ELSEVIER

Fusion Engineering and Design 29 (1995) 43–50

Fusion Engineering and Design

Using the shield for thermal energy storage in pulsar

G.T. Sager [a], D.-K. Sze [b], C.P.C. Wong [a], C.G. Bathke [c], J.P. Blanchard [d], C. Brimer [e], E.T. Cheng [f], L.A. El-Guebaly [d], M.Z. Hasan [g], F. Najmabadi [h], S. Sharafat [g], I.N. Sviatoslavski [d], L. Waganer [e]

[a] *General Atomics, PO Box 85608, San Diego, CA 92186-9784, USA*
[b] *Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439, USA*
[c] *Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[d] *University of Wisconsin at Madison, Madison, WI 53706, USA*
[e] *McDonnell Douglas Aerospace, PO Box 516, Mail Code 3064204, St. Louis, MO 63166-0516, USA*
[f] *TSI Research Inc., 225 Stevens Avenue, Suite 203, Solana Beach, CA 92075, USA*
[g] *University of California at Los Angeles, Los Angeles, CA 90024, USA*
[h] *University of California at San Diego, San Diego, CA 92037, USA*

Abstract

The PULSAR pulsed tokamak power plant design utilizes the outboard shield for thermal energy storage to maintain full 1000 MW(e) output during the dwell period of 200 s. Thermal energy resulting from direct nuclear heating is accumulated in the shield during the 7200 s fusion power production phase. The maximum shield temperature may be much higher than that for the blanket because radiation damage is significantly reduced. During the dwell period, thermal power discharged from the shield and coolant temperature are simultaneously regulated by controlling the coolant mass flow rate at the shield inlet. This is facilitated by throttled coolant bypass. Design concepts using helium and lithium coolant have been developed. Two-dimensional time-dependent thermal hydraulic calculations were performed to confirm performance capabilities required of the design concepts. The results indicate that the system design and performance can accommodate uncertainties in material limits or the length of the dwell period.

1. Introduction

The PULSAR design study [1,2] has evaluated the pulsed, inductively driven tokamak power plant to assess whether economies can be attained which are more favorable than those of the steady state, non-inductively driven tokamak. In an idealized sense, the operating cycle of the pulsed tokamak consists of a "burn" phase, during which fusion power is produced by a plasma with confinement sustained in part by an inductively driven plasma current. The burn phases are separated by a "dwell" phase consisting of plasma termination, transformer recharge and plasma start-up. Systems code analysis has identified an optimal operating cycle consisting of a 2 h fusion power burn phase and a dwell phase lasting about 200 s. Tokamak power plants which retain this pulsed output characteristic face severe technological and economical barriers to acceptance. Market and regulatory forces are likely to bar entry of a baseline-sized 1000 MW(e) plant with pulsed electric output to the distribution grid [3]. Thermal cycling of heat transport and power conversion

SSDI 0920-3796(94)00388-2

equipment would require development of new technologies [4]. In order to eliminate these impediments, thermal energy storage (TES) is required to provide uniform electrical output and minimize thermal cycling of the balance-of-plant equipment.

Two design requirements are specified for the TES system for PULSAR: it must be sufficiently large to discharge about 500 GJ at a steady rate of about 2500 MW(t) and it must deliver the working fluid at a constant temperature to the primary heat exchanger. Several conventional TES systems were evaluated during the PULSAR study. A new concept utilizing the outer shield appeared to satisfy the above energy storage requirements best.

The shield TES concept exploits the indigenous volumetric nuclear heating in the shield to store heat directly during the burn phase and utilizes coolant mass flow control to regulate the thermal output during the dwell phase. The concept possesses several key features. Heat is directly deposited in the shield. No inefficiencies associated with heat transfer to external systems are incurred. The shield is large, about twice the size of all blankets in PULSAR. It may be operated at a significantly higher temperature than the blanket because radiation damage is reduced in the shield. Similarly, material selection is less impacted by radiation damage considerations. Thus, while the shield must be designed as a high power heat exchanger, these combined features make the shield thermal storage concept very attractive.

The shield TES concept was developed for PULSAR variants employing helium coolant and silicon carbide fiber–matrix composite (SiC–SiC) structural material and lithium coolant and vanadium alloy structural material. In Section 2 the alternative concepts considered during the study are summarized. The shield TES concept and operation are described qualitatively in Section 3. Design descriptions and thermal analyses of the helium- and lithium-cooled shield TES systems are provided in Section 4. Estimates of additional equipment and incremental costs are given in Section 5. Several critical issues and impediments which must be resolved are described in Section 6. Section 7 contains the conclusions of the study.

2. Alternative thermal energy storage concepts

Several thermal energy storage systems have been developed for other energy technologies (e.g. solar energy and industrial furnaces) or investigated in previous conceptual studies of fusion power plants (e.g. [5,6] respectively). Those which possess large energy capacity, high power and temperature capabilities were reviewed. These concepts are storage of the hot working fluid and sensible or latent heat storage in secondary media in an external reservoir.

Storage of the hot working fluid [6] utilizes external reservoirs into which a side stream of hot coolant is diverted during the burn phase. During the dwell phase, the accumulated coolant is discharged to the primary heat exchanger and collected in separate cold reservoirs. Helium, lithium and sodium working fluids were considered. The low volumetric heat capacity and the high pressure and temperature of helium resulted in unacceptable costs and safety concerns. Use of sodium (in an intermediate loop) or lithium may be acceptable but is considered an alternative owing to safety concerns about increased liquid-metal and tritium inventories.

Energy storage of sensible heat in an external reservoir of secondary media involves heat transfer from a primary coolant side stream during the burn phase and heat transfer from the secondary media to the primary coolant during the dwell phase. The secondary media may be selected for optimal storage properties (e.g. thermal conductivity, volumetric heat capacity and cost). Sensible heat transfer during charge and discharge of the system results in a maximum achievable coolant temperature during discharge which is significantly lower than that during the burn phase. Minimizing this differential leads to large storage units with large heat transfer surface areas. The temperature differential can be further reduced by directing the entire primary coolant stream through the system during well and burn phases. This option reduces the average operating temperature and increases pumping requirements. Either option would significantly expand the plant nuclear facility envelope.

Some advantages, relative to external storage of sensible heat, may be obtained by utilizing external molten salt systems to store energy as latent heat [7]. These advantages may include reduced temperature drop and smaller system size. However, heat transfer is impeded by heterogeneous solid- and liquid-phase formation. Agitators and other forms of control have been investigated, but the added complexity is detrimental to the system [8]. Furthermore, postulated decomposition and subsequent media replacement during the 40 year operating life of the system may adversely impact plant availability.

3. Conceptual description

Fig. 1 shows schematically the coolant flows during the burn phase of the helium-cooled variant (the

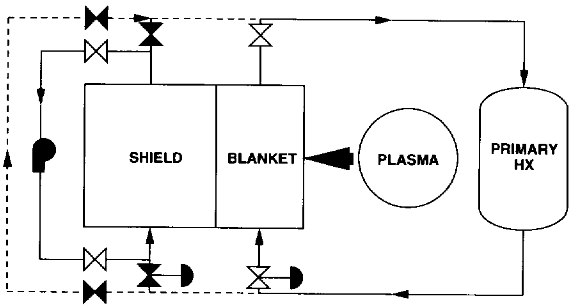

Fig. 1. Schematic diagram of coolant flow paths during the burn phase for the helium-cooled variant. Heat is accumulated in the shield and uniformly redistributed with recirculating low velocity coolant. Closed valves are highlighted with shaded icons. Inactive coolant paths are shown as broken lines for clarity.

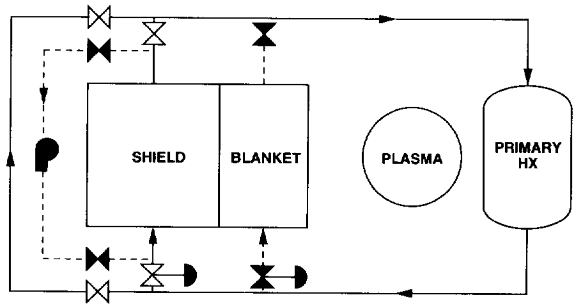

Fig. 2. Schematic diagram of coolant flow paths during the dwell phase for the helium-cooled variant. The blanket is isolated. Thermal energy discharge from the shield is regulated by controlling the coolant mass flow rate with a throttle valve. Closed valves are highlighted with shaded icons. Inactive coolant paths are shown as broken lines for clarity.

lithium-cooled variant is similar). Heat discharged from the blanket and inner shield comprises the entire energy delivered to the primary heat exchanger. Gate valves isolate the outer shield from the primary coolant stream. Low velocity coolant is circulated in a closed loop to equilibrate the heat distribution throughout the shield which otherwise would be concentrated at the front where nuclear heating is peaked. The shield is sized such that the energy accumulated in the shield is equal to the energy discharged during the dwell phase. On the assumptions that the plant has reached thermal equilibrium [1] and the shield is perfectly insulated,

$$P_{\text{shield}} = \frac{\tau_{\text{dwell}}}{\tau_{\text{burn}}} P_{\text{th}} \tag{1}$$

where P_{shield} is the thermal power generated in the outer shield, τ_{dwell} is the dwell time, τ_{burn} is the burn time and P_{th} is the average thermal power of the plant.

The coolant flows during the dwell phase of the helium-cooled variant are shown schematically in Fig. 2. The blanket is isolated from the primary coolant flow, thus minimizing thermal cycling. (Some provision may be required to accommodate decay heating of a few per cent of full power.) Gate valves open, aligning the outer shield with the primary coolant flow. Thermal discharge from the shield is regulated by controlling mass flow rates, utilizing a bypass to accommodate the residual coolant flow. Basic mass and energy conservation properties ensure that the primary coolant delivers steady state thermal power at constant temperature to the primary heat exchanger. As the discharge phase progresses, the mass flow rate of coolant entering the shield increases to accommodate the reduction in the bulk shield temperature. Once the bypass flow has been completely choked, maximizing the flow through the shield, the coolant temperature and heat transfer rate cannot be simultaneously regulated. This maximum thermal discharge length must exceed the dwell time and will be regarded as a measure of the feasibility of a given design.

[1] Initial start-up from cold conditions requires net energy flows into the shield by external heating or partial power operation over several cycles until thermal equilibrium is reached. At thermal equilibrium, the shield temperature field is periodic with period given by the burn–dwell cycle length.

4. Shield design and thermal–mechanical performance

Key properties of the helium- and lithium-cooled variants are listed in Table 1. Basic configurations were selected on the basis of considerations of mechanical integrity, fabricability and reliability. Structural and bulk shielding materials were selected on the basis of the aforementioned considerations and anticipated thermal and radiation shielding requirements.

The helium-cooled shield, shown in Fig. 3, is a nested shell configuration consisting of several SiC–SiC composite shells containing coolant channels of 1 cm in diameter oriented in the poloidal direction. The voids between the shells are filled with a ternary sphere pack of silicon carbide (85% packing fraction). The neutron spectrum and fluence in the shield induces helium production in SiC at the end of the life which is lower by a factor of about 40 than that in the first wall or blanket. This reduced gas production is key to the high

Table 1
Key properties for shield thermal analysis

	Helium cooled	Lithium cooled
Tokamak geometry		
Major radius R (m)	7.8	7.5
Minor radius a (m)	1.95	1.88
TES shield geometry		
Volume (m^3)	1120	856
Estimated height (m)	12	11.7
Coolant channel configuration	Circular	Annular
Coolant channel diameter (m)	0.01	0.024
Channel wall thickness (m)	0.001	0.004
Coolant volume fraction (%)	10	10
Structure volume fraction (%)	15	15
Packed-bed volume fraction (%)	75	75
Fusion thermal power (MW)	2260	2302
Length of burn phase (s)	7200	7200
Length of dwell phase (s)	200	200
Coolant	He, 10 MPa	Li
T_{inlet} (°C)	350	300
T_{outlet} (°C)	750	600
Material properties		
Structure	SiC–SiC composite	V alloy
Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	17	28
Volumetric heat capacity ($\times 10^6\ J\ m^{-3}\ K^{-1}$)	3.84	3.66
Temperature limit (°C)	1300	750
Operating temperature (°C)	≤950	≤725
Packed bed	SiC, 80% ternary sphere pack	80% Tenelon, 20% lithium
Effective thermal conductivity ($W\ m^{-1}\ K^{-1}$)	15	22.6
Effective volumetric heat capacity ($\times 10^6\ J\ m^{-3}\ K^{-1}$)	3.26	6.32

temperature capability of the helium-cooled shield. Packed-bed thermal conductivity is based on sintered Hitaceram SC-101 (70 $W\ m^{-1}\ K^{-1}$ at 1000 °C) and accounts for sphere pack gap resistance and irradiation to fluence of 3×10^{24} neutrons m^{-2}.

The lithium-cooled shield, shown in Fig. 4, is an annular tube-in-shell configuration consisting of uniformly distributed vanadium annular cylinders (10 cm outer diameter) contained in a vanadium shell. The cylinders contain flowing lithium in the annular region. The remaining voids are filled with Tenelon spheres at 80% packing fraction, immersed in lithium to improve the thermal conductivity of the packed bed. Key elements in the design are the high temperature limit for the vanadium structure and the use of lithium in the packed bed. Estimates of end-of-life neutron damage (21 displacements per atom (dpa)) and helium production (9 at.ppm) for vanadium in the shield are about two orders of magnitude smaller than the postulated limits. Consequently, the temperature limit (750 °C) for vanadium alloy is higher than that for the first-wall and blanket components (700 °C). Circulation of lithium through the packed bed in the tokamak magnetic field is expected to be quite difficult and thus precludes continuous tritium extraction. Use of natural lithium (the reference choice) results in a cumulative production of about 5.6 kg of tritium in the shield after 30 full power years. The maximum tritium inventory in the stagnant lithium is limited by diffusion to the circulating lithium. Simple mass transfer analysis, assuming a diffusion barrier factor of 100 due to the nitride coating in the coolant tube, indicated that the equilibrium tritium partial pressure is about 10^{-7} Torr. For PULSAR-II this corresponds to a tritium inventory of about 70 g, which is expected to have an insignificant impact on the overall safety properties. Non-breeding liquid metals, sodium, potassium and NaK were also considered. Sodium and NaK were found to be unacceptable owing to excessive production of ^{24}Na, which led to a preliminary safety rating of LSA 3. Nucleate boiling

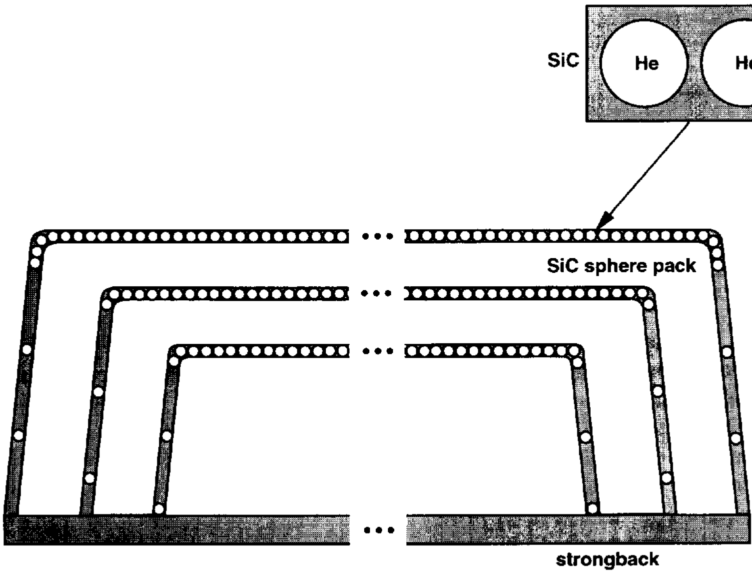

Fig. 3. Schematic diagram of a nested shell configuration (midplane cross-section) for the helium-cooled variant. Poloidally flowing helium is contained in channels imbedded in SiC–SiC composite shells. Silicon carbide sphere pack fills the void between shells.

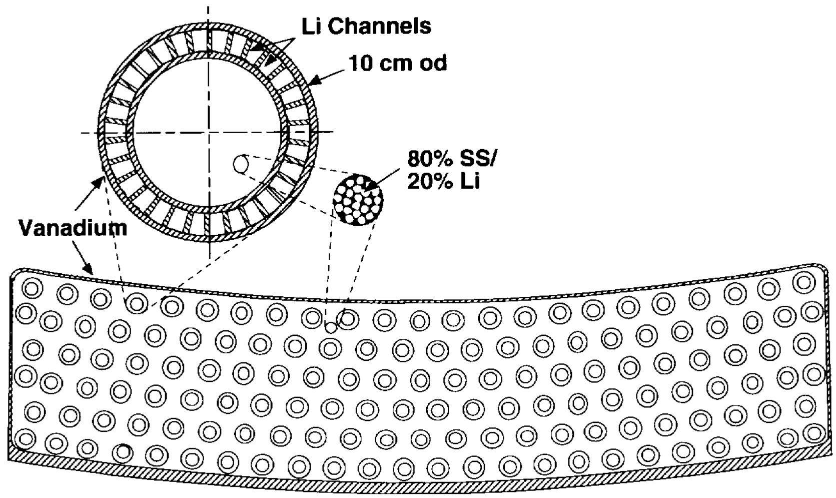

Fig. 4. Schematic diagram of the tube-in-shell configuration (midplane cross-section) for the lithium-cooled variant. Poloidally flowing lithium is contained in annular channels. Voids are filled with Tenelon sphere pack immersed in liquid lithium.

of stagnant potassium (boiling point, 760 °C) in the packed bed introduces significant uncertainties in heat transfer performance owing to void formation. Pressurization of the shield module to suppress boiling was considered but introduces new accident modes. Therefore use of potassium is reserved in the event that other considerations yield lithium unacceptable.

The TES shield must absorb enough nuclear heating during burn (cf. Eq. (1)) and provide adequate shielding of the superconducting magnets (summarized in Table 2). One-dimensional neutronics analysis was performed with the ONEDANT code [9] to determine outboard blanket thickness, which influences the total shield heating, and the shield thickness which influences magnet shielding.

Table 2
Radiation limits for superconducting magnets

Peak fast neutron fluence to Nb_3Sn (neutrons cm^{-3})	10^{19}
Peak nuclear heating in winding pack ($mW\ cm^{-3}$)	2
Total nuclear heating (kW)	50
Peak dose to GGF polyimide insulator (rad)	10^{11}
Peak dpa in Cu stabilizer (dpa)	6×10^{-3}

Thermal performance of the shield was assessed by simulating thermal discharge from a single average coolant channel with two-dimensional time-dependent thermal hydraulic calculations using the TAC2D code [10]. The calculations account for axial variations in the coolant properties and axial and radial variations in the packed bed and tube temperature fields. The total heat transferred to the coolant was regulated by adjusting the inlet coolant mass flow rate throughout the discharge simulation.

The thermal performance of the reference helium-cooled shield is summarized in Fig. 5. The curve plotted against the left-hand ordinate depicts the fraction of the total primary coolant mass flow rate directed through the shield. The fractional mass flow rate never exceeds unity during the dwell phase. This is an indication that the reference case possesses excess heat transfer capability. This capability could be utilized by decreasing the shield operating temperature or the number of coolant channels, at the expense of increasing the pumping power (shown plotted against the right-hand ordinate).

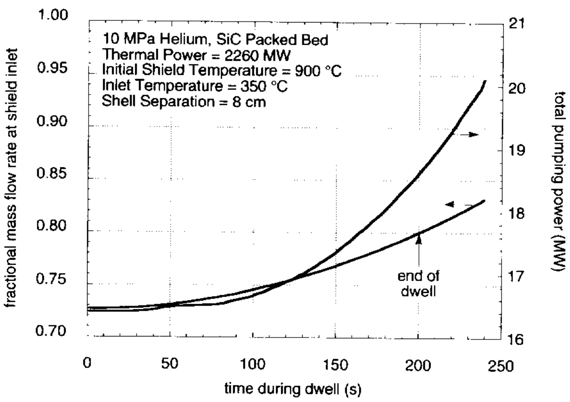

Fig. 5. Characteristic thermal performance of reference helium-cooled variant during the dwell phase. The required thermal performance is confirmed because the fractional mass flow rate remains below unity throughout discharge.

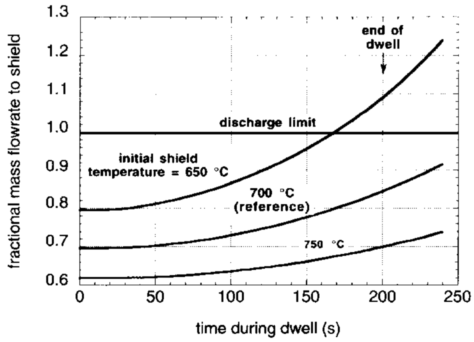

Fig. 6. Characteristic thermal performance of reference lithium-cooled variant during the dwell phase. The required thermal performance is confirmed because the fractional mass flow rate remains below unity throughout discharge.

The reference case represented a compromise between these competing properties and results in a system less sensitive to uncertainties in material limits or heat transfer properties.

The thermal performance of the reference lithium-cooled shield is summarized in Fig. 6, which shows the fractional mass flow rate schedule required to sustain full thermal power discharge during the dwell phase. The fractional mass flow rate remains below unity throughout the phase; thus heat transfer capability is sufficient to satisfy the temperature and power criteria. Also shown are flow rate schedules, assuming other initial shield temperature fields. The results suggest that a reasonably large temperature window exists for operation of the shield.

At the initiation of the dwell phase, 300–350 °C coolant is redirected through the 700–900 °C shield, inducing thermal stresses which are largest at the inlet. A transient thermal stress analysis was conducted to determine whether these stresses adversely limit the shield lifetime. The coolant tubes in the shields were modeled with a one-dimensional finite difference code, assuming azimuthal symmetry, in which the tube was free to expand in the axial direction, but it was not allowed to bend. The tube thickness was adjusted until the calculated stresses were below fatigue limits for the shield lifetime. A conservative limiting case in which the coolant temperature instantaneously dropped from 900 to 350 °C was considered for the helium-cooled variant. Wall thicknesses of 1–2 mm satisfy the stress limits and, when compared with the 1 mm design value, indicate some margin against uncertainties. Stresses due to 300 °C coolant at the lithium-cooled shield inlet were expected to exceed fatigue life limits. In order to reduce these stresses, the coolant is routed through the blanket

Table 3
Additional shield equipment required for thermal energy storage

Component	Quantity	He-cooled shield	Li-cooled shield
Temperature			
Homogenized circuit			
Circulator–pumps	34	8 in, 1 kW	6 in
Gate valves	34	8 in	6 in
Piping	320 m	8 in insulated Incaloy at 900 °C	6 in insulated ferritic at 650 °C
Main shield piping			
Gate valves	34	24 in	10 in
Throttle valves	34	24 in	10 in
		8 in	6 in
Piping	64 m	12 in insulated ferritic at 350 °C	6 in insulated ferritic at 300 °C
	256 m	20 in insulated ferritic at 350 °C	10 in insulated ferritic at 300 °C
	192 m	24 in insulated Incaloy at 900 °C	10 in insulated ferritic at 650 °C
	32 m		10 in insulated ferritic at 600 °C

before entering the shield during the dwell phase. The resulting coolant temperature at the shield inlet decays approximately linearly from 600 to 300 °C in about 40 s. Under these conditions, the stresses are much less severe than for the helium-cooled variant and shield lifetime will be limited by other forces.

5. Incremental costs

In order to assess the economic impact of utilizing the outer shield for thermal energy storage, cost estimates were obtained for the additional equipment required for operation. Table 3 lists auxiliary equipment considered. Equipment was sized to accommodate the most demanding hydraulic requirements during operation, at the end of the burn and dwell phases. Circulators and piping required for heat redistribution during the burn phase were sized to limit the maximum temperature difference in the helium-cooled shield to less than 200 °C. The total incremental costs of the shield TES is about US $\$(5-10) \times 10^6$, an insignificant fraction of the total PULSAR capital cost.

6. Critical issues

Use of the shield for thermal energy storage introduces several issues, both generic to TES systems and specific to the shield concept, which are aggravated by the shield proximity to the tokamak. Although several issues have been identified during the course of the study, a detailed design effort will be required to develop a complete characterization of critical issues. The shield retains many critical issues of the blanket and first wall connected with uncertainties of material properties and damage subject to cyclic loading, high temperature and radiation fluence. Although the expected end-of-life fluence is significantly smaller for shield components, these impacts are difficult to assess and could be comparable with those in the blanket and first wall.

The mechanical design of the shield is likely to be more difficult. Cyclic thermal expansion must be accommodated by mechanical attachments to support structures. Some coolant transport equipment including manifolds, valves and bypass piping will be located close to the shield. Component layout must account for penetrations and integration with adjacent components (e.g. magnets and vacuum vessel) and be compatible with maintenance requirements. Thermal insulation resistant to radiation damage will be required.

The shield concept requires a somewhat complex thermal control system of pumps, valves and bypass pipes. A systematic and comprehensive study is required to design the control system completely. This would include hardware specification, configuration and reliability. Control concepts and software must be developed for start-up from cold conditions and approach to equilibrium and account for all important system properties. For instance, coolant mass transfer delays which can induce a large thermal stress on the shield structure are particularly important for the lithium-cooled variant. Fault conditions (e.g. loss of flow) must be identified and actively or passively controlled.

7. Conclusions

Thermal energy storage is required to remove technological and economical impediments for the acceptance of an inductively driven tokamak with pulsed electrical power input. The helium- and lithium-cooled PULSAR fusion plants can use the outboard shield for thermal energy storage. The shield exploits direct nuclear heating, accumulating energy during the burn phase. Thermal energy discharge and coolant temperature are regulated simultaneously during the dwell phase by controlling the mass flow rate through the shield and an associated bypass.

Several key features favorably differentiate the shield TES concept from other concepts considered. Because the shield is located in a reduced radiation environment, it can be operated at a much higher temperature than the blanket. There is no reduction in coolant temperature inherent in indirect external storage schemes. The shield is an intrinsic component of the fusion plant and, consequently, does not lead to an expanded nuclear facility envelope to accommodate large heat exchangers or reservoirs required by other TES systems. Estimates of additional equipment required to configure and operate the shield have been obtained and insignificantly impact the total plant economics.

Thermal–mechanical and shielding analysis support the following observations. Robust design solutions exist for both the helium- and the lithium-cooled shield variants. A relatively large design window of operating temperatures and heat transfer configurations has been identified. Operating temperatures, heat transfer capabilities and thermal stresses of the reference designs are well within anticipated design limits. The thermal hydraulic properties of the two variants are quite different. The helium-cooled variant exploits high temperature capability and a large volume (required for radiation shielding). The more compact lithium-cooled variant exploits a high thermal conductivity Tenelon–lithium packed bed and large coolant volumetric heat capacity.

While these conceptual design studies have identified no feasibility issues, several design solutions would be required for successful deployment. These design issues, not addressed in the present study, include mechanical design compatible with thermal cycling and maintenance procedures, thermal insulation, thermal control, and fault detection and response.

Acknowledgments

This work was supported by the US Department of Energy under Contract DE-AC03-89ER52153.

References

[1] R.W. Conn et al., The requirements of a fusion demonstration reactor and the STARLITE study, Rep. UCLA-PPG-1394, 1992. (Institute of Plasma and Fusion Research, University of California at Los Angeles).

[2] The PULSAR Tokamak Design Study, Rep., in press (Institute of Plasma and Fusion Research, University of California at Los Angeles).

[3] Pulsed fusion reactor study, Rep. AEA FUS 205, 1992 (AEA Fusion).

[4] G.T. Sager et al., Limitations of power conversion systems under transient loads and impact on the pulsed tokamak power reactor, 15th IEEE–NPSS Symp. on Fusion Engineering, 1994.

[5] D.R. Glenn, Technical and economic feasibility of thermal energy storage, Rep. COO-2258-1, 1976 (General Electric Company).

[6] B. Badger et al., UWMAK-II: a conceptual tokamak power reactor design, Fusion Technology Program Tech. Rep. UWFDM-112, 1975 (University of Wisconsin).

[7] Y. Abe et al., Peak load coverage by molten salts latent thermal storage, Proc. IECEC, 1984, p. 1114.

[8] R.J. Petri et al., High temeprature composite thermal energy storage (TES) systems for industrial applications, Proc. IECEC, 1986, p. 873.

[9] R. O'Dell et al., User's manual for ONEDANT: a code package for one-dimensional, diffusion accelerated, neutral particle transport, Tech. Rep. LA-9184-M, 1982 (Los Alamos National Laboratory).

[10] R.H. Boonstra, TAC2D: a general purpose two-dimensional heat transfer computer code, Rep. GA-A14032, 1976 (General Atomics).