-II contains much less conducting material than in UWMAK-I so that the "soak" of the poloidal field of the plasma current into the blanket is much more rapid. Consequently, the plasma inductance changes little during the current rise phase and there is much less tendency for the plasma current to overshoot. After the plasma current has been fully established, the core flux is increased slowly to make up for the resistive voltage drop in the plasma.

The value of the plasma resistivity has been anomalously high relative to the Spitzer value. Neoclassical theory predicts a reduction in conductivity in the banana regime due to trapped electron effects. The predicted variation is(5)

$$\sigma(r) = \sigma_{sp}(1 - 1.95 (\frac{r}{R})^{1/2} + .95 (\frac{r}{R}))$$

where σ_{sp} is the Spitzer conductivity. Assuming a flat temperature profile, we can average $\sigma(r)$ over the minor radius and obtain, for UWMAK-II parameters, $\langle\sigma\rangle = (\sigma_{sp}/3.65)$. In addition, the conductivity can be reduced due to impurities

Table I

Electron Temperature (KeV)	Resistivity* (ohm-cm)	Resistivity**
.01	2×10^{-3}	7.3×10^{-3}
.1	8×10^{-5}	2.9×10^{-4}
1.0	3×10^{-6}	1.1×10^{-5}
10	1×10^{-7}	3.65×10^{-7}
15	6.66×10^{-8}	2.43×10^{-8}

* Based on Spitzer resistivity

** Based on neoclassical resistivity assuming a flat temperature profile. The conductivity is assumed to vary as

$$\sigma = \sigma_{sp} \left[(1 - 1.95 \left(\frac{r}{R}\right)^{1/2} + .95 \left(\frac{r}{R}\right)\right]$$

where σ_{sp} is the Spitzer conductivity. The values in the table are obtained by averaging over the minor cross section.

by the effective Z of the plasma. For Z_{eff} defined as

$$Z_{eff} = \frac{1}{n_e} \sum_j n_j Z_j^2 ,$$

we have

$$\langle\sigma\rangle = \frac{\sigma_{sp}}{3.65\ Z_{eff}}$$

or, for the resistivity, η,

$$\eta = \eta_{sp} (3.65) Z_{eff} .$$

For a 90 minute burn time, the volt-second requirement is 41.7 Z_{eff} for the Spitzer resistivity case. Therefore, using the neoclassical resistivity implies 152.3 Z_{eff} volt-seconds are required.

In UWMAK-II, the use of a carbon curtain means that there should be essentially no high Z impurities in the plasma. Low Z impurities, like Z=6 for carbon, give rise to low Z_{eff} even for relatively high concentrations. For reasons described in Section II-B-5(3) on the divertor operation, we have taken $Z_{eff} \simeq 1$ during the burn phase. Thus, the volt-seconds required is taken as 152.

The transformer coil locations and currents have been determined in the following manner. First, a field line generated only by the plasma current and passing through R = 3.60 meters was calculated. This R was chosen consistent with the size of the D-windings, the anticipated size of the transformer coils, and the space required for supporting structure in the center. A surface current $\Delta I = H\Delta S$ was calculated along the field line. The currents within each 2 meter interval along this field line were then lumped together and placed at the center of each interval. Such a procedure gives the center and radius of each coil. The coil T_6 listed in Table II, however, covers a larger interval and has been raised one meter to leave enough space for the reinforcement structure shown by the shaded area on the "D" shown in Fig. 1. The transformer coils and currents determined in this manner will give minimum magnetic field contribution at the plasma. This field is less than 50 gauss for the UWMAK-II system.

The transformer currents determined above only fix the ratio between the transformer coil currents, not the magnitude of the currents. The rate of change of current is important and depends on the rate of magnetic flux change required to induce current in the plasma loop. All the divertor currents are programmed to rise with the plasma current. In addition, the same ratio of currents is these coils is maintained in order to keep the plasma cross-section and equilibrium condition at all times. The divertor coils give a net current of -5.26 MA and they contribute about 30% of the flux needed to energize the

Table II

Divertor Current

	R(m)	Z(m)	$I(10^6 \text{amp})$
D1	8.2	6.5	-3.70
D2	8.8	10.0	+4.89
D3	11.5	12.3	-1.46
D4	11.5	9.5	+3.40
D5	14.6	8.0	-1.57
D6	19.0	5.0	-6.82

Transformer Current

	R(m)	Z(m)	$I_o(10^6 \text{amp})$ initial current	$I_s(10^6 \text{amp})$ (end of start-up)	$I_f(10^6 \text{amp})$ (final current)
T1	3.61	1.00	2.74	1.66	-4.13
T2	3.72	3.00	2.64	1.60	-3.99
T3	3.94	4.99	2.39	1.45	-3.61
T4	4.25	6.96	2.26	1.37	-3.41
T5	4.66	8.92	1.89	1.14	-2.85
T6	5.43	13.50	2.22	1.15	-3.36
T7	6.50	15.05	2.21	1.34	-3.34
T8	7.25	17.00	1.66	1.00	-2.51
T9	8.22	19.3	1.46	0.88	-2.20

Change of Transformer Current

	$-\Delta I_s$	$-\Delta I_B$	$-\Delta I$
T1	1.08	6.87	7.95
T2	1.04	6.63	7.67
T3	0.94	6.00	6.94
T4	0.89	5.67	6.56
T5	0.75	4.74	5.49
T6	1.07	5.58	6.65
T7	0.87	5.55	6.42
T8	0.66	4.17	4.83
T9	0.58	3.66	4.22

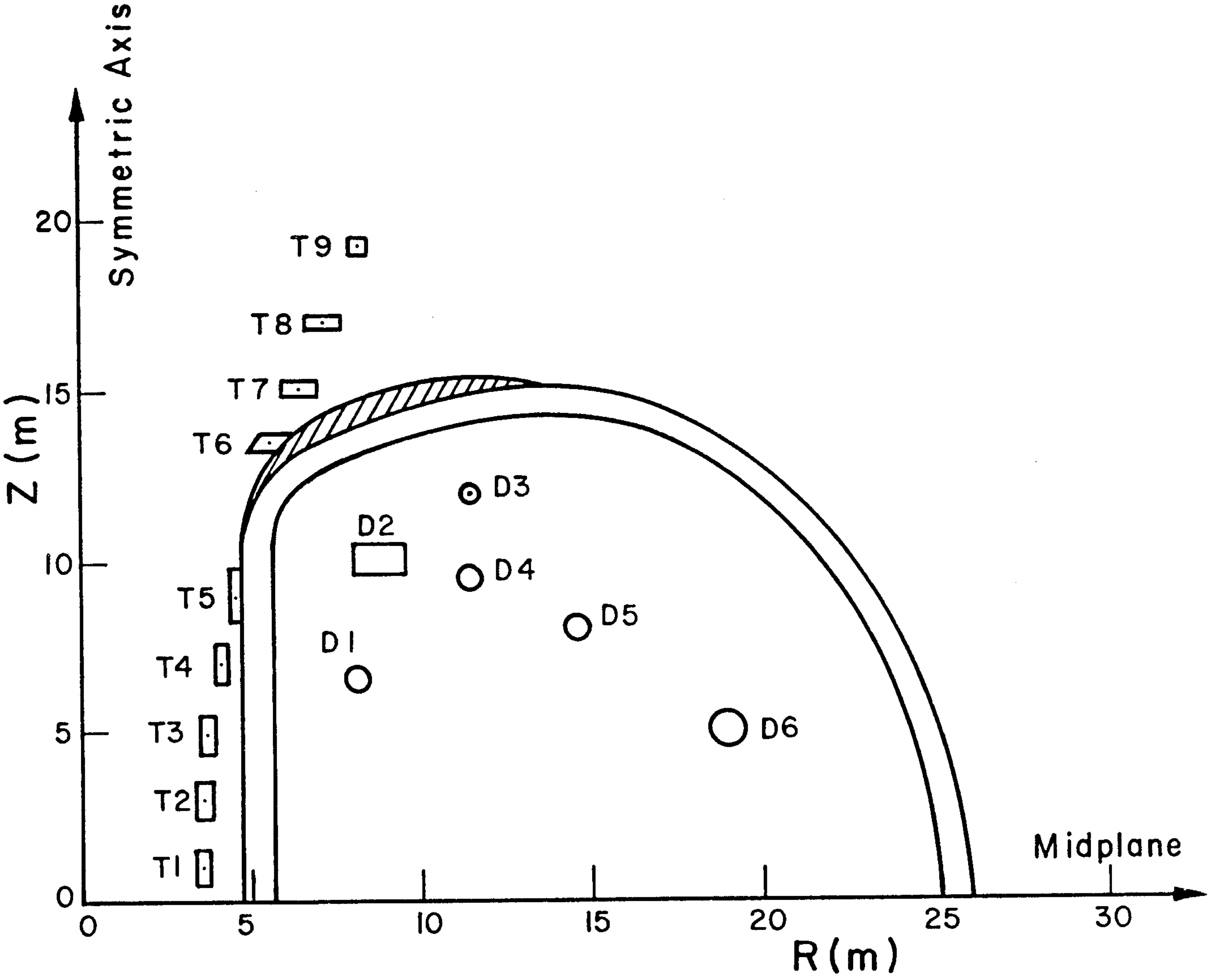
Symmetric Axis
Z (m)
20
15
10
5
0
T9
T8
T7
T6
T5
T4
T3
T2
T1
D1
D2
D3
D4
D5
D6
Midplane
0
5
10
15
20
25
30
R (m)

Figure 1

the plasma during the startup or to de-energize the plasma during shutdown. The transformer must therefore provide the remaining 70% of the flux.

During the burn, the divertor coil currents remain constant and flux needed to produce the 152 volt-sec due to plasma resistivity has to be provided by the transformer alone. The current changes during startup, ΔI_S, and during the burn, ΔI_B, have been calculated according to the method described previously.(6) The values of ΔI are listed in Table II . The total current change from startup to the end of burn is $\Delta I = \Delta I_B + \Delta I_s$.

In principle, one can program the current in the transformer coils to vary from 0 to ΔI. However, we pointed out in our earlier work(6) that the energy stored in the poloidal field and power requirements to drive the OH and VF coils will be lowest if the currents are programmed to vary from $+\Delta I/2$ to $-\Delta I/2$. In addition, the minimum total energy stored does not occur at zero-current, but occurs at -0.9MA in coil T1. Therefore, the current is again off-set by this much, i.e. the current is programmed from $(\Delta I/2 - .9)$ to $-(\Delta I/2 + 0.9)$. Another merit of doing this is that the maximum currents in the transformer will be approximately $\Delta I/2$, rather than ΔI, and this will clearly save on the cost of the coils.

The transformer coil currents at the beginning and the end of startup and at the end of plasma burn are also listed in Table II. The waveforms for the complete operating cycle for plasma current, divertor currents, transformer currents, the total stored energy in the poloidal field, and the power requirements for the coils are shown in Fig. 2 and Fig. 3. These figures require some further explanation.

The complete operating cycle is divided into four phases: the startup phase, 10 sec; the burn phase, 5400 sec (90 min); the shutdown phase 100 sec; and the pump out and recharging phase, 150 sec. (Notice the difference of time scale used for each phase in the figure). Curve I shows the plasma current rising linearly from zero to the full current, 14.9 MA, in 10 sec. A 20 sec time is provided for beam heating and other heating at this point to bring the plasma to the operational temperature during the burn, ~15 keV. The plasma current remains constant for 5400 sec during the burn and then decreases linearly in 100 sec to zero during shut down. We have pointed out previously that the divertor current must be programmed to follow the plasma current so that the waveform for the currents in the divertor coils is the same as that for I_{plasma}.

The current waveforms of each coil of transformer are the same and can be demonstrated by that of T1, shown by Curve II in Fig. II. During the startup phase, the current of T1 is initially at +2.75 MA and drops to +1.66 MA in 10 sec. During the burn phase, the divertor current is no longer changing so that the transformer alone provides the required flux. This is done by decreasing the current in coil T1 from +1.66 MA to -4.13 MA. The curve has a very small slope because of the long burn time. The total volt-sec requirement for the burn is 152. During the shutdown phase, the current in T1 rises back to -3.06 MA. The current is then held constant for 50 seconds during the purge of the chamber so as not to induce gas breakdown and further interaction with the walls. Then, over the next 150 seconds, the coil is recharged to +2.75 MA. This completes a cycle and the system is now ready for fuel gas load and restart.

The total energy storage and power requirements in each phase are shown by Curve II in Figure 2 and the power requirements is shown in Figure 3. We notice that the energy decreases in the first few seconds during startup. This means that the system discharges so that the power requirement is negative (output power). The same thing happens during shutdown and the first part of the recharging phases. This energy has to be transferred back to the energy storage system. The energy storage rises to a maximum of 1.9 MW-hr at the end of the 10 sec startup. It takes about 1000 MW_e to accomplish this charging.

During the burn phase, the energy stored in the poloidal field decreases slightly to a minimum at I_{TI} = 0.9 MA. It then increases to a maximum of 2.9 MW-hr at the end of the burn phase. This is the highest value of the stored energy. However, since it is reached over the very long burn time, the power requirements are minimal and can be met by the electrical bridges provided to transfer power during startup. Further, since 100 sec is provided for shutdown, the power output is only 120 MW.

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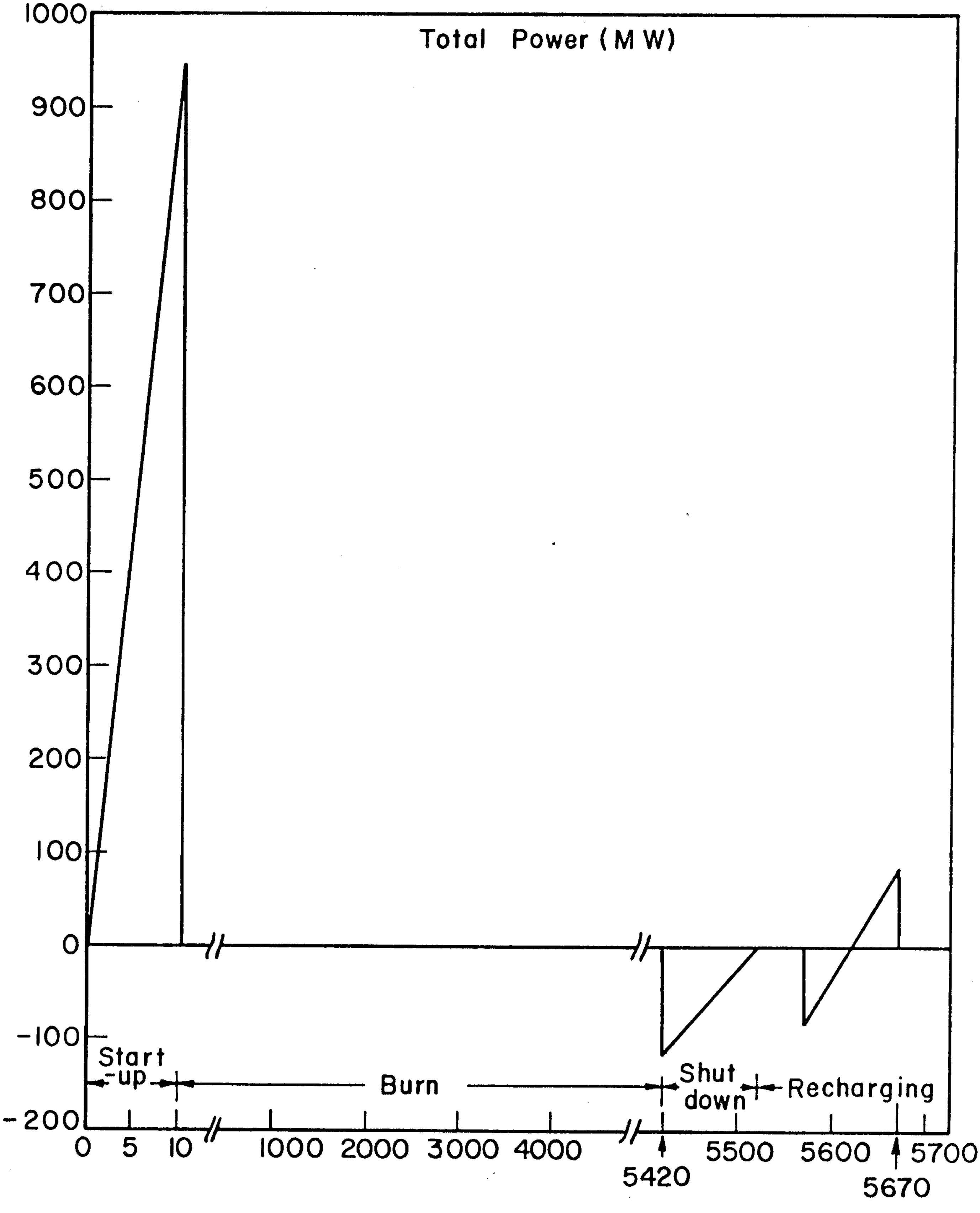

Figure 2 -- Plasma Current, Transformer Current and Total Poloidal Energy Storage During Start-up, Burn, Shut-down and Charging Period. Note the Difference in Time Scale in Each Period.

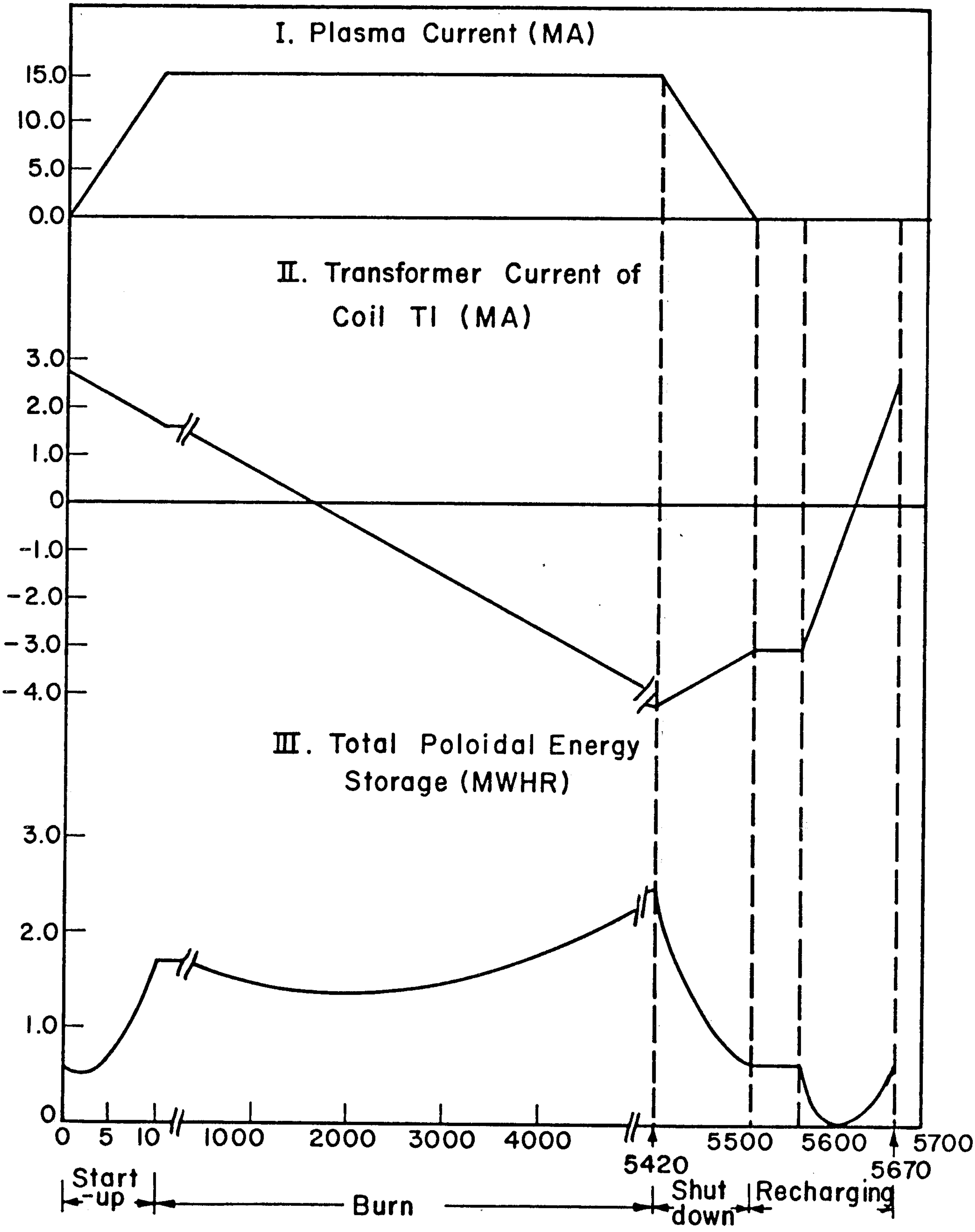

Figure 3 ---- Power Requirements During Start-up, Burn, Shut-down and Recharging Periods. Note the Difference of Time Scale in Each Period.

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