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PRIMARY LOOP CONDITIONING AND DESIGN CONSTRAINTS OF Li–Pb COOLED TANDEM MIRROR REACTORS DURING START-UP/SHUTDOWN OPERATIONS

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Engineering considerations during start-up/shutdown operations, and during transients induced by power level variations are considered in this paper. Flooding of cold blanket modules with hot Li–Pb results in severe strain transients that may lead to fatigue failure. The entire primary system, including blanket modules, must therefore be pre-conditioned. We first analyze, and present results of design, for a pre-heat system for the Mirror Advanced Reactor Study (MARS). The pre-heat system is based on helium gas pre-heating for the primary piping and blanket modules. Operational transients induced by partial power variations, or by loss of fusion power are then considered. It is found that the response of the primary loop system is dictated by how fast pumps can accommodate power fluctuations. Pump transients are modeled with a focus on the time dependent power balance through the pump system. Time constants for a representative pump are also derived. Finally, the situation of a total loss of pump power is investigated. In this case, natural circulation due to boyancy pressure differences is shown to be sufficient for the removal of decay afterheat immediately after a loss of pump power.

1. Introduction

It is being recognized that conceptual fusion reactor designs must demonstrate the ability to accommodate operational scenarios, as a part of the design basis. Recently, the design study, START [1], at UCLA, has focused on this particular question. The objectives of the study are the analysis, design and performance evaluation of both Tandem Mirror and Tokamak reactors during start-up/shutdown operation. In a companion paper [2], we have demonstrated the necessity of primary loop/blanket system pre-heating. In this paper, we investigate design issues related to the transient performance of the primary loop/blanket system. In particular, we perform analysis for the following:

(1) Primary loop/blanket system conditioning and pre-heating.
(2) Primary loop pump transients due to partial power variations.
(3) Design of a decay heat removal system for a total loss of pump power.

In section 2, we discuss primary loop/blanket pre-heating. This includes an analysis of the various pre-heating options, and the design of a gas pre-heating system. Section 3 is concerned with the analysis of pump transients. In section 4 we present the results of calculations for the use of natural circulation as a means for removal of decay afterheat. Finally, conclusions and recommendations are presented in section 5.

2. Blanket/primary loop pre-heating

It is shown in a companion paper [2] that freezing of the coolant during initial flooding is not a severe problem and may not cause any serious blockage. The thermal stresses induced during initial startup, however, were found to exceed the ultimate stress. This suggests that preheating is needed for the blanket and the primary loop.

2.1. Pre-heating options

Two preheating options are considered here: electrical and gas preheating. Each option will be investigated with respect to its feasibility, and its compatibility with the blanket and primary loop design considerations.

2.1.1. Electrical preheating

Consideration has been given to electrically heat the

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blanket and the primary loop. Neutron effects on electric heaters make blanket modules inaccessible for this method of heating. The primary loop, however, may be heated electrically (e.g., strap heaters). Subsequently, heat may be conducted through the primary piping into the blanket. Our analysis indicates that this heating method requires very long times as well as extremely high temperatures outside the blanket in order to maintain the blanket temperature high enough (i.e., about 350 °C). It is obvious here that the heat conducted into the blanket should at least be equal to the heat loss of the blanket to the environment. The heat loss of one blanket module is estimated to be about 85 kW at 400 °C. For the sections of the primary pipe just before the blanket modules, the following relation holds.

$$k\left(\frac{\partial T}{\partial z}\right)_{\text{primary pipe}}=\frac{q_{\text{loss}}}{2A_{\text{c,pipe}}},\tag{1}$$

where $A_{\text{c,pipe}}$ is the cross-sectional area of the primary pipe and Q_{loss} is the heat loss for one blanket module. Assuming that the pipe size is 30″ O.D. and 2″ thick, we obtain:

$$\frac{\partial T}{\partial z}=200\ \text{K/cm},\tag{2}$$

It is clear that such large temperature gradient requires extremely high temperatures outside the blanket. Therefore, it is concluded that preheating based on conduction alone is not feasible.

2.1.2. Gas pre-heating

Convective heating by hot gas has been considered as a method of preheating the primary loop and the blanket. In this method hot gas is pumped through the primary piping and the blanket. It is assumed that each primary (preheating) loop serves 6 blanket modules and there are 14 such loops. In this section performance of such a system will be investigated.

2.2. Gas selection criteria

Before modeling the preheating system, it is appropriate to conduct an investigation on the performance of different gases as preheating fluids. Among the parameters to be considered are: reactivity with LiPb and with HT-9, diffusion into the wall, price, and pumping power. One possible criterion based on pumping power is to select the gas that requires the least pumping power for the same heat transfer capability. It should be noted here that we are not relying on the pumping power to heat up the primary loop. Therefore, it is logical to try to minimize the pumping power since a higher pumping requires a larger pump.

2.2.1. Pumping power figure of merit

Consider a hot gas flowing through a pipe with inner diameter D and length L. Fig. 1 shows the physical model. The objective here is to express the pumping power in terms of the thermophysical properties of the gas. Pumping power is related to pressure drop as:

$$P=\frac{\pi}{4}D^2V_g\Delta p,\tag{3}$$

where

$$\Delta p=f\frac{L}{D}\tfrac{1}{2}\rho_g V_g^2.\tag{4}$$

The friction factor, f, for a turbulent flow may be written in terms of Reynolds number as:

$$f=0.413\ \text{Re}^{-1/4},\tag{5}$$

where

$$\text{Re}=\rho_g V_g D/\mu_g.\tag{6}$$

Combine eqs. (3)–(6) to obtain:

$$P=0.1622\mu_g^3 L\ \text{Re}^{2.75}/\rho_g^2 D^2.\tag{7}$$

The heat transfer relation for turbulent flow inside a pipe is

$$\text{Nu}=\frac{q''D}{k_g(T_g-T_w)}=0.023\ \text{Re}^{0.8}\text{Pr}_g^{0.33}.\tag{8}$$

The Reynolds number may be eliminated from eqs. (7) and (8) to obtain:

$$P=6.94\times10^4\frac{\mu_g^3 LD^{1.44}q''^{3.44}}{\rho_g^2 k_g^{3.44}(T_g-T_w)^{3.44}\text{Pr}_g^{1.13}}.\tag{9}$$

A figure of merit based on pumping power may then be

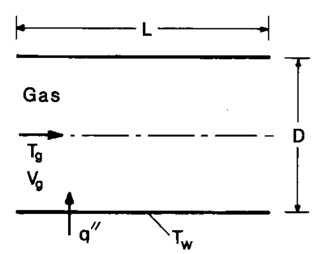


Fig. 1. Model for gas selection criterion based on pumping power.

Table 1
Data on various preheating gases [3]

Gas selection criteria	He	Ar	N_2
• Reactivity with LiPb	None	None	None
• Reactivity with tubes	None	None	Stainless steel
• Diffusion into walls	None	None	None
• Price $/100 SCF	9.25	7.50	5.00
• Pumping power (figure of merit) $F \times 10^{-8}$	7.69	1.48	0.417

defined as

$$F=\frac{1}{P}=1.44\times10^{-5}\frac{\rho_g^2 k_g^{3.44}(T_g-T_w)^{3.44}\mathrm{Pr}_g^{1.13}}{\mu_g^2 L D^{1.44} q''^{3.44}}. \quad (10)$$

$$F \propto \rho_g^2 k_g^{3.44}\mathrm{Pr}_g^{1.13}/\mu_g^3 \quad (11)$$

2.2.2. Gas selection data [3]

The gases considered are He, Ar and N_2. Table 1 lists the relevant data for these gases. It is seen that, except for the pumping power, Ar and He gases are equally satisfactory. The pumping power figure of merit for He, however, is seen to be about 5 times higher which means that helium is an overall better heat transfer fluid.

2.3. Modeling for gas preheating

Fig. 2 shows the preheating diagram. The preheating loop consists of the gas heater, primary pipes and the blanket. The hot gas leaving the gas heater passes through 1/2 of the primary pipes before entering the blanket. Subsequently, the gas passes through the remaining half of the pipes before entering the gas heater. The following simplifying assumptions are made in analyzing the model.

(1) No heat is lost from the primary pipes.
(2) Each half of the pipes are represented by an average temperature (i.e., $T_{p,1}$ and $T_{p,2}$).
(3) The temperature of the gas in each component is assumed to be the average of the temperatures of gas entering and exiting
(4) Temperature of the hot gas leaving the gas heater is constant and does not vary with time.

2.3.1. Formulation

Each primary loop consists of four components: the first half of the pipes, the blanket, the second half of the pipes, and the gas heater. The hot gas transfers heat to the pipes and the blanket while it receives heat from the heater. Simple energy balance equations may be written for each component to relate the gas temperature drop to the temperature rise in the component.

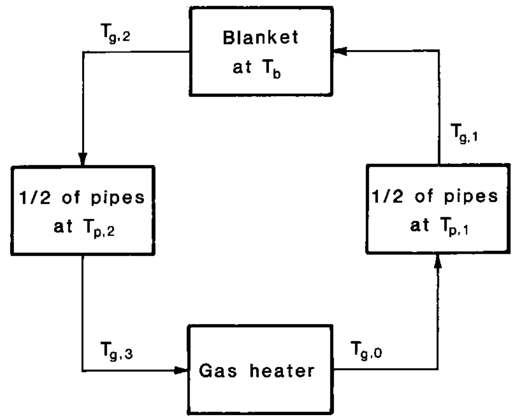


Fig. 2. Gas pre-heating model for primary loop and blanket.

2.3.2. First half of pipes

$$q_{p1}=\pi D_p L_p h_p\left(\frac{T_{g,0}+T_{g,1}}{2}-T_{p1}\right), \quad (12)$$

$$q_{p1}=\dot{m}_g c_{p,g}(T_{g,0}-T_{g,1}), \quad (13)$$

$$q_{p1}=m_{p1}c_{p,p}\frac{dT_{p1}}{dt}. \quad (14)$$

Eq. (12) represents heat transfer between the pipes and the gas. Eq. (13) the heat loss to the gas temperature drop. Finally, eq. (14) relates the heat transfer rate to the rise in the pipe temperature. Here subscripts p and p1 relate to primary pipe and first half of the primary pipe, respectively.

2.3.3. Second half of pipes

Similar equations may be written for the second half of the pipes.

$$q_{p2}=\pi D L_p h_p\left(\frac{T_{g,2}+T_{g,3}}{2}-T_{p2}\right), \quad (15)$$

$$q_{p2}=\dot{m}_g c_{p,g}(T_{g,2}-T_{g,3}), \quad (16)$$

$$q_{p2}=m_{p2}c_{p,p}\frac{dT_{p2}}{dt}. \quad (17)$$

2.3.4. Blanket

Heat is transfered from the gas to the tubes and the beams and thereafter to the reflector, the shield and eventually to the environment. The heat transfer rate may be written in terms of the gas average temperature and the tube inside temperature (blanket inside temperature, T_{bi}),

$$q_b = nA_t h_t \left(\frac{T_{g,1} + T_{g,2}}{2} - T_{bi} \right), \tag{18}$$

where n is the number of blanket modules per preheating loop. The heat transfer rate may also be written in terms of the temperatures of the gas and the blanket as:

$$q_b = \dot{m}_g c_{p,g} (T_{g,1} - T_{g,2}), \tag{19}$$

$$q_b = nm_b c_{p,b} \frac{dT_b}{dt} + nA_{bo} h_{bo} (T_{bo} - T_e). \tag{20}$$

The second term in the right hand side of eq. (20) accounts for the heat loss to the ambient. T_b represents the blanket average temperature. Assuming that steady state temperature profile exists in the blanket, T_b may be written in terms of inside and outside temperatures of the blanket as (T_{bi} and T_{bo}, respectively):

$$T_b = \gamma_1 T_{bi} + \gamma_2 T_{bo}, \tag{21}$$

where

$$\gamma_1 = 1 + \left[\ln\left(r_{bo}^2/r_{bi}^2\right)\right]^{-1} - \left(1 - r_{bi}^2/r_{bo}^2\right)^{-1}, \tag{22}$$

and

$$\gamma_2 = \left(1 - r_{bi}^2/r_{bo}^2\right)^{-1} - \left[\ln\left(r_{bo}^2/r_{bi}^2\right)\right]^{-1}. \tag{23}$$

The blanket inside and outside temperature are also related through the heat transfer rate as

$$q_b = nA_{bi} k_b \frac{T_{bi} - T_{bo}}{r_{bi}(\ln r_{bo}/r_{bi})}. \tag{24}$$

There are 11 unknowns: $T_{g,1}$, $T_{g,2}$, $T_{g,3}$, T_{p1}, T_{p2}, T_{bi}, T_{bo}, T_b, q_{p1}, q_{p2}, q_b and 11 equations (eqs. (12)–(21) and (24)) to be considered. Therefore a solution may be obtained. The boundary and initial conditions are as follows:

$$T_{g,0} = \text{const.}, \qquad t > 0, \tag{25}$$

$$T_{p1} = T_{p2} = T_{bi} = T_{bo} = T_b = T_i \qquad t = 0. \tag{26}$$

2.3.5. Solution

Since the equations contain several parameters, the

Table 2
Definition of constants used throughout eqs. (27)–(37)

$a_1(\pi D_p L_p h_p)^{-1}$	$a_2 = (\dot{m}_g c_{p,g})^{-1}$
$a_3 = (m_{p1} c_{p,p})^{-1}$	$a_4 = 2a_3/(2a_1 + a_2)$
$a_5 = a_2 a_4/a_3$	$a_6 = a_4 a_5$
$a_7 = a_5(T_{g,0} - T_i)$	$b_1 = (nA_t h_t)^{-1}$
$b_2 = (\dot{m}_g c_{p,g})^{-1}$	$b_3 = (nm_b c_{p,b})^{-1}$
$b_4 = (nA_{bo} h_{bo}) b_3$	$b_5 = (r_{bi}/A_{bi} k_b) \ln(r_{bo}/r_{bi})$
$b_6 = (2b_1 + b_2)/2$	$b_7 = 1 + b_5/b_6$
$b_8 = b_5/b_6$	$b_9 = b_3/b_6 + b_4 b_8$
$b_{10} = \gamma_1 + \gamma_2 b_7$	$b_{11} = b_4 b_7 + b_3/b_6$
$b_{12} = b_{11}/b_{10}$	$b_{13} = b_9/b_{10}$
$b_{14} = (\gamma_2 b_8 a_6 - b_9 a_5)/b_{10}$	$b_{15} = b_{13}/b_{12}$
$b_{16} = b_{14}/(b_{12} - a_4)$	$b_{18} = b_{16}(T_{g,0} - T_i)$
$b_{17} = (1 - b_4/b_{12})T_i - b_{15} T_{g,0} - b_{16}(T_{g,0} - T_i)$	
$b_{19} = b_{15} T_{g,0} + (b_{14}/b_{12}) T_i$	$b_{20} = [b_1(1/2b_1 + 2/b_2)]^{-1}$
$b_{21} = (1/b_2 - 1/2b_1)/(1/2b_1 + 1/b_2)$	$b_{22} = b_{20} b_{19} + b_{21} T_{g,0}$
$b_{23} = b_{20} b_{17}$	$b_{24} = b_{20} b_{18} - b_{21} a_7$
$b_{25} = b_7 b_{19} - b_8 T_{g,0}$	$b_{26} = b_7 b_{18} + b_8 a_7$
$c_1 = (\pi D_p L_p h_p)^{-1}$	$c_2 = (\dot{m}_g c_{p,g})^{-1}$
$c_3 = (m_{p2} c_{p,p})^{-1}$	$c_4 = (c_1/c_3 + c_2/2c_3)^{-1}$
$c_5 = c_4 b_{22}$	$c_6 = c_4 b_{23}$
$c_7 = c_4 b_{24}$	$c_8 = c_5/c_4$
$c_9 = c_6/(c_4 - b_{12})$	$c_{10} = c_7/(c_4 - a_4)$
$c_{11} = T_i - c_8 - c_9 - c_{10}$	$c_{12} = (1/c_2 - 1/2c_1)/(1/2c_1 + 1/c_2)$
$c_{13} = [c_1(1/2c_1 + 1/c_2)]^{-1}$	$c_{14} = c_{12} b_{22} + c_{13} c_8$
$c_{15} = c_{12} b_{23} + c_{13} c_9$	$c_{16} = c_{12} b_{24} + c_{13} c_{10}$
$c_{17} = c_{13} c_{11}$	

solution may become complicated, unless appropriate constants are defined. The definitions of constants are given in table 2. The results for the unknowns in terms of series of the constants a, b, and c are written as:

$$T_{g,1} = T_{g,0} - a_7 \, e^{-a_4 t}, \tag{27}$$

$$T_{g,2} = b_{22} + b_{23} \, e^{-b_{12} t} + b_{24} \, e^{-a_4 t}, \tag{28}$$

$$T_{g,3} = c_{14} + c_{17} \, e^{-c_4 t} + c_{15} \, e^{-b_{12} t} + c_{16} \, e^{-a_4 t}, \tag{29}$$

$$T_{p1} = T_{g,0} - \left(T_{g,0} - T_i\right) e^{-a_4 t}, \tag{30}$$

$$T_{p2} = c_8 + c_{11} \, e^{-c_4 t} + c_9 \, e^{-b_{12} t} + c_{10} \, e^{-a_4 t}. \tag{31}$$

$$T_{bi} = b_{19} + b_{17} \, e^{-b_{12} t} + b_{18} \, e^{-a_4 t}, \tag{32}$$

$$T_{bo} = b_{25} + b_7 b_{17} \, e^{-b_{12} t} + b_{26} \, e^{-a_4 t}, \tag{33}$$

$$T_b = \left(\gamma_1 b_{19} + \gamma_2 b_{25}\right) + \left(\gamma_1 b_{17} + \gamma_2 b_7 b_{17}\right) e^{-b_{12} t} + \left(\gamma_1 b_{18} + \gamma_2 b_{26}\right) e^{-a_4 t}, \tag{34}$$

$$q_{p1} = \left(a_4/a_3\right)\left(T_{g,0} - T_i\right) e^{-a_4 t}, \tag{35}$$

$$q_{p2}\left(T_{g,2} - T_{g,3}\right)/c_2, \tag{36}$$

$$q_b = \left(T_{g,1} - T_{g,2}\right)/b_2. \tag{37}$$

In addition, the power and energy required by the gas heater may be calculated as:

$$P_g = \dot{m}_g c_{p,g}\left(T_{g,0} - T_{g,3}\right), \tag{38}$$

$$E_g = \int_0^t P_g \mathrm{d}t. \tag{39}$$

2.3.6. Gas preheating results

In order to perform a sample calculation for the transient response of the preheating loop, the following assumptions are made:

(1) there are six blanket modules served by each loop ($n = 6$),
(2) the inner diameter of the primary pipe = 0.66 m.
(3) preheating gas is He,
(4) gas velocity in blanket = 5 m/s,
(5) primary pipe length = 862 m,
(6) temperature of gas leaving the heater = 500 °C.

Table 3 lists the values of all parameters for the MARS blanket design. Fig. 3 shows the transient temperature for each component. They all start initially at room temperature and increase with time. It is seen that it takes about 51 minutes for the temperature inside the blanket to reach the desired 350 °C. Obviously this time becomes shorter as the temperature of the hot gas leaving the gas heater is increased. Fig. 4 shows the power and the total energy required for the gas heater. It is seen that the power starts at a maximum value of about 10 MW and thereafter decreases with time. For the preheating period of 51 min, about 5.3 MWh of energy is needed. Next the pumping power will be estimated.

2.3.7. Pumping power

The required pumping power is proportional to the volume flow rate and the pressure drop as:

$$P = \frac{\dot{m}_g}{\rho_g} \Delta P. \tag{40}$$

Table 3
Parameters for MARS blanket

Parameter	Definition	Value
A_t	Tube and beam heat transfer area per module (m^2)	1.38×10^2
V_t	Gas velocity in the blanket (m/s)	5.00
h_t	Heat transfer coefficient in tubes and beam (W/m^{2}K)	2.02×10^1
$\dot{m}_g$	Gas flow rate (kg/s)	5.42
h_p	Heat transfer coefficient in the pipe (W/m^{2}K)	1.76×10^2
$2L_p$	Total length of the primary pipes per loop (m)	6.16×10^1
$2m_p$	Total mass of the pipes per loop (kg)	2.80×10^4
m_b	Mass of one blanket module, (based on a $2m$ long module) (kg)	3.40×10^3
A_{bo}	Outside area of one blanket module (m^2)	2.32×10^1
h_{bo}	Heat transfer coefficient outside blanket, (W/m^{2}K)	1.00×10^1
r_{bo}	Outside radius of blanket (m)	1.84
r_{bi}	Inside radius of blanket (m)	6.00×10^{-1}
k_b	Thermal conductivity of blanket (W/mK)	1.95×10^1
$c_{p,g}$	Heat capacity of gas (helium) (J/kgK)	5.20×10^3
$c_{p,p}$	Heat capacity of the pipes (J/kgK)	5.60×10^2
n	Number of blanket modules per loop	6

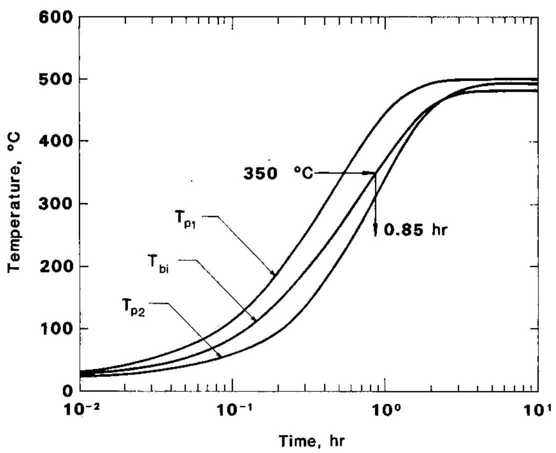


Fig. 3. Transient temperatures of the blanket and the primary pipes during pre-heating with He at 500 °C.

The pressure drop is the summation of the losses in the pipes and the blanket,

$$\Delta p = \Delta p_p + \Delta p_b, \tag{41}$$

where

$$\Delta p_p = f \frac{2 L_p}{D_p} \tfrac{1}{2} \rho_g V_p^2, \tag{42}$$

$$\Delta p_b = f \frac{L_t}{D_t} \tfrac{1}{2} \rho_g V_t^2. \tag{43}$$

For the case considered here

$$\Delta p_p = 1.23 \times 10^3 \text{Pa}, \tag{44}$$

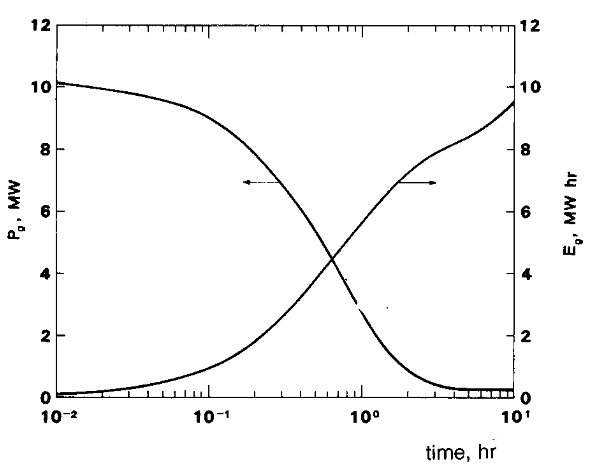


Fig. 4. Power requirements for gas pre-heating.

$$\Delta p_b = 9.30 \times 10^{-1} \text{Pa}. \tag{45}$$

From eq. (40) the pumping power is calculated as

$$P = 5.02 \times 10^4 \text{W}. \tag{46}$$

3. Analysis of pump transients

3.1. Modeling

In this section the effect of fluid acceleration on pump transients is studied. Special consideration is given to pump startup. Assuming that the torque (electrical) is generated instantaneously, a transient power balance may be written as

$$P = Q \Delta p + \frac{\mathrm{d}}{\mathrm{d}t}(E_f) + \frac{\mathrm{d}}{\mathrm{d}t}\left[\tfrac{1}{2} I_p (2\pi N)^2\right] + \tau_{fric}(2\pi N), \tag{47}$$

where

P = applied power,
Q = volumetric flow rate,
Δp = pressure drop,
E_f = kinetic energy of the fluid,
I_p = moment of inertia of the pump moving parts,
N = pump speed (revolution per unit time)
τ_{fric} = frictional torque exerted on the pump moving parts.

The last two terms in eq. (47) depend on the size and characteristics of the pump and have to be supplied by the manufacturer for each pump.

Frictional losses may be written in terms of the total power by defining a pump efficiency as

$$\eta_{pump} = \frac{P - \tau_{fric} 2\pi N}{P} = 1 - \frac{\tau_{fric} 2\pi N}{P}, \tag{48}$$

or

$$\tau_{fric} 2\pi N = (1 - \eta_{pump}) P. \tag{49}$$

Because information is not available on pump characteristics, it is appropriate to assume a constant efficiency during any transient process. Employment of eq. (49) in eq. (47) yields,

$$\eta_{pump} P = Q \Delta p + \frac{\mathrm{d}}{\mathrm{d}t}(E_f) + \frac{\mathrm{d}}{\mathrm{d}t}\left[\left(\tfrac{1}{2} I_p (2\pi N)^2\right]. \tag{50}$$

The pressure drop in a closed loop may be written as:

$$\Delta p = K_1 Q. \tag{51}$$

The kinetic energy of the fluid and the pump moving parts may also be written as:

$$E_f = K_2 Q^2, \tag{52}$$

$$\tfrac{1}{2} I_p (2\pi N)^2 = K_3 Q^2. \tag{53}$$

Substitution of eqs. (51)–(53) in eq. (50) yields a relation which governs the transient flow rate Q.

$$\eta_{\text{pump}} P = K_1 Q^2 + (K_2 + K_3) \frac{dQ^2}{dt}. \tag{54}$$

The following initial conditions apply:

$$Q = Q_0, \quad P = P_0 = (K_1/\eta_{\text{pump}}) Q_0^2 \quad \text{at } t = 0, \tag{55}$$

$$P = P_1 = (K_1/\eta_{\text{pump}}) Q_1^2 \quad \text{at } t > 0, \tag{56}$$

where Q_1 is the steady state value corresponding to P_1. Eq. (54) with initial condition (55) and (56) may be solved for $Q(t)$ as:

$$Q^2(t) = Q_1^2 - (Q_1^2 - Q_0^2) \exp\{-K_1 t/(K_2 + K_3)\}. \tag{57}$$

In terms of powers, $Q(t)$ can be written alternatively as:

$$Q^2(t) = \frac{\eta_{\text{pump}}}{K_1} [P_1 - (P_1 - P_0) \exp\{-K_1 t/(K_2 + K_3)\}]. \tag{58}$$

In the special case of startup (zero initial power) that is $P_0 = 0$, eq. (58) reduces to

$$Q^2(t) = \frac{\eta_{\text{pump}} P_1}{K_1} (1 - \exp\{-K_1 t/(K_2 + K_3)\}). \tag{59}$$

It should be noted that $(K_2 + K_3)/K_1$ is the characteristic time of the system and is a measure of how fast the flow rate changes.

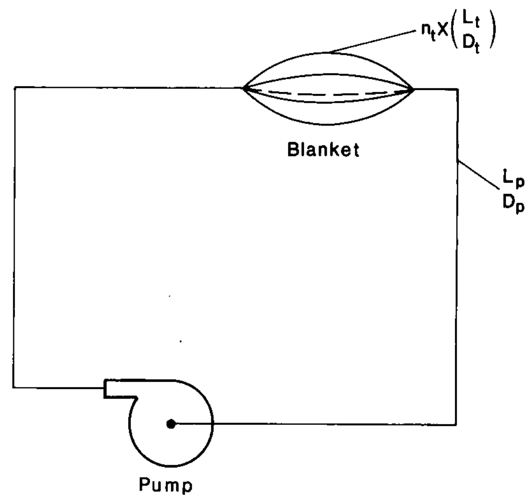
3.2. Evaluation of the Constants K_1, K_2, and K_3

In the MARS blanket design, each primary loop serves 6 modules. The coolant flows through the primary pipes and the blanket tubes and beams. Although the tubes and beams have different sizes, they could very well be represented by an average size. Fig. 5 shows the simplified primary loop configuration.

3.2.1. The constant K_1

Total pressure drop in the primary loop is the summation of those in the primary pipe and in the blanket

$$\Delta p = \Delta p_p + \Delta p_b. \tag{60}$$



DP	DIAMETER OF PRIMARY PIPE	0.66 M
NT	NUMBER OF TUBES AND BEAMS PER LOOP	912
LT	AVERAGE LENGTH OF TUBE	2.50 M
DT	AVERAGE DIAMETER OF TUBE	0.10 M

Fig. 5. Schematic of the primary loop.

The pressure drop in the pipe is due to friction losses, that is,

$$\Delta p_p = f \frac{L_p}{D_p} \tfrac{1}{2} \rho V_p^2, \tag{61}$$

where

$$f = \frac{64}{\text{Re}} = \frac{64\mu}{\rho V_p D_p}. \tag{62}$$

Substitution of eq. (62) in eq. (61) yields

$$\Delta p_p = 32 \mu L_p V_p / D_p^2. \tag{63}$$

In terms of volume flow rate, Q,

$$\Delta p_p = \frac{128}{\pi} \frac{\mu L_p}{D_p^4} Q. \tag{64}$$

The pressure drop in the blanket is due to MHD effects [4] and is given by:

$$\Delta p_b = 2 V_t B^2 \sigma_w \delta_w L_t / D_t \tag{65}$$

The velocity in the tube can be written in terms of the total volume flow rate, Q, as:

$$Q = n_t \frac{\pi}{4} D_t^2 V_t. \tag{66}$$

Eliminating V_t from eqs. (65) and (66) yields the following:

$$\Delta p_b = \frac{8}{\pi n_t} \frac{B^2 \sigma_w \delta_w L_t}{D_t^3} Q. \quad (67)$$

Using eqs. (64) and (67), the total pressure drop may be written from equation (60) as:

$$\Delta p = K_1 Q, \quad (68)$$

where

$$K_1 = \frac{128}{\pi} \frac{\mu L_p}{D_p^4} + \frac{8}{\pi n_t} \frac{B^2 \sigma_w \delta_w L_t}{D_t^3}. \quad (69)$$

3.2.2. The constant K_2

The kinetic energy of the coolant flowing in the primary loop is written as:

$$E_f = \tfrac{1}{2}\rho\left(\frac{\pi}{4}D_p^2\right)L_p V_p^2 + n_t\left\{\tfrac{1}{2}\rho\left(\frac{\pi}{4}D_t^2\right)L_t V_t^2\right\}. \quad (70)$$

The velocities V_p and V_t are written in terms of Q as:

$$Q = \frac{\pi}{4}D_p^2 V_p = n_t \frac{\pi}{4} D_t^2 V_t. \quad (71)$$

The velocities V_p and V_t may be eliminated from eqs. (70) and (71) to obtain:

$$E_f = K_2 Q^2, \quad (72)$$

where

$$K_2 = \frac{2}{\pi}\rho\left(L_p/D_p^2 + L_t/n_t D_t^2\right). \quad (73)$$

3.2.3. The constant K_3

The kinetic energy of the pump moving parts is written as:

$$E_p = \tfrac{1}{2} I_p (2\pi N)^2. \quad (74)$$

In centrifugal pumps the flow is proportional to the pump speed according to homologous theory [5], which yields:

$$2\pi N = K_4 Q. \quad (75)$$

The constant K_4 depends on the pump characteristics and may be obtained from data furnished by the pump manufacturer. Introduction of eq. (75) in eq. (74) yields:

$$E_p = K_3 Q^2, \quad (76)$$

where

$$K_3 = \tfrac{1}{2} I_p K_4^2. \quad (77)$$

3.3. Numerical results

As it was mentioned before, the primary loop has a characteristic time of $(K_2 + K_3)/K_1$ (see eq. (57)). Here we are interested in the numerical values of K_1, K_2, and K_3 for the MARS blanket. The constants K_1 and K_2 are calculated as:

K_1 from eq. (69)

$$K_1 = 33.5 + 4.39 \times 10^5 = 4.40 \times 10^5 \text{ kg/m}^4\text{s}. \quad (78)$$

K_2 from eq. (73)

$$K_2 = 8.42 \times 10^5 + 1.63 \times 10^3 = 8.43 \times 10^5 \text{ kg/m}^4. \quad (79)$$

In order to obtain numerical value for the constant K_3, we will use manufacturer's data on a similar pump [6]. The inertia is assumed to be about 64 kg m^2. For the constant K_4, assuming a flow rate of 8360 GPM at 857 RPM, we calculate,

$$K_4 = \frac{2\pi \times 857 \text{ RPM}}{8360 \text{ GPM}} = 170 \text{ 1/m}^3. \quad (80)$$

The constant K_3 is calculated from eq. (77) as

$$K_3 = \tfrac{1}{2} \times 64 \times (170)^2 = 9.25 \times 10^5 \text{ kg/m}^4. \quad (81)$$

The characteristic time may now be calculated as,

$$(K_2 + K_3)/K_1 = 4.02 \text{ s}. \quad (82)$$

Apart from the numerical result for the characteristic time, two observations may be made from the calculations. From the calculations for K_1 (eqs. (69) and (78)), it is clear that the MHD pressure drop is dominant and the pressure drop in the primary pipes is negligible. This will minimize the error due to the assumption that the flow in the primary pipes is laminar. It should be noted from calculations for K_2 (eqs. (73) and (79)), that the kinetic energy of the coolant in the blanket is negligible with respect to the total kinetic energy.

4. Natural circulation in LiPb cooled fusion reactor

4.1. Introduction

In this section the possibility of natural circulation in the MARS blanket and its primary loop is investigated. In the event of loss of pump power, the fusion power may be shut off immediately but heat deposition will continue in the blanket structure in the form of decay afterheat (~ 1% of full power). It is desired that the decay afterheat be removed by natural circulation.

Natural circulation is caused by buoyancy forces and has long been considered in pressurized and boiling water reactors [7]. There, the water vaporizes and creates a large density difference (large buoyancy forces) which results in natural circulation. In the MARS blanket, where the coolant is LiPb, however, there is no phase change. Therefore, the buoyancy forces are relatively small and are due only to thermally induced density difference only. In all the above cases heat must be removed during coolant circulation. In a BWR the vapor generated is discharged at the top of the core and is replaced by cold water. For LiPb cooled fusion reactors, heat must be removed by passing the coolant through a steam generator or a special water tank. Fig. 6 shows the schematic of such an arrangement. It should be noted that the position of heat sink is critical and should be at the highest elevation in order to generate natural circulation.

4.2. Analysis

The driving force for natural circulation is the buoyancy force. It has to overcome the frictional and magnetic forces opposing the circulation. Therefore, for any given situation the circulation rate is determined by balancing the buoyancy and opposing forces:

$$\Delta p_B = \Delta p_M + \Delta p_F, \tag{83}$$

where Δp_B is pressure difference due to buoyancy forces and Δp_M and Δp_F are pressure losses due to magnetic forces and friction, respectively. Assuming that flow is laminar, pressure drop due to friction may be written as:

$$\Delta p_F = C_F Q, \tag{84}$$

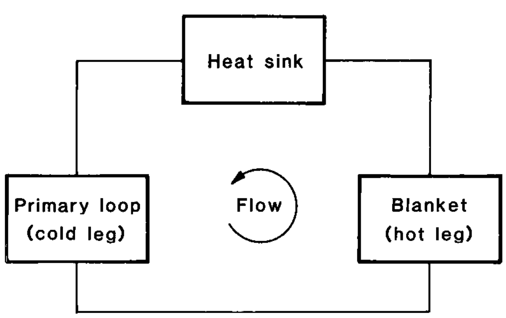


Fig. 6. Schematic of natural circulation arrangement.

where Q is the volume flow rate. The magnetic pressure drop is written as

$$\Delta p_M = C_M Q. \tag{85}$$

The pressure difference due to buoyancy, ΔP_B, is caused by the density difference between the hot and cold legs, that is:

$$\Delta p_B = g\int_0^{H_p}(\rho_C - \rho_H)\mathrm{d}z \tag{86}$$

$$= g\rho\beta\int_0^{H_p}(T_H - T_C)\mathrm{d}z, \tag{87}$$

where H_p is the length of the hot or cold legs in the direction of the gravity. Having a constant heat generation rate, the temperature increase is proportional to the inverse volume flow rate,

$$\Delta p_B = C_B Q^{-1}, \tag{88}$$

where C_B, the proportionality constant, should be obtained for each individual case. Substitution of eqs. (84), (85) and (88) in eq. (83) yields the following for the volume flow rate, Q.

$$Q = [C_B/(C_F + C_M)]^{1/2}. \tag{89}$$

Next we will obtain parametric relations for the constants C_F, C_M, and C_B.

4.2.1. Evaluation of the constants C_F, C_M, and C_B

Fig. 7 shows the physical model used to represent the MARS blanket and primary loop. The following assumptions are made:

(1) Blanket tubes and beams are approximated by an average straight tube (H_b, D_b).
(2) Heat deposition rate is constant (no spatial variation across the tubes and beams).
(3) Heat sink is located at an elevated point.
(4) Heat is removed at the rate generated.

4.2.2. Friction losses, C_F

Pressure drop due to frictional losses in a pipe may be written in terms of the volume flow rate. Assuming a laminar flow:

$$\Delta p_F = f\frac{L_p}{D_p}\tfrac{1}{2}\rho V_p^2, \tag{90}$$

where

$$f = 64/\mathrm{Re} = 64\mu/\rho V_p D_p, \tag{91}$$

$$Q = \frac{\pi}{4}D_p^2 V_p. \tag{92}$$

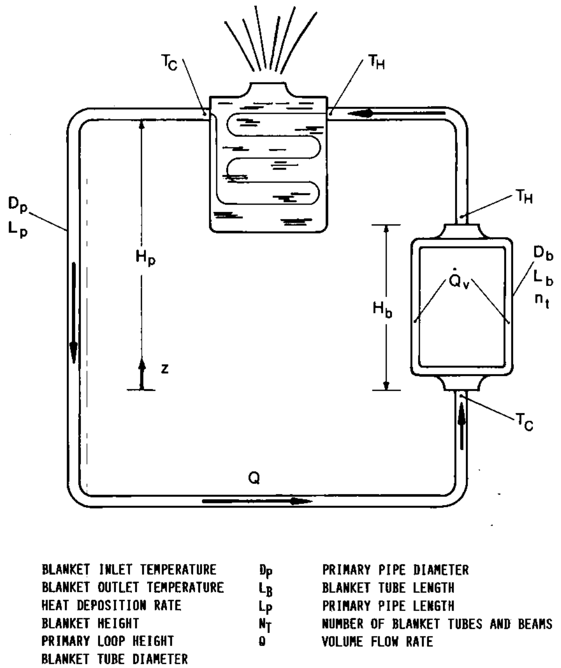


Fig. 7. Physical model representing MARS blanket and primary loop.

Substitution of eqs. (91) and (92) in eq. (90) yields the following:

$$\Delta p_F = C_F Q, \tag{93}$$

where

$$C_F = 128\mu L_p/\pi D_p^4. \tag{94}$$

4.2.3. MHD pressure drop, C_M

Pressure drop due to MHD forces of a flow of conducting liquid in a thin conducting pipe is written as [4]

$$\Delta p_M = \frac{2B^2\sigma_w\delta_w H_b}{D_b} V_b. \tag{95}$$

The velocity in the blanket, V_b, is written in terms of the total volume flow rate as:

$$Q = \frac{\pi}{4} D_b^2 n_t V_b, \tag{96}$$

where D_b and H_b in eqs. (95) and (96) are diameter and length of an average tube in the blanket. Substitution of eq. (96) in eq. (95) yields:

$$\Delta p_M = C_M Q,$$

where

$$C_M = 8B^2\sigma_w\delta_w H_b/\pi n_t D_b^3. \tag{97}$$

4.2.4. Buoyancy pressure difference, C_B

The pressure drop due to difference in fluid temperatures in hot and cold legs is written from eq. (87) as

$$\Delta p_B = g\rho\beta\left\{(H_p - H_b)(T_H - T_C) + \int_0^{H_b}[T_H(z) - T_c]\mathrm{d}z\right\}. \tag{98}$$

The difference in fluid temperatures may be written in terms of heat generation rate through an energy balance on the blanket as:

$$T_H(z) - T_c = \frac{\pi}{4}\frac{n_t \dot{Q}_v D_b^2}{\rho c_p Q} z. \tag{99}$$

Substitution of eq. (99) in eq. (98) and integration yields:

$$\Delta p_B = C_B Q^{-1}, \tag{100}$$

where

$$C_B = \frac{\pi}{4}\frac{\beta g n_t \dot{Q}_v D_b^2 H_b}{c_p}(H_p - H_b/2). \tag{101}$$

4.2.5. Coolant and wall maximum temperature

It is important that the temperature of the coolant and the structural material do not exceed their limits. Maximum coolant temperature occurs at the blanket outlet. The decay afterheat is mainly generated in the tube wall and has to be transfered to the coolant. This results in a tube temperature higher than the coolant temperature. The coolant exit temperature is obtained from eq. (99) as

$$T_H = T_c + \frac{\pi}{4}\frac{n_t \dot{Q}_v D_b^2 H_b}{\rho c_p Q}. \tag{102}$$

In order to obtain the wall temperature, the heat transfer coefficient on the coolant side has to be known. The coolant flow in the blanket tubes may be considered as slug flow, that is a flow with uniform velocity and no turbulence. This approximation is valid for flow of liquid metals under the influence of strong magnetic fields. Neglecting the heat lost to the environment, the wall condition is assumed to be a constant heat flux since all the heat generated within the tube material has to be transfered to the coolant. The surface heat flux is obtained by writing an energy balance.

$$\pi D_b q'' = \frac{\pi}{4} D_b^2 \dot{Q}_v. \quad (103)$$

For a slug flow and constant heat flux, it can be easily shown that a Nusselt number defined as:

$$\mathrm{Nu} = \frac{q'' D_b}{k(T_{wall} - T_H)}, \quad (104)$$

is equal to 8[8]. The wall temperature is obtained by combining eqs. (103) and (104) as:

$$T_{wall} = T_H + \dot{Q}_v D_b^2 / 4\,\mathrm{Nu}\,k, \quad (105)$$

where

$$\mathrm{Nu} = 8, \quad (106)$$

for slug flow in circular tubes.

4.3. Numerical results for MARS blanket

Table 4 lists the values of the necessary parameters for the MARS blanket. Assuming that the decay afterheat is some fraction of the heat deposition rate at full power, that is:

$$\dot{Q}_v = \eta \langle \dot{Q}_{v,fp} \rangle. \quad (107)$$

The following numerical results are obtained from equations (89)–(106).

$$C_B = 1.04 \times 10^4 \eta \text{ kgm}^2/\text{s}^3, \quad (108)$$

$$C_M = 3.66 \times 10^5 \text{ kg/m}^4\text{s}, \quad (109)$$

$$C_F = 3.33 \times 10^1 \text{ kg/m}^4\text{s}, \quad (110)$$

$$Q = 0.168 \eta^{1/2} \text{ m}^3/\text{s}, \quad (111)$$

$$T_H = 350 + 980 \eta^{1/2} \text{ °C}, \quad (112)$$

$$T_{wall} = 350 + 980 \eta^{1/2} + 258 \eta \text{ °C}. \quad (113)$$

Fig. 8 shows the dependence of Q, T_H, and T_{wall} on the fraction of full power, η. Often, the practical limit is for the temperature of the structural material. For the MARS blanket this limit is set at 500 °C. It is seen from fig. 8 that decay afterheat up to 2.3% of the full power heat deposition rate is removed by natural circulation while the wall temperature remains below the 500 °C limit.

4.4. Heat sink requirements

Heat should be removed from the coolant at the rate generated in the blanket. It may be assumed that the heat is removed by generating steam. The rate of steam generated can be written as:

$$\dot{m}_w h_{fg} = \rho Q c_p (T_H - T_C), \quad (114)$$

$$\dot{m}_w = 83.1 \eta \text{ kg/s}. \quad (115)$$

Let's consider decay afterheat at a rate of 1% full power heat deposition, $\eta = 0.01$. Then the feed water rate is calculated as

$$\dot{m}_w = 0.83 \text{ kg/s (0.83 litre/s)}. \quad (116)$$

Table 4
Values of the parameters for the MARS planket

Parameter	Value
T_c (°C)	350
$\langle \dot{Q}_{v,fp} \rangle$ * (W/m^3)	13.7×10^6
H_b (m)	3
H_p (m)	10
D_b (m)	0.1
D_p (m)	0.66
L_p (m)	62
n_t	912
ρ (kg/m^3)	9350
β (K^{-1})	0.78×10^{-4}
c_p (J/kg K)	159
B (T)	4.7
σ_w (mho)	0.95×10^6
δ_w (m)	0.0025
μ (kg/ms)	0.0025

* Averaged across the tubes and beams

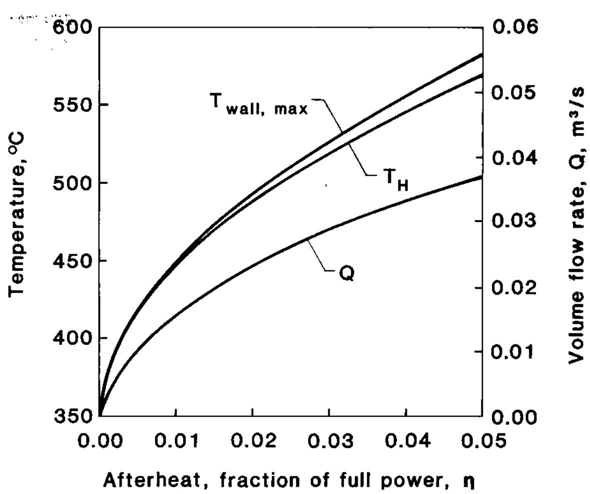


Fig. 8. Variation of heat transfer parameters as a function of afterheat fraction of full power.

If no feedwater is available, then one may rely on the water inventory in the steam generator. For a typical steam generator (say 1.30 m^3 water capacity), the dryout time may be calculated as

$$t_{dryout} = 1570 \text{ s}. \quad (117)$$

That is the water inventory can accommodate the heat sink requirements for about 26 min.

5. Summary and conclusions

In this paper, consideration has been given to primary loop conditioning and design constraints during startup and shutdown. Included are blanket and primary loop preheating, analysis of pump transients, and natural circulation in Li–Pb cooled blankets in the event of loss of pumping power.

It is concluded that the primary loop should be preheated and that the gas preheating method is the most feasible one. Helium is found to be suitable for preheating. Having a gas supply temperature of 500 °C, and desiring the blanket temperature to reach 350 °C, it is estimated that 51 min of preheating is necessary.

Pump transients are also analyzed. The inertia of the moving parts of the pump is estimated from manufacturer's data on a typical liquid metal pump. It is observed, rather surprisingly, that the response time is relatively short, on the order of seconds.

Consideration is given to natural circulation as a removal mechanism for afterheat in the event of loss of pumping power. It is shown that afterheat may be removed by natural circulation without experiencing extreme temperatures in the coolant and blanket if a heat sink is provided at an elevated position in the primary loop.

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References

[1] R.W. Conn et al., A study of start-up and fractional power operation of tandem mirror fusion reactors, UCLA Report PPG-764 (1983).

[2] K. Taghavi and N.M. Ghoniem, Transient thermal-hydraulics considerations of tandem mirror Li–Pb cooled blankets during start-up/shutdown operations, Nucl. Engrg. Des./Fusion 1 (1984) 369, this issue.

[3] Yevick, Editor, Fast Reactor Technology: Plant Design (MIT Press, 1966).

[4] B. Badger et al., WITAMIR-I, a tandem mirror reactor study (1980).

[5] V.L. Streeter and E.B. Wylie, Fluid Mechanics, 6th ed. (McGraw-Hill, New York, 1975).

[6] R.W. Atz, private communication, Rockwell International Corporation (1983).

[7] M.M. El-Wakil, Nuclear Heat Transport (International Textbook Company, 1971).

[8] E.R.G. Eckert and R.M. Drake, Analysis of Heat and Mass Transfer (McGraw Hill, New York, 1972).