ORNL/TM-10194

ornl

OAK RIDGE NATIONAL LABORATORY

MARTIN MARIETTA

Application of Thermal and Flywheel Energy Storage in Orbiting Nuclear Burst Power Systems

R. P. Wichner
M. Olszewski

OPERATED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A08 Microfiche A01

ORNL/TM-10194

Engineering Technology Division

APPLICATION OF THERMAL AND FLYWHEEL ENERGY STORAGE IN ORBITING NUCLEAR BURST POWER SYSTEMS

R. P. Wichner
M. Olszewski

Date Published - March 1987

Notice: This document contains information of a preliminary nature. It is subject to revision or correction and therefore does not represent a final report.

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under Contract No. DE-AC05-84OR21400

CONTENTS

ACKNOWLEDGMENTS

A number of people have most willingly provided information to this survey for which the authors wish to express grateful acknowledgment. Theodore Mroz of NASA's Lewis Research Center provided an extensive description of the elements of NASA's Advanced Solar Dynamic Program. Steve Johnson, also of NASA Lewis, provided the description of the fabrication and development program for the Solar Dynamic electric power system conducted within the Space Station Program. Nanette Faget provided descriptive reports and discussion concerning related thermal storage effects at NASA's Johnson Space Center. We also wish to thank Rich Gay and Jan Ives of the Rocketdyne Division of Rockwell Corp. for discussions describing recent contributions to the Space Station Program. Information concerning flywheel research was provided by Claude Kickler of NASA's Langley Research Center and Ernie Rodriguez of the NASA Goddard Space Flight Center.

Within ORNL the authors are indebted to James Martin of the Engineering Technology Division for an overview of DOE sponsored thermal storage research, Richard Strehlow of the Chemistry Division for the information on electromagnetic energy storage, and to John Moyers of the Engineering Technology Division for numerous expert opinions particularly relating to thermodynamic cycles. We wish to express appreciation also to Roy Thoma, Energy Division, for discussion on molten salt compatibility. The potentially useful method for coupling a sensible heat reservoir to a thermodynamic cycle shown in Fig. 1.2 was devised by R. E. MacPherson (now retired), D. B. Lloyd and J. C. Moyers of the Engineering Technology Division. The authors are also indebted to David O'Kain for his overview of flywheel technology development activities at the Enrichment Technology Applications Center.

APPLICATION OF THERMAL AND FLYWHEEL ENERGY STORAGE IN ORBITING NUCLEAR BURST POWER SYSTEMS

R. P. Wichner
M. Olszewski

ABSTRACT

A survey was conducted of currently available thermal energy storage and flywheel energy storage technology and development programs as they may apply to nuclear-based, burst power systems. The manner in which such storage systems may be used in closed cycle, regenerable burst systems is described for a number of cases utilizing the Boiling Potassium Rankine and Dual Loop Lithium Cooled LMRs and the Direct Cycle Brayton HTGR. In general, energy storage devices for such systems enable use of smaller power system components by allowing continuous operation over the duration of both the bursts and the regeneration time. The degree of size reduction depends principally on the required regeneration time.

The requirements for both heat supply (front end) and cycle heat rejection storage are examined. It is concluded that the technology for front-end heat storage, which requires heat storage materials in the 1200 to 1600 K temperature range (and possibly higher for HTGR Brayton Cycle Systems) does not currently exist. A NASA advanced materials program, whose charter extends up to 1400 K, may ultimately provide technology support at the low end of the required temperature range. No current program is designed to extend this capability above 1400 K. Materials for cycle heat rejection storage, in the anticipated temperature range of about 700 to 1200 K, may be available from on-going development programs in support of solar dynamic power systems for the Space Station in solar receiver configurations. Enhanced capability for cycle heat rejection involves use of lithium hydride, which at this stage must be considered speculative in view of its tendency for dissociation and large volume change on melting. Some support for determining the feasibility of LiH use is being provided in a DOD program.

Flywheel energy storage in regenerable, nuclear-based burst power systems allows continuous operation of all the major power components which permits size reduction of the reactor, turbine-generator and heat rejection systems relative to nonstorage cases. Projected specific power requirements of 2.5 kWe/kg and stored energies of 450 kJ/kg, have, however, not been proven to date in NASA, DARPA or DOE programs. It is further observed that no flywheel energy storage development programs currently exist except for that projected by the MMW SDI Program.

1. INTRODUCTION

1.1 Objectives and Scope

The purpose of this report is to present an overview of current thermal and kinetic energy storage technology programs and to assess their relevancy to nuclear burst power systems. A companion but separate report by Argonne National Laboratory [Fee, S. C. (to be published)] covers the fuel cell energy storage option. When compared against SDI program needs, this survey would aid in the definition of the energy storage program requirements in a way which utilizes available technology and avoids duplication of effort.

Toward this goal, a general discussion of thermal and flywheel storage characteristics is provided in Sect. 1. For thermal storage, this general discussion includes an overview of potentially available storage materials, ranges of stored energy density and utilization temperatures, and broadly, anticipated compatibility behavior with container materials for each type of thermal storage material. A similar overview of flywheel energy storage is presented covering expected ranges of kinetic stored energy.

The manners in which thermal and flywheel energy storage devices may be applied to nuclear burst power systems are outlined in Sect. 2. Flowsheets for Boiling Potassium Rankine, Lithium Cooled Dual Loop LMR and HTGR Direct cycle Brayton Nuclear systems are shown for cases involving no energy storage, heat supply (front-end) and cycle heat rejection (back-end) thermal storage and flywheel energy storage. The effect of the energy storage option on the duty cycles of major systems components is shown on the presumption that the burst capability is regenerated over approximately one orbit cycle. Other assumed regeneration times would lead to qualitatively similar alterations in duty cycle resulting from the application of energy storage. This section also describes the type of thermal storage units required and estimated temperature ranges for which they must be applied.

Sections 3 and 4, respectively, summarize the thermal energy and flywheel storage programs of possible relevancy to SDI requirements.

The programs themselves, in this survey which covers past and current NASA, DOD and DOE development programs, are outlined in more detail in Appendices A through F. A preliminary evaluation is presented regarding the applicability of the energy storage technology developed by these programs to SDI nuclear burst power systems.

1.2 Application of Flywheel and Thermal Energy Storage in Orbiting Nuclear Energy Systems

This report presents a description of current development programs in thermal and kinetic energy storage technology and an evaluation of status and potential of each technology. A comparison is then presented relative to projected SDI burst systems requirements for the purpose of highlighting the principal areas of development required for nuclear-based burst power systems.

It is important to point out that the potential use of energy storage devices in such systems interacts strongly with the presumed system concept. This is true both qualitatively and quantitatively; i.e., both the manner in which an energy storage device is used and the operational conditions of the device depend on the nature of the system. Therefore, the conclusions presented here also depend strongly on the system type assumed at this time.

In this regard, the principal assumption adapted here is that a closed cycle nuclear system is employed to provide prime power which is then conditioned for the weapon's use. Closed cycle systems by their nature require heat rejection which may be either a thermal reservoir or a large radiator. It is further presumed that the burst systems are to be regenerated over some time period. For specificity, we have assumed regeneration within one orbit cycle, but assumed regeneration over any other time period would alter the discussion only qualitatively.

For a current view of closed cycle, nuclear burst power systems we have used information provided by a NASA LeRC/Sandia briefing held in Washington [J. Smith, et al. (March 1986)] and descriptions implied in the Multimegawatt Program Plan (April 1986) and a communication from W. H. McCulloch (May 1986). However, it is recognized that these systems concepts are in a rapidly evolutionary phase. The conclusions presented here regarding energy storage program needs would undoubtedly require re-evaluation at a time when systems concepts are more firmly set.

According to current terminology, the short bursts of electric power for weapons operation are provided by a power conditioning system supplied by prime power from a turbine/alternator driven by a nuclear reactor or from some intermediate energy storage device. Thus, energy storage considered in this report refers either to storage of the prime power for supply to the power conditioning units or to the storage of reject heat from the production of prime power in the thermodynamic cycle. However, the nature of energy storage by flywheels is such that it may provide both functions. Flywheels which store prime power may in principle also be designed to be downloaded in bursts if provided with a sufficiently large capacity generator. Thus, it may be possible or advantageous for flywheels to perform both energy storage and power conditioning.

A number of means for providing prime energy storage may be considered. The reactor output heat may be stored as latent or sensible heat by placement of a thermal storage device in the primary coolant loop. This is directly analogous to the thermal storage function added to solar receivers in solar dynamic power systems to provide shadow power. Alternatively, the nuclear power system may generate electric power which could then be stored either as mechanical energy in flywheels, chemical energy in batteries, in electromagnetic fields or as electrostatic energy within dielectric materials. This report deals with the first two storage devices, i.e., thermal storage and mechanical energy storage by means of flywheels. However, comparisons with the other prime storage methods are briefly touched on in Sect. 1.3.

Incentives for thermal storage in the primary system are the reduction of the required size of the nuclear reactor and the allowance of continuous reactor operation; i.e., the reactor and primary system would not need to be designed for repeated starts and stops for the duration in which bursts are required. However, use of thermal storage in the primary cooling system would still require burst mode operation of the energy conversion system. In contrast, flywheel energy storage and the other types of prime energy storage being considered, receive electric energy from the energy conversion system. Hence their use allows continuous operation of both the reactor and energy conversion systems for the duration in which burst energy is supplied. These considerations are reflected in the comparisons of the duty cycles of the major system components for burst systems with and without prime energy storage.

In contrast to a number of available methods for storing prime power, the nature of power production by thermodynamic cycles is such that reject heat at the back end may be stored only by thermal storage devices. The primary advantage to be gained by back-end cycle heat storage is a reduction in the size of the ultimate heat reject system to space. That is, the reject heat load to space may be distributed over the duration of regeneration instead of just during burst operation. This is accomplished by dumping the reject heat initially to a heat storage device which itself is cooled by a secondary system discharging heat to space. Doing so reduces the required radiator size, and may also serve to reduce the total heat rejection system weight. Some additional benefits resulting from back-end thermal storage may also be considered. A net increase in system hardness and lowered orbit drag would result from use of a smaller radiator; also procedures for in-orbit assembly may be eased or completely eliminated. It may also be true that use of back-end thermal storage results in optimization of the power system to a higher thermal efficiency by means of a reduction in the heat reject temperature. This would be accomplished by use of a somewhat larger radiator size than indicated by its improvement in duty cycle resulting from the use of the storage device.

1.3 Energy Storage Options and Ranges

1.3.1 Thermal Energy Storage (TES)

As described more fully in Sect. 2, thermal energy storage in orbiting nuclear energy systems may be used either as a high temperature energy reservoir for providing burst power, or as a sink for reject heat from the thermodynamic cycle. Application of energy supply or front end heat storage in burst mode operation permits use of smaller nuclear power plants, which is the main benefit to be traded against the added weight of the storage system. Similarly, application of TES for cycle heat rejection permits use of smaller radiators, which is the principal trade benefit against the added weight of the low temperature TES device. One should note that smaller radiators contribute benefits in several areas: (1) possible lower weight of the heat reject system, (2) smaller system size facilitating fabrication and assembly, (3) hardening of the system to impacts, (4) reduction of drag thereby reducing the rate of orbit decay. In addition, use of thermal storage in the heat reject system may lead to lower optimum values of the cycle reject temperature, which would in turn improve cycle thermal efficiency and reduce the size of the power supply.

At this stage, prior to performance of these trade-off studies, the temperature ranges of interest for front end or heat rejection TES can only be approximated. However, we may reasonably assume that heat rejection storage would optimize somewhere between 700 and 1200 K while front end TES would require temperatures in the 1300 to 1800 K range. In general, Brayton cycle systems using a recuperator would reject heat at the lower end of the cited temperature range, possibly even below 700 K. Rankine and Brayton cycle systems with no recuperation would likely optimize at a higher heat rejectors temperature, possibly in the 1000 to 1200 K range.

1.3.1.1 High Temperature Phase Change Materials (PCM's). Peak efficiencies of power cycles and components employed in power cycles are generally attained for a relatively narrow range of temperature, flow and fluid property conditions. Hence use of thermal storage components in thermodynamic cycles for either energy supply (front end) or for heat rejection most would conveniently employ a phase change material (PCM) at its transition temperature. Ideally, the PCM supplies or receives thermal energy near its transition temperature differing only by the temperature driving force required to effect the heat transfer. The PCM would be selected to yield the highest practical heat of transition per unit mass at the temperature required for the particular thermodynamic cycle.

The storage mechanism in this case is the internal energy difference due to the change in atomic rotational and translational kinetic energy caused by the transition between the solid and the liquid phase. Since the phase change is nearly isothermal and reversible, the latent heat is related to the entropy changed by change by

$$\Delta S_f = \frac{\Delta H_f}{T_f} , \qquad (1.1)$$

where ΔS_f and ΔH_f are respectively the entropy and the heat of fusion at the phase transition temperature, T_f.

<u>Metal and Alloy PCM's</u>. Most metals generally have fairly low entropies of fusion, indicative of small changes in atomic velocities across the phase transition. Figure 1.1 [Barol (1985)] illustrates the well-known rule that ΔS_f values for most metals lie between 6 and 10 (J/g-atom K). Nevertheless, metals are considered as candidate heat storage materials due to their high thermal conductivity and generally

ORNL DWG 86 4652 ETD

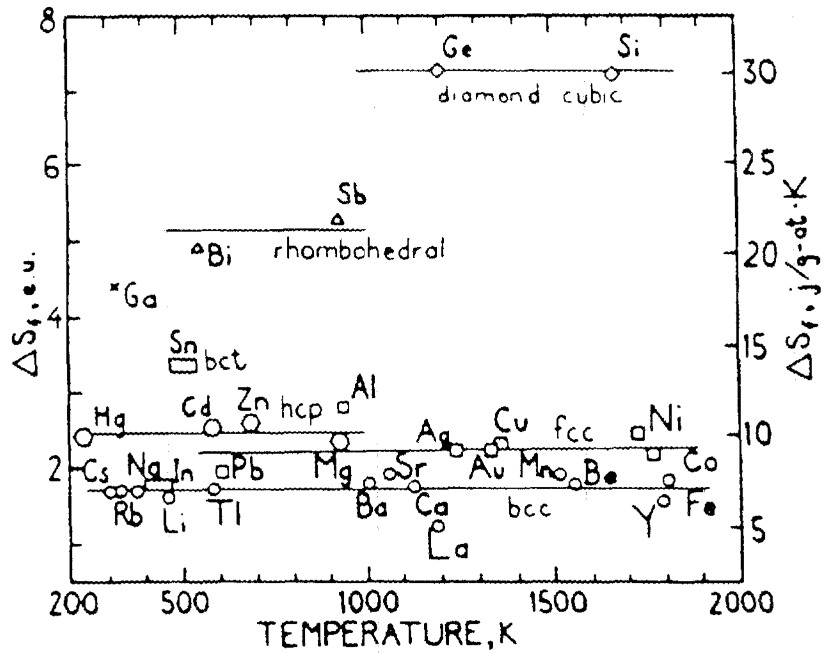


Fig. 1.1. Fusion entropy change for metals [reproduced from Barol (1985) in Mobley and Rapp (1986)].

lower volume change on melting in comparison to molten salt systems. In addition, a few metals, which actually lie near the border of the metal/non-metal boundary of the periodic table, possess significantly higher entropies of fusion, and hence would be particularly desirable phase change materials. Figure 1.1 shows that Ge and Si possess values of ΔS_f near 30 J/g-atom K, about three times the general value for most metals. (In addition, boron, with a phase change entropy of 22 J/g-atom K at a temperature of 2300 K should be kept in mind as a potentially useful component of metallic PCMs for extremely high temperature applications.)

The latent heats of eutectic alloys may be estimated from Eq. (1.1) by using the transition entropies of the pure alloy components molar-averaged for the eutectic composition, ΔS_e, and the eutectic transition temperature, T_e, instead of T_f, the fusion temperature of the pure material. Thus, for the eutectic,

$$\Delta H_e = \Delta S_e T_e \quad (1.2)$$

If significant solid solutions form on freezing at the eutectic composition, the heat and entropies of forming the solid solutions must in addition be taken into account by methods described by Barol (1985) and Birchnell and Reichman (1980). These methods were employed in the estimation of the latent heats of the eutectic Si alloys listed in Table 1.1 [Hoffman et al. (1985)]. However, the simple rule applies [from Eq. (1.2) and Fig. 1.1] that alloys containing a high percentage of Si yield high latents heats due to both the high eutectic temperature and the high transition entropy of Si.

In Table 1.1 [Hoffman et al. (1985)] a series of Si-based eutectic alloys are listed with congruent melting temperatures ranging from 1683 K (for pure Si) to ~850 K for the Al-12 Si alloy. Latent heats range from 1921 kJ/kg projected for the V-95 Si alloys to 571 for Al-12 Si.

As noted above, other metal alloy systems may be considered based on the other two metals possessing high transition entropies, Ge and B.

Table 1.1. Silicon eutectics for heat storage [Hoffman et al. (1985)]

Alloy	Eutectic melt temperature (K)	Eutectic composition (wt % Si)	Calculated heat storage capacity (kJ/kg)
Si	1683	100	1804
V-Si	1673	95	1921
Zr-Si	1633	75	1685
Ti-Si	1603	78	1570
Cr-Si	1593	75	1515
Mn-Si	1451	51	1090
Be-Si	1363	61	1812
Mg-Si	1213	57	1212
Ca-Si	1296	61	1111
Ni-Si	1239	38	609
Cu-Si	1075	16	422
Al-Si	850	12	571

A universal difficulty in the use of metallic PCM's is their incompatibility with container materials. Most molten metals tend to be solvents for potential container materials; hence, practical realization of the attractive features of metallic PCMs rests with the development of stable means for containment. One method being explored for the Si-Al alloy is self-encapsulation in Si [Mobley and Rapp (1986) and Martin (1986)]. Several procedures for fabricating a stable Si coating for an Al-Si PCM have been tested with only partial success at this time.

Molten Salt PCMs. Molten salts and especially fluoride salts, have the following attractive properties for use as PCMs: (1) they generally have high latent heats, (2) they possess high chemical stability which renders them compatible with many containment materials, (3) there are many pure and eutectic (binary and ternary) systems to choose from over a wide temperature range.

The negative aspects of molten salts lie in their low thermal diffusivity and often high degrees of volume change on phase transition which place a burden on the mechanical design of the container. In addition, high corrosiveness of molten fluorides have on occasion been observed caused by inadequate impurity control.

An attractive procedure for increasing the effective thermal diffusivity of molten fluorides is through use of metal-salt systems, called "slush systems" (see section below).

A list of candidate molten salts with latent heats greater than 500 kJ/kg consisting of pure, binary eutectic and ternary eutectic systems is given in Table 1.2. Five groups of PCMs are listed in order of phase transition temperature from 600–800 K up to 1400–1600 K. Note, there is only one carbonate with sufficiently high latent heat to qualify in this temperature range. LiOH is currently a leading contender for use in the solar collector component of the solar dynamic power system of NASA's Space Station Program, the version which employs the Organic Rankine Cycle. At this writing, two concepts are being evaluated: an Organic Rankine Cycle (ORC) requiring a heat storage medium in the 750 K range, and a Closed Brayton Cycle (CBC) system requiring heat storage in the vicinity of 1100 K. An evaluation procedure by designers and developers of each candidate power system weighed the following PCM properties: (1) magnitude of the latent heat, (2) material compatibility, (3) thermal diffusivity, and (4) magnitude of volume change on melting. A screening and testing procedure has settled on use of LiOH as the PCM for the ORC and the $LiF-22CaF_2$ eutectic for the CBC.

The latent heats given for the fluoride eutectics in Table 1.2 are estimates provided by Misra and Whittenberger (1986) using identical procedures employed for the Si-based metallic eutectics cited above. Numerous additional pure and eutectic molten salt compositions are provided in the compilation by Janz et al. (1978).

The extremely high latent heat per unit mass of LiH stands out prominently in Table 1.2; at 2845 kJ/kg it is more than 2.5 times that of LiF, the nearest competitor. In addition, its high specific heat renders it an attractive for sensible heat storage as well. However,

Table 1.2. Candidate pure and eutectic molten salt PCM's[a]

Temperature range (K)	PCM	Transition temperature (K)	Latent heat (KJ/kg)
600–800	LiOH[b]	746	873
800–1000	LiH	962	2845
	LiF-14.5AlF_3	983	721
	Li_2CO_3	996	606
1000–1200	LiF-22CaF_2[b]	1039	745–761
	NaF-32CaF_2	1083	520–560
	NaF-23MgF_2	1103	640–670
	LiF	1118	1087
	NaF-27CaF_2-36MgF_2	1178	520
1200–1400	CaF_2-50MgF_2	1253	610–650
	NaF	1268	789
	NaF-60MgF_2	1273	700–732
	$NaMgF_3$	1303	711
	FeF_2	1373	553
1400–1600	MgF_2	1536	933

[a]Fluoride values from Misra and Whittenberger (1986).

[b]Selected for the Solar Dynamic Receiver in the Space Station Program; LiOH for the Organic Rankine Cycle and LiF-22CaF_2 for the Closed Brayton Cycle system.

practical utilization requires contending with its high H_2 pressure (0.03 atm at its melting point for LiH with Li present as a second phase) with its attendant containment problem as well as its large volume change on melting.

Use of Oxides or Oxygen-Bearing Salts as High Temperature PCM's. There exist numerous metal oxide eutectics with melting points in the 1100 to 1800 K range, as well as other types of oxygen-bearing salts, such as silicates, borates, chromates, etc. Most of these would not be considered as potentially useful PCMs due to their inherent incompatibility with the refractory alloy cladding materials that would have to be used at these elevated temperatures. Most of these materials are oxidative at temperatures near melting and the refractory alloys are particularly susceptible to oxidative attack.

Possible exceptions to the above generality are the oxides of the alkali metals and alkaline earths which have high chemical stability and thus may be compatible with high temperature alloy cladding [Mahefky and Beam (1977)]. A few possibilities based on Li_2O eutectics are listed in Table 1.3. We note that PCMs based on light materials like Li_2O would generally possess high specific latent heat. The chemical compatibility of such materials would also be improved by addition of a liquid Li metal phase to suppress oxidative attack on the cladding.

Table 1.3. Alkali metal and alkaline earth oxide eutectics as possible high temperature heat storage media

PCM (mol-%)	Tm (K)	Latent heat (kJ/kg)
BeO-21.5 Li_2O	1023	1139
Na_2O-24.0 Li_2O	1043	400
Li_2O-38.8 SiO_2	1300	673
Li_2O-25 GeO_2	1333	871
Li_2O-40 GeO_2	1391	738
Li_2O	1843	1506

Use of Metal-Salt "Slush" Systems. Adding excess metal to the salt systems is an attractive option for coping with some of the problems posed by use of pure or eutectic salt PCMs, such as low thermal diffusivity, high volume change on phase transition, and a vulnerability to chemical impurities with attendant container corrosion difficulty. The excess metal would remain liquid across the salt phase transition temperature, and thus there would be some sacrifice in the magnitude of the effective latent heat per unit mass of storage material. The most obvious benefit of adding excess liquid metal is enhancement of the effective thermal diffusivity of the PCM mixture due to the presence of a continuous metallic phase. The alkali metal itself is known to be generally a benign material to many potential container materials. Use of "slush" systems with metals other than alkali metals needs to be examined with respect to the compatibility of the liquid metal with the container. In general, high temperature liquid metals (except alkali and alkaline earth metals) are good solvents for candidate containers.

The presence of a continuous liquid phase would also tend to relieve stresses on the container structure due to volume changes which occur on phase transition.

1.3.1.2 Low temperature PCMs for cycle heat rejection. Low temperature TES for cycle heat rejection would likely optimize in the 700 to 1200 K temperature range* where numerous PCM options are available, several of which are listed in Table 1.4. For cycle heat rejection near the low end of the temperature range, use of LiOH at 747 K and storage capacity of 1025 kJ/kg appears to be a good selection. This is the PCM material which is the current leading candidate for Organic Rankine Cycle Solar Dynamic System (see Appendix A) for the Space Station Program and hence has been the subject of an extensive materials compatibility testing program.

At the high end of the projected heat rejection temperature range, serious consideration must be given to the use of LiH, with a nominal melting temperature of 962 K and an extremely high specific heat of fusion of 2840 kJ/kg. However, use of LiH as a PCM at 962 K entails some problems including: (1) loss of hydrogen from the PCM by virtue of the modest hydrogen overpressure due to decomposition and subsequent

*Brayton cycle systems with recuperation would reject heat at the low end of thus range, and possibly below 700 K. Rankine systems and Brayton cycle systems without recuperation would likely require heat rejection at the upper end of the stated range.

Table 1.4 Some possible low temperature PCM's for cycle heat rejection (700–1200 K range)

Material	Temperature (K)	Heat of fusion (KJ/kg)
Carbonate Salts		
Li_2CO_3	996	606
K_2CO_3-47Li_2CO_3	761	342
Other binary and ternary eutectics	700–980	~150 to ~400
Fluoride Salts		
KF-33LiF	767	620
KF-29LiF-12NaF	728	683
Other binary and ternary eutectics	700–1200	~400 to ~600
Chloride Salts		
LiCl	883	469
KCl-44NaCl		
Other binary and ternary eutectics	700–800	~250 to ~500
Metals and Alloys		
Al	932	387
Al-12Si	850	571
Cu-16Si	1075	422
Other Salts		
LiOH	747	1025
LiH	962	2840

diffusion through the container, (2) fairly large volume change on melting, and (3) low thermal conductivity. These may not be insurmountable problems; i.e., addition of excess Li to LiH would partially suppress the H_2 overpressure and increase the effective thermal conductivity.

A large number of carbonate binary and ternary eutectics are available with melting temperatures in the 700 to 1000 K range. Except for

Li_2CO_3, however, (T_m = 996 K, latent heat = 606 kJ/kg) these appear to be characterized by a generally lower range of specific heat storage levels than available from fluorides, LiOH and LiH. A similar statement applies to the available chloride salts.

As noted in Sect. 1.3.1.1, metallic PCMs as a class possess low heats of fusion and present difficult compatibility behavior with containers. A few exceptions, however, have unusually high heats of fusion such that an incentive exists for attempting practical application to take advantage of their high thermal diffusivities. Two possibilities are the Al-12 Si and Cu-16 Si eutectics with melting points of 850 and 1075 K respectively (see Table 1.1). Use of metallic PCM's for heat rejection purposes may ease the general compatibility problem with container metals compared with higher temperature applications.

1.3.1.3 Use of Sensible Heat for TES. Since best cycle efficiencies over the period of operation are obtained with constant, high turbine inlet temperature and constant, low heat rejection temperature, thermal energy storage is most advantageously provided by a constant temperature device such as one based on a PCM. However, energy may also be stored as sensible heat, which represents the sum of atomic and electronic kinetic energies of the storing medium. As such, the specific sensible heat content of a medium is, to a first approximation, proportional to its temperature. Therefore, it is less convenient to couple a sensible heat reservoir to a Rankine or Brayton power conversion loop than an approximately isothermal PCM heat reservoir.

Nevertheless, sensible heat reservoirs may be used by adopting one of the following four procedures.

Velocity and rotation rate control. In this method, a control system sheds load and diminishes loop pressure to maintain constant working fluid velocities and turbine rotation rates as the front-end sensible heat reservoir loses temperature. This is a common control principle employed in Brayton systems, but would be more difficult to apply to Rankine systems since a loop pressure change would affect boiler and condenser behavior.

A sensible heat reservoir for cycle heat rejection would be used in the same way; i.e., as the reservoir temperature level rises, causing a loss of cycle thermal efficiency, load would be shed and loop pressure lowered to maintain constant loop velocities and turbine rotation rates.

Non-Controlled, Direct Coupling. If the sensible heat reservoir is sufficiently large, its temperature variation over the duty cycle may be small enough to cause acceptably small changes in turbine and cycle efficiency. This principle is currently being examined in a solar receiver concept for a closed Brayton cycle solar dynamic system (see Appendix A.2.2). This concept, in which a solid Be sensible heat reservoir of sufficient size to maintain cycle temperature variation to within 56 K, is being weighed against more conventional fluoride salt PCM storage systems.

Isothermal coupling through an intermediate loop. In this coupling procedure, the sensible heat reservoir discharges its heat to (or accepts heat from) an intermediate loop. Flows in the intermediate loop are controlled in a way such that it presents a constant temperature heat supply to (or heat rejection from) the primary loop. A method for accomplishing this behavior is illustrated in Fig. 1.2. The intermediate loop contains two pump and two mixing tee's. The mixing rates are controlled by the three temperature controlled throttle valves so as to maintain constant temperature at the control point, the exit from the primary loop heat exchanger.

This system has the advantage of enabling use of sensible heat reservoirs while maintaining constant heat supply (or rejection) temperatures, an advantage which must be traded against the weight penalty for the intermediate system and the ΔT loss in the additional heat exchanger.

This coupling procedure would most conveniently apply for implementing cycle heat rejection to a sensible heat reservoir. For front end heat supply, the initial reservoir temperature would need to be significantly higher than the maximum primary loop temperature. Therefore, heat supply by this method may be out of the question.

However, heat rejection by this coupling procedure could utilize both the sensible and latent heat of the storage medium thereby augmenting the storage capacity.

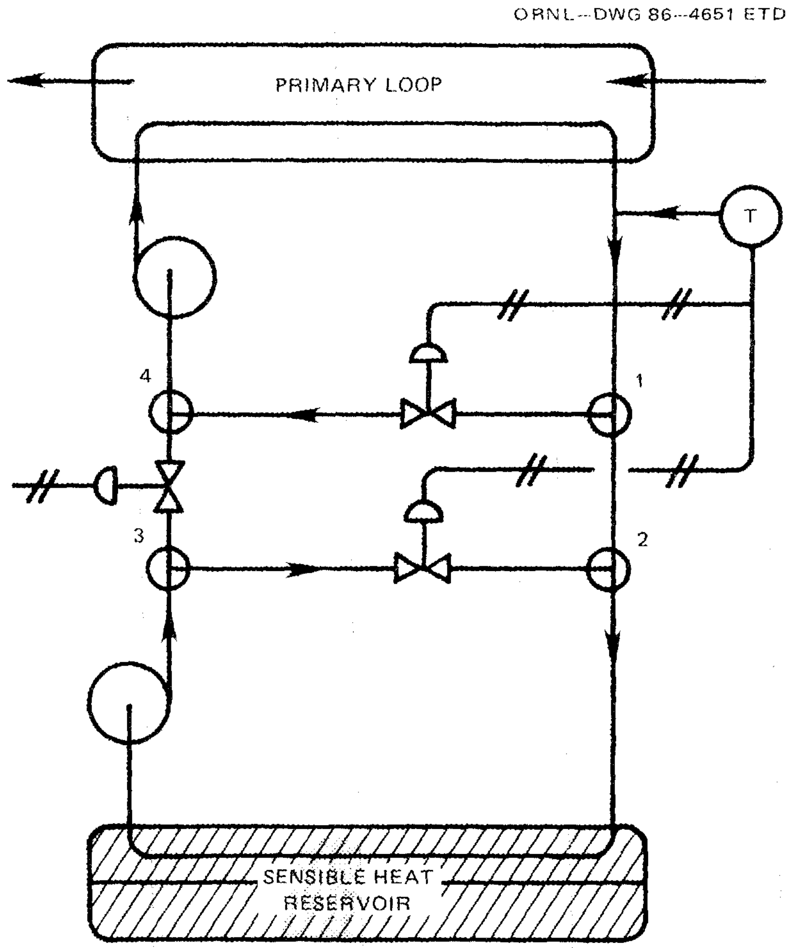


Fig. 1.2. Flow schematic for coupling sensible heat reservoir to thermodynamic cycle for constant temperature heat rejection or supply (see acknowledgements).

Figure 1.3 illustrates the degree to which sensible heat absorption may augment latent heat storage for two cases: (1) heat rejection to a LiOH reservoir initially at 300 K with absorption up to an 800 K heat rejection temperature. (2) Heat rejection to a LiH reservoir initially at 300 K, with heat absorption up to 1000 K, the cycle heat rejection temperature. For both these case, sensible heat absorption more than doubles the heat storage capacity: for LiOH, the increase is from 850 kJ/kg as a pure PCM at 746 K up to 2200 kJ/kg for a combined PCM/sensible up to 800 K.

ORNL DWG 86 4650 ETD

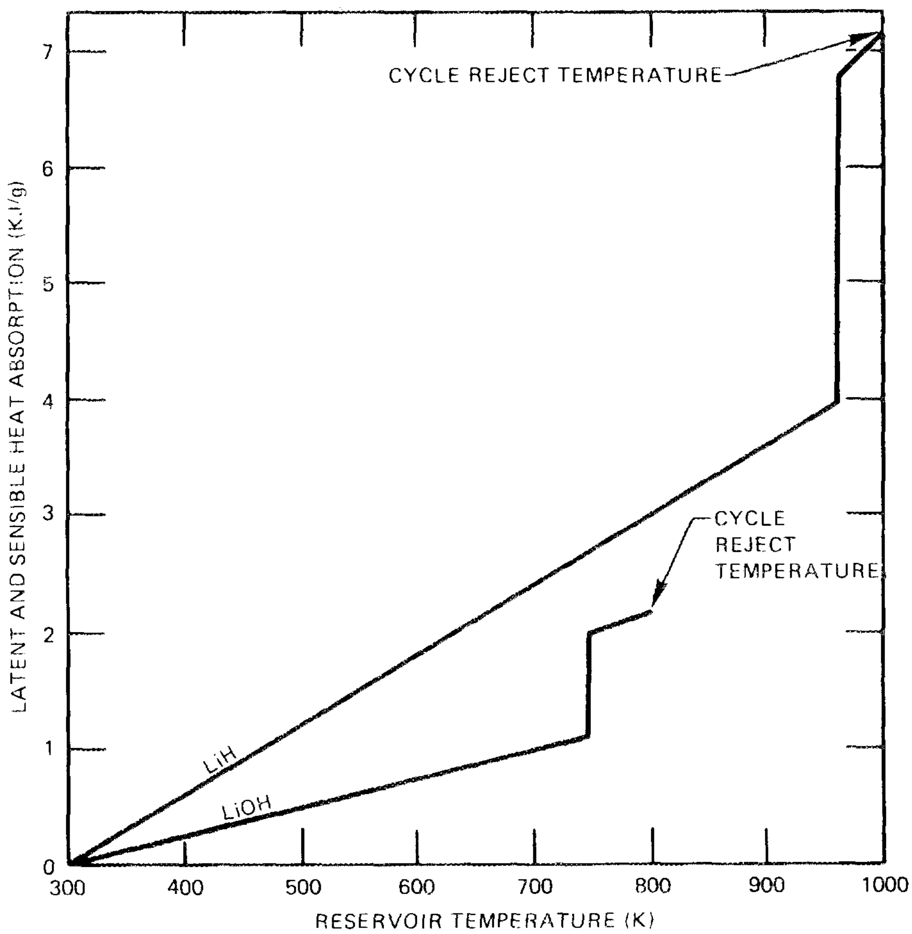


Fig. 1.3. Combined sensible and latent heat rejection capacities of LiH and LiOH.

1.3.1.4 Container compatibility considerations. The compatibility of a container with its contents most often depends on its resistance to oxidation, which could be either an inherent resistance or a protection by virtue of a stable coating, and a sufficiently small solubility for the service life and conditions. Other mechanisms become important in special circumstances. Hydrogen embrittlement could be a compatibility factor for a LiH container which would be subjected to a hydrogen dissociation pressure. Carburization effects may come into play with a molten carbonates, and similarly nitriding may be compatibility factor in the interaction of molten nitrate and metal containers.

These conditions are of minimal concern when dealing with fluoride salts of the alkali metals (Li, Na, K) and the alkaline earths (Be, Mg, Ca) or mixtures thereof. Both the cations (Li^+, Na^+, etc.) and the F^- anions of these salts are among the most stable in existence and hence can pose no oxidation threat to any metallic container. However, moisture or an organic contaminant in the fluoride would form the aggressive acid, HF, which attacks all types of container metals. Hence, good molten fluoride compatibility requires high purity in the salt.

In addition to good behavior relative to oxidation, metals generally possess low solubility in fluoride salts of the alkali and alkaline earth metals. This is especially true for the small cation salts, LiF and NaF which form tight ionic bonds permitting little interionic solution.

Some further beneficial chemical features of these molten fluorides are their chemical simplicity and their inability to dissociate to form a gas phase under any realizable conditions. The first is due to the fact that all of the involved salt elements are monovalent, which contributes to their chemical simplicity. The second feature is that molten fluorides do not react chemically to static pressure change, as do carbonates, nitrides and hydrides. Therefore, their chemical composition and their compatibility behavior do not depend on equilibration with decomposition gases (again, as carbonates, nitrides and hydrides do).

All of the above features apply in kind but to a lesser degree to chlorides. The Cl^- anion is still quite stable and, as with the fluorides, there is no oxidation threat to metals from pure chlorides. However, it is far less electronegative than F^- due to its larger size, therefore, it bonds less strongly with the cation and so permits generally higher metallic solubility. Therefore, we may anticipate somewhat poorer compatibility with metals for the chlorides relative to the fluorides.

Of the numerous elements with multivalent cations which form fluorides, only Fe (as FeF_2) would be considered as a PCM due to a melting point strategically located at 1373 K. (However, its heat of fusion is a marginal 550 kJ/Kg.) The chemical stability of this salt relative to disproportionation (i.e., formation of Fe^{+3} and deposition of Fe^{0}) and the degree of metal solubility in FeF_2 remain to be determined.

Molten salts which may decompose to form a gas phase present an added degree of chemical complexity. For example, the carbonate ion at high temperature may decompose to form O_2^- ion and O_2 gas to a degree depending on the static pressure. At high temperature, the CO_2 formed by the decomposition may be corrosive to metals and there is evidence that metal solubility is also affected by the degree of CO_3^{--} decomposition. Ultimately, metal oxides will precipitate at high degrees of dissociation by reaction of the cation with O_2^-. Thus, both container compatibility and salt stability become complex issues with carbonates at high temperature relative to the molten halides.

Other oxygen-bearing salts, such as borates, silicates or aluminates, are sometimes mentioned for use at very high temperatures, i.e., for $T > 1400$ K. While these materials cannot be totally dismissed at this stage, they present some potentially formidable difficulties. It is likely that these salts would oxidize the refractory metal container material required at these elevated temperatures. In addition, they each tend to form several metal-oxygen gas species at elevated temperatures. Hence, to some unknown degree the melt composition and behavior depends on the pressure within the container and the disposition of the gas phase.

A few metals, for example Si, possess sufficiently high specific latent heats to be considered for use as a PCM. However, molten metals in general (except the alkali metals Li, Na, etc.) tend to be good solvents and hence present difficult container compatibility situations.

1.3.2 Flywheel energy storage

Use of flywheels for prime energy storage. The application of flywheel energy storage to Boiling Potassium and Dual Loop, Li-cooled LMR's and HTGR heat supply systems is depicted in flowsheets provided in Sect. 2. These flowsheets illustrate how flywheel storage would be utilized in the systems, the major system components, and the way the duty cycles of each major component are affected in systems with prime energy storage. For each case, the benefit of reduced reactor size must be traded against the added weight and complexity of the storage device.

Flywheel energy storage, however, has an additional benefit not shared by other methods — prime energy storage in flywheels in addition to the purely storage function, may be designed to provide pulsed electric power. In other words, the flywheels could provide a power conditioning as well as a storage function in burst mode operation.

Flywheels have seen limited use in space. Primarily they have been used in the attitude control system (e.g. control moment gyro systems) for spacecraft. Since the energy storage requirements have not been the major design concern, low performance metal rotors have been used.

A flywheel sprint power module would consist of three major subsystems: rotor, suspension and power components. The rotor includes the shaft and web structure that connects the rim to the shaft. The power components include the motor used to charge the flywheel and the generator that is used to discharge the sprint power module. In general, the energy density of the unit is fixed primarily by the performance of the rotor while the specific power is determined by the generator.

The flywheel system can be configured in a variety of ways; a baseline configuration uses a tandem arrangement with a flywheel of $\beta = 0.2$ (β is the ratio of inside to outside diameter). A hub is shrunk fit within the rotor base and the generator and motor are then coupled to either end of the hub. This configuration offers the greatest flexibility in choosing a motor and generator to match the needs of the application. In the concentric configuration the motor/generator and bearings are mounted within the base of the rotor ring. Because of the absence of a central hub component, this design is very efficient in volume utilization. However, the motor/generator is restricted to the permanent magnet (PM) brushless type. The third concept would incorporate either the motor or generator within the rotor base but would have the other attached by means of a hub shaft. This concept offers the design flexibility of the tandem concept and would show some of the volume efficiencies of the concentric design.

The rotor would be suspended using active magnetic bearings. This overcomes the lubrication problems associated with ball bearing systems and provides a means for adjusting the bearing stiffness in operation.

When charging or discharging a single flywheel rotor, the change in angular momentum results in a net moment being applied to the spacecraft structure. This moment can result in an undesirable change in attitude of the craft. The use of two counterrotating flywheel rotors aligned on a common spin axis eliminates the net moment applied to the spacecraft. In addition, it is possible to use the moment associated with the energy storage flywheels to control the attitude of the spacecraft. This eliminates the need for an independent attitude control system and reduces the overall mass of the craft.

Kinetic energy may be stored in a flywheel up to the theoretical point at which the material tensile strength at the outer radius may withstand rupture caused by stresses induced by the centrifugal force. In general, the maximum energy density of a flywheel rotor can be expressed as a product of material and geometrical factors and is given by

$$E = K \cdot (\sigma/\rho) \tag{1.3}$$

where σ is the ultimate tensile strength of the material, ρ is the material density and E is the stored energy per unit mass of flywheel material. The rotor shape factor K for various configurations applicable to composite rotors is given in Fig. 1.4 (from O'Connell, 1980). The maximum value of K is unity, and as indicated in Fig. 1.4, a thin circular ring has a shape factor of 0.5.

As illustrated in Table 1.5, it is necessary to use flywheel rotors constructed of composite materials to achieve energy densities of interest for space application (Hoffman, 1985). As new fibers with higher strength become available the energy density of flywheels can be increased. The newest graphite material available has a tensile strength of 5200 MPa (750 ksi). This yields an ultimate energy density for the fibers of 3465 kJ/kg and represents a threefold increase over previous graphite fibers. Flywheel rotors using this material have attained a storage density of 878 kJ/kg at ultimate speed (Olszewski, 1986).

ORNL--DWG 86--4793 ETD

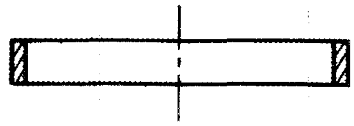
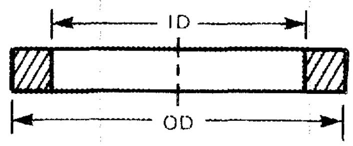
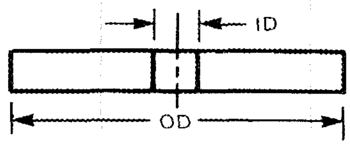
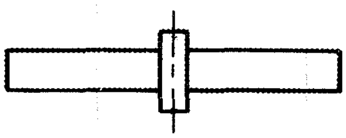
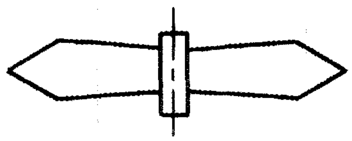
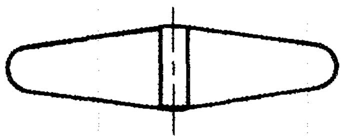
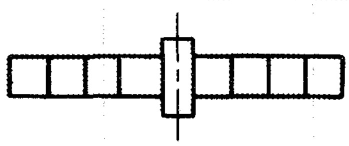
DESCRIPTION		SHAPE FACTOR K
IDEAL THIN RING		0.5
THICK RIM		0.438 ID/OD = 0.8
PIERCED DISK		0.305 ID/OD = 0.1
CIRCUMFERENTIALLY WRAPPED FLAT DISK		0.43
CIRCUMFERENTIALLY WRAPPED FLARED DISK		0.47
TAPE OVERWRAP		0.35
MULTIRIM		0.45

Fig. 1.4. Flywheel rotor configurations.

In actual service, the useful storage density is lower than the ultimate due to two factors. The first arises from safety and reliability considerations. To prevent failure during service the maximum operation speed is limited to 60 to 90% of the ultimate. In rotor tests involving the new high strength graphite fibers, for instance, it was

Table 1.5. Characteristics of materials used in flywheels

Material	Ultimate tensile strength (σ) MPa	Density (ρ) g/cm^3	σ/ρ [kJ/kg (Wh/kg)]
Steels			
4340	1517	7.7	197 (54.7)
18 Ni (300)	2070	8.0	25.9 (71.8)
Composites			
E-glass/epoxy	1379	1.9	726 (201.6)
S-glass/epoxy	2069	1.9	1089 (302.5)
Kevlar[a]/epoxy	1930	1.4	1379 (382.9)
Graphite/epoxy	1586	1.5	1057 (293.7)
Other			
METGLASS[b]	2627	8.0	328 (91.1)

[a]Kevlar is a trademark of Du Pont.

[b]METGLASS is a registered trademark of the allied Corporation, Morristown, N.J.

determined that the ultimate speed was 1400 m/s and the maximum operating speed should be set at 1200 to 1275 m/s (Olszewski, 1986). The second factor to be considered is the depth of discharge (also known as the operating speed ratio). Typically the ratio between minimum and maximum operating speeds ranges from 1:2 to 1:4. Since energy is related to speed squared this represents a depth of discharge of 75 to 90%.

The manner in which a flywheel is loaded and unloaded and its means of support also influences the upper limit value of specific stored energy. If the physical support as well as the coupling with the generator is achieved using electromagnetic forces, then a thin rim geometry is feasible.

Flywheels which are rotated on shafts and downloaded by engaging a clutch to a generator are capable of significantly less stored specific energy due to shear stresses induced during the transients. The woven fiber construction has extremely low shear strength, essentially that of the polymer matrix. For mechanical support, the weaving strategy must provide fibers for high shear strength near the hub where shear stresses are highest during a transient, and maximal tensile strength near the rim where the tensile load is a maximum at rated rotational speed.

If such a weaving strategy can be achieved, the stored energy density penalty would only be about a factor of 2 for the mechanical support relative to magnetic coupling. The penalty would be due to requiring a disc geometry for the flywheel as opposed to the more advantageous thin rim geometry.

Power components

In applications where the output/input power ratios are small and the power levels do not exceed 0.5 MW, the permanent magnet (PM), ironless, brushless system can be used as both motor and generator. In applications where the output/input power ratio is large (in excess of 2), the PM system would be used only in the motor mode. In applications involving short output power pulses (1 second or less), the homopolar generator (HPG) would be the output device. For pulses in the millisecond range, the compulsator would be used.

The GE technical literature (GE 1983) indicates availability of a permanent magnet (samarium-cobalt) motor with a power density of ~8 kWe/kg operating at 20,000 rpm. The Air Force has been developing with Rockwell International a 5 MW PM generator (AFWAL 1980) designed to operate with an uncooled rotor at 22 kWe/kg and 15,000 rpm. Thus far, a power density of 11 kWe/kg has been achieved; and the developers see no impediment to reaching the full design power density. Further advances in power density may be possible with a new PM material containing neodymium, iron, and boron. This material has field densities ~24% greater than that of samarium-cobalt, but the relatively low curie temperature (585 K) may limit its use. The PM motor is attractive because it is brushless and has a high efficiency (~96%).

Advanced generator technologies are being investigated at the Center for Electromechanics — University of Texas (CEM-UT) with attention focusing on homopolar generators (HPG) and compulsators. The homopolar machine (Gully et al. 1984) is the only DC rotating machine without a commutator. In this device, the entire monolithic rotor acts as the armature conductor resulting in very low internal impedance. The HPG has been developed specifically for pulsed power application and is inherently a high current (1 to 2 MA), low voltage (50 to 100 V) machine. Typical pulse widths are on the order of 0.1 to 0.5 seconds. The all iron rotor (AIR) concept being developed at CEM-UT is designed to minimize stray fields. At present, maximum tip speed is limited to 220 m/s because of brush wear. Since the brushes are located at the outer rotor diameter energy density is thus constrained by brush speed. To date, the Center has operated an AIR machine with a power density of 50 kW/kg. This machine 6.2 MJ per pulse (1.5 MA at 50 V in a 0.083 s pulse). If the brush speed could be raised to 280 m/s, thereby allowing higher currents, the energy delivery per pulse would be raised to 10 MJ. Efforts are currently being made to modify the AIR design. The new design could result in a power density of 200 kW/kg; however, to get kV bus voltage will require an inductor. The inductor adds mass (about as much as the AIR) and volume. Current CEM-UT inductors receive 50 V and output 1.2 kV.

The compulsator (Weldon et al. 1978) appears to be the generator best suited to pulsed power needs. It is a high power compensated pulsed alternator and differs from a conventional synchronous machine in that it has an additional stationary winding in series with the rotating armature winding. The function of this additional winding is to compensate the internal inductance of the machine at one point in the cycle (usually at peak voltage) though flux compression. At present, the peak power limitation is in the range of 3 to 4 GW/m^2 of rotor surface area. Compulsators appear to work best in the 6 to 15 kV range.

Suspension

Magnetic bearings will be used for suspension of the flywheels in order to provide long lifetime and reliable operation. Magnetic bearings have been developed by SNIAS (France), TELDIX (Germany), Draper Laboratories, and NASA for suspension of flywheel rotors and have proven to be reliable. The use of electromagnets can provide for an adjustable stiffness. Because they can be designed to produce almost zero jitter, magnetic bearings have been recommended for use on the space telescope platform.

1.3.3 Relation to Other Energy Storage Options

Prime energy for burst power may also be reversibly stored as chemical energy or in electrostatic and magnetic fields. However, TES is unique among the energy storage options in its application to the thermal discharge side of the thermodynamic cycle. Prime energy storage by all options except TES requires the production of electricity from the nuclear heat source in a thermodynamic cycle, which is usually in the 20 to 40% efficiency range. Thus from 80 to 60% of the nuclear heat produced requires rejection, either directly by radiation or indirectly from an intermediate TES system.

Prime storage as thermal energy also differs from the other options in that the thermodynamic cycle which makes electricity from heat is placed in the intermediate loop, and not directly in the primary coolant loop of the nuclear reactor. This is more clearly shown in Sect. 2 where flowsheets are shown for various burst power systems with and without prime and back-end storage systems.

Chemical energy storage utilizes the internal energy inherent in chemical bonds which generally involve the outer subshell or valence electrons. Energy stored in chemical bonds may be released in a number of ways.

(1) Reactants with high bond energies may be allowed to react irreversibly (in the thermodynamic sense) to form material with lower bond energies, the difference in energies being equal to the enthalpy change of the reaction, ΔH. The "released" energy manifests itself as sensible heat of the reaction products which, by virtue of its elevated temperature, may drive a heat engine to make electricity. This process would have the efficiency of the selected thermodynamic cycle, which ranges generally between 20 and 40%.

(2) For some systems, the reaction may be made to proceed reversibly (thermodynamically) by preventing the direct chemical reaction and instead providing an electron pathway through a load, leading ultimately to the lower energy level electron configuration in the reaction products. Not all energetic systems are amenable to such transformation, which occur in batteries and fuel cells, due to various physical and

chemical property problems. For those that may occur in this way, a degree of stored energy is "released" as useful work in the electrical circuit equal to the free energy change of the reaction, ΔG. In general, ΔG is numerically less than ΔH, the heat released by an irreversible reaction, by an amount equal to $T\Delta S$, where T is the cell temperature and ΔS is the entropy change between reactants and products. Thus, the ratio $\Delta G/\Delta H$ may be termed the theoretical cell efficiency, and the energy amount at least equal to $T\Delta S$ must be drawn off as waste heat analogous to the heat rejection process required in a temperature-driven thermodynamic cycle [Fee, D. C. (to be published)].

In general, cell efficiencies defined by the ratio $\Delta G/\Delta H$ diminish with increasing temperature (in contrast to a heat engine), whereas reaction and mass transport rates increase with temperature. Therefore batteries and fuel cells are made to operate at some optimum temperature balancing these two competing tendencies. As an example the H_2/O_2 fuel cell releases a ΔG of ~12,500 kJ/kg with 90% theoretical efficiency at 400 K. At a cell operating temperature of 1273 K, projected for some advanced systems, a free energy release as useful work of ~9810 kJ/kg occurs with a cell efficiency of 77% as a theoretical upper limit.

(3) Stored chemical energy may also be released by photon emission in various ways, namely by general incandescence at high temperature, and in special cases by low temperatures phosphoresence and by laser emission of coherent light. Chemical photon emission is generally a low efficiency process with no application to energy storage systems.

All chemical storage systems are in principle regenerable, however in practice some of the most energetic systems are difficult to regenerate. For example, alkali metal/halogen systems possess high specific stored energy, but cannot be regenerated without the traditional problems involved in molten salt electrolysis. The most energetic, proven regenerable chemical storage system is provided by H_2/O_2 which has an upper limit storage capacity of ~10,000 kJ/kg based on reactant weight.

Energy may be stored in an electromagnetic field either as internal energy within a concentrating medium (a ferromagnetic) or intrinsically in the field itself, essentially in a vacuum. For relatively low values of the applied field, 10^3 Oe* and below, soft† ferromagnetic materials such as the iron alloy Supermendur may concentrate an applied field, achieving energy densities of up to ~0.02 kJ/kg in the soft magnet material. However, the magnetic permeability which is the concentrating factor, declines toward unity for applied fields above about 10^4 Oe, so that above this level the magnetic energy density in the ferromagnetic does not significantly differ from that of a vacuum.

Thus for intense fields of 10^4 Oe and above, we may speak of a specific stored magnetic energy defined as the energy content of the field itself per unit mass of inductor coil. Prior to the advent of superconducting coils, specific magnetic energy densities on the order of 10^{-3} kJ per kg of coil were generally feasible. Superconducting coils allow much higher currents per mass of coil and energy densities of ~5 kJ/kg have been achieved. Structural limitations appear to place a maximum value of about 10 kJ/kg for stored electromagnetic energy in the field of superconducting coils.

Dielectric storage. An electric field applied across a dielectric stores energy in the medium to a degree proportional to the dielectric constant and the square of the field strength. Since the field strength itself equals the applied voltage across the medium per unit width, a given available voltage yields a volumetric energy storage that increases as the square of the reciprocal of the width. Thus, there is a high premium for wafer-thin media in high energy content dielectrics, and consequently fabrication techniques are often a limiting factor. Dielectric storage of prime energy for burst power would require a flowsheet similar to that for a flywheel storage; i.e., the primary loop would generate a continuous DC electric supply for reload following burst and make up for electrical leakage. As with flywheels, a possibility exists for performance of a power conditioning function in addition to storage of prime power.

---

*Oersted = 79.58 A/m; Oersted is the common magnetic intensity unit.

†"Soft" designates a ferromagnetic material which does not retain significant magnetic field on removal of the applied field, as opposed to "hard" ferromagnetics which may be permanent magnets.

Electric internal energy is stored in a dielectric material by three mechanisms: (1) electron polarization caused by a relocation of loosely bound electrons by the electric field; (2) atom polarization caused by an average displacement of nucleii in a field, and (3) dipole orientation, i.e., a partial alignment of permanent dipoles by the imposed electric field. Predictive theories regarding the relative contributions from these sources to the total induced polarization have not been developed with reliability. Therefore, although it is known that certain classes of ceramics possess high dielectric constants, it can not be theoretically predicted to what degree material development may achieve improvements. It should also be noted that besides high dielectric constant there are other property requirements for a high storage density material, i.e., (1) no retention of polarization on removal of the field as this would not permit full energy recovery; (2) sufficiently low electric conductance to minimize leakage; (3) high dielectric strength on the order of 1000 V/μ is desired; (4) long-term chemical stability under operating conditions.

Much of the intensive development in the area of dielectric energy storage in the past decade has been directed toward use of impregnated polymeric films such as Mylar and polypropylene. The chief development incentives have been the rejection of polychlorinated biphenyl (PCBs) impregnants in power capacitors for environmental reasons and new applications required for laser and space power system devices. Though the impregnated polymerics possess relatively low dielectric constant, generally from 2 to 10, their chief advantage lies in available high precision thin film manufacturing techniques allowing attainment of near theoretical maximum electrical stresses. According to a recent review (Reed, 1981) such systems may be stressed to 200 to 400 V/μ for a short term. The highest reported degree of energy storage (Reed, 1981) is 0.1 kJ/kg) which may be approaching the upper achievable limit for this class of capacitor.

Use of electrical capacitive energy storage for space power application would require more stable materials than the polymerics as well as more competitive degrees of energy storage. It is therefore natural to consider use of ceramic dielectrics which possess superior stability as well as higher inherent dielectric constant. For example, some linear dielectrics (i.e., constant dielectric constant with applied field) such as TiO_2, $CaTiO_3$, and $SrTiO_3$ possess dielectric constants of ~200 and inherent breakdown voltages of ~1000 V/μm for thin wafers. Assuming fabrication procedures for achieving such high stress may be developed, an electric stress of 1000 V/μm on a dielectric of $k_e = 200$ corresponds to an energy storage of 20 kJ/kg.

Higher dielectric constants on the order of 2000 are reported for so-called ferroelectric materials such as $BaTiO_3$. However, according to Shirn and Burn (in Reed, 1981), these materials assume a permanent polarization in a phenomenon analogous to magnetic hysteresis such that full energy recovery is not possible. Ferroelectrics are therefore not considered to be the most advantage direction for high energy-density capacitive storage. Instead, a more promising approach may be use of so-called antiferroelectric materials such as La-modified, mixed $PbZrO_3$-$PbTiO_3$ (PLTZ) which have dielectric constants of ~2000 and show no hysteresis loss. However, PLTZ is reported to have been stressed at only 40 V/μm thus far, yielding energy densities below that of the polymerics.

There is obviously a large incentive for probing toward the ultimate achievable specific energy density in dielectric materials. It is not clear at this time what that is, but we may note that if PLTZ can be fabricated and stressed to 1000 V/μm its energy density would be ~200 kJ/kg, which may be a competitive value considering the simplicity that dielectric storage offers and its potential additional power conditioning function. Exacting fabrication procedures for 50 μm thin wafers with minimal perturbation of electric field due to thickness or property variations to prevent breakdown and parallel leakage represent major development hurdles.

2. APPLICATION OF THERMAL AND FLYWHEEL ENERGY STORAGE TO NUCLEAR POWER SUPPLY SYSTEMS

2.1 Introduction

This section describes in a general way the manner in which thermal and flywheel energy storage systems may be applied to closed cycle nuclear systems for supplying burst power. The purpose is to illustrate how such an energy storage system may be fit into the overall flowsheet and how the duty cycles* of the major components are affected by the incorporation of the energy storage system. The following burst system flowsheets are reviewed here:

1. Boiling Potassium Rankine Burst Systems
   - Fig. 2.1. No energy storage
   - Fig. 2.2. Thermal storage condenser
   - Fig. 2.3. Thermal storage in the primary loop and thermal storage condenser
   - Fig. 2.4. Flywheel storage prime
2. Lithium Cooled Liquid Metal Reactor Burst System
   - Fig. 2.5. No energy storage
   - Fig. 2.6. Thermal storage condenser
   - Fig. 2.7. Thermal storage in the primary loop and thermal storage condenser
   - Fig. 2.8. Flywheel storage prime
3. HTGR Brayton Burst Systems
   - Fig. 2.9. No energy storage
   - Fig. 2.10. Thermal storage of cycle heat rejection
   - Fig. 2.11. Flywheel storage prime
   - Fig. 2.12. Thermal storage in primary loop.

Each flowsheet also indicates the approximate temperature ranges that may be expected at reactor inlet, outlet and intermediate locations

---

*The duty cycle is defined as the time span within a cycle encompassing bursts plus power system regeneration that a component is active. A regeneration time approximately equal to an orbit period is here assumed. However, the discussion is similar for other assumed power regeneration times.

in the power conversion system. Each of these are presented in an approximate and preliminary fashion as a general indication of the effect of energy storage on the duty cycle, and the temperature level range at which thermal storage systems would be required to operate in these nuclear supply systems.

In the flowsheets that follow it is assumed that the housekeeping power system is continuous and completely separate and provides the necessary power to startup the alert mode (AL). It is further assumed that the alert and burst system power is provided by the same reactor source. However, since the alert mode and burst power levels are so far apart, each function must be provided with a separate energy conversion system. The flowsheets show only the burst mode. The power ratio between the burst and alert modes is of the order of a factor of 100 and therefore is too large to accommodate in a single power conversion control range. It should be noted that energy storage in a regenerating system permits a reactor power reduction about equal to the ratio of burst series duration to the total cycle time, which includes the burst plus regeneration time. Thus if a 20 min burst series were followed by about a 2000 min regeneration period, an energy storage capability would effect a factor of 100 reduction in burst power system size. In such case, the burst and alert mode power conversion systems would be comparable, and only one system would be needed. In the flowsheets that follow, however, the duty cycles shown in the legends were developed assuming an engagement time of about 20 min and a regeneration time within an orbit period of about 100 min. In this case, prime energy storage affects a burst system size reduction of about a factor of five, which is insufficient to eliminate the need for separate burst and alert mode power conversion systems.

The following abbreviations are used in the power system flowsheets:

A	Alternator
AL	Alert mode
BU	Burst mode
C	Compressor
ECP	Electric circulating pump (motor-driven or electromagnetic)
EFP	Electric feed pump

FH	Feed heater
FW	Flywheel
HK	Housekeeping mode
HTGR	High temperature gas-cooled reactor
G	Generator
JP	Jet pump
K	Potassium
LMR	Liquid metal reactor
NaK	Sodium-potassium eutectic
M	Motor
MHX	Main heat exchanger
PP	Prime power
RAD	Radiator
RC	Radiator-condenser
S	Liquid separator zone
T	Turbine
T/A	Turbo-alternator
TS	Thermal storage
TS-P	Thermal storage prime
TS-C	Thermal storage condenser

It should be noted that each thermal storage reservoir shown symbolically in the following figures as a box labeled TS-C or TS-P may be either a nearly isothermal unit based on a phase change material (PCM) or one that stores sensible heat in addition to latent heat. For the latter case, the discussion in Sect. 1.3.1.3 applies describing the manner in which a sensible heat reservoir may be used in power conversion systems; i.e. they must either be large enough to minimize the temperature variation (and attendant efficiency loss) or an "isothermalizing" system, as shown in Fig. 1.2, must be adopted.

2.2 Boiling Potassium Rankine Systems

Figures 2.1 through 2.4 illustrate the Rankine conversion system employing the Boiling Potassium Reactor with respectively, no storage, TES for condensing, TES for front end storage and for condensing and flywheel storage of prime power. Shown with each figure are the duty cycles of the reactor, turbine-alternator, radiator condenser, and where appropriate, the duty cycles for the storage devices.

The non-storage case, Fig. 2.1, illustrates some features common to the rest. First, EFPs are shown for loop circulation (either motor-driven centrifugal or electromagnetic) rather than turbine-drive pumps

ORNL–DWG 86–4645 ETD

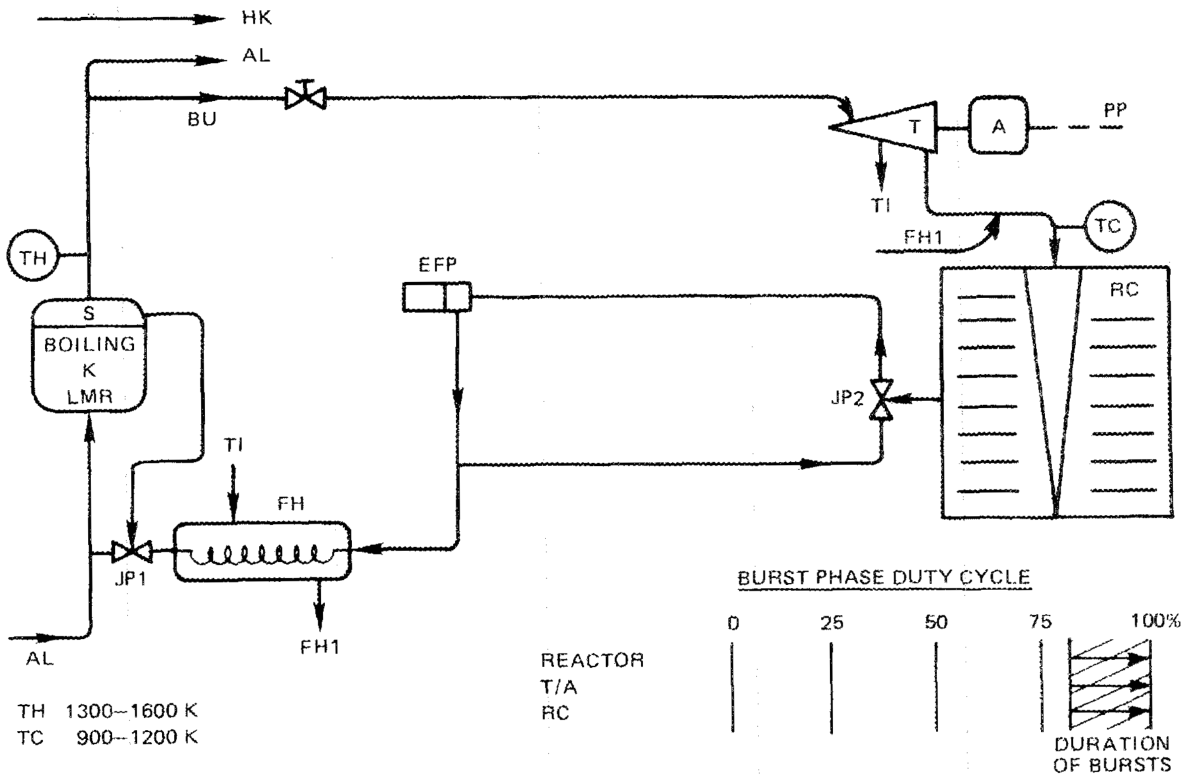


Fig. 2.1. Boiling Potassium Rankine burst system — no energy storage.

primarily because they are better suited for startup using alert mode electric power. Turbine drives may prove lighter and more efficient, but are miscast in stop-and-start systems. Also note that jet-pumps are used for pumping the near-saturated liquids from the reactor separator and from the condenser to the feed heater. In this case, one EFP drives the two jet pumps shown. As indicated, reactor exit temperatures in the range 1300 to 1600 K may be considered and turbine exit temperatures may range from 900 to 1200 K. The duty cycle indicates that the burst system would operate only for the burst power portion of the orbit, here shown as 20% of orbit cycle time.

Figure 2.2 illustrates the system employing a TES device as a condenser, with ultimate cycle heat rejection being performed by a radiator. A pumped NaK loop is used to transfer heat from the condenser to the radiator. The principal benefit relative to Fig. 2.1 is the smaller

ORNL-DWG 86-4647 ETD

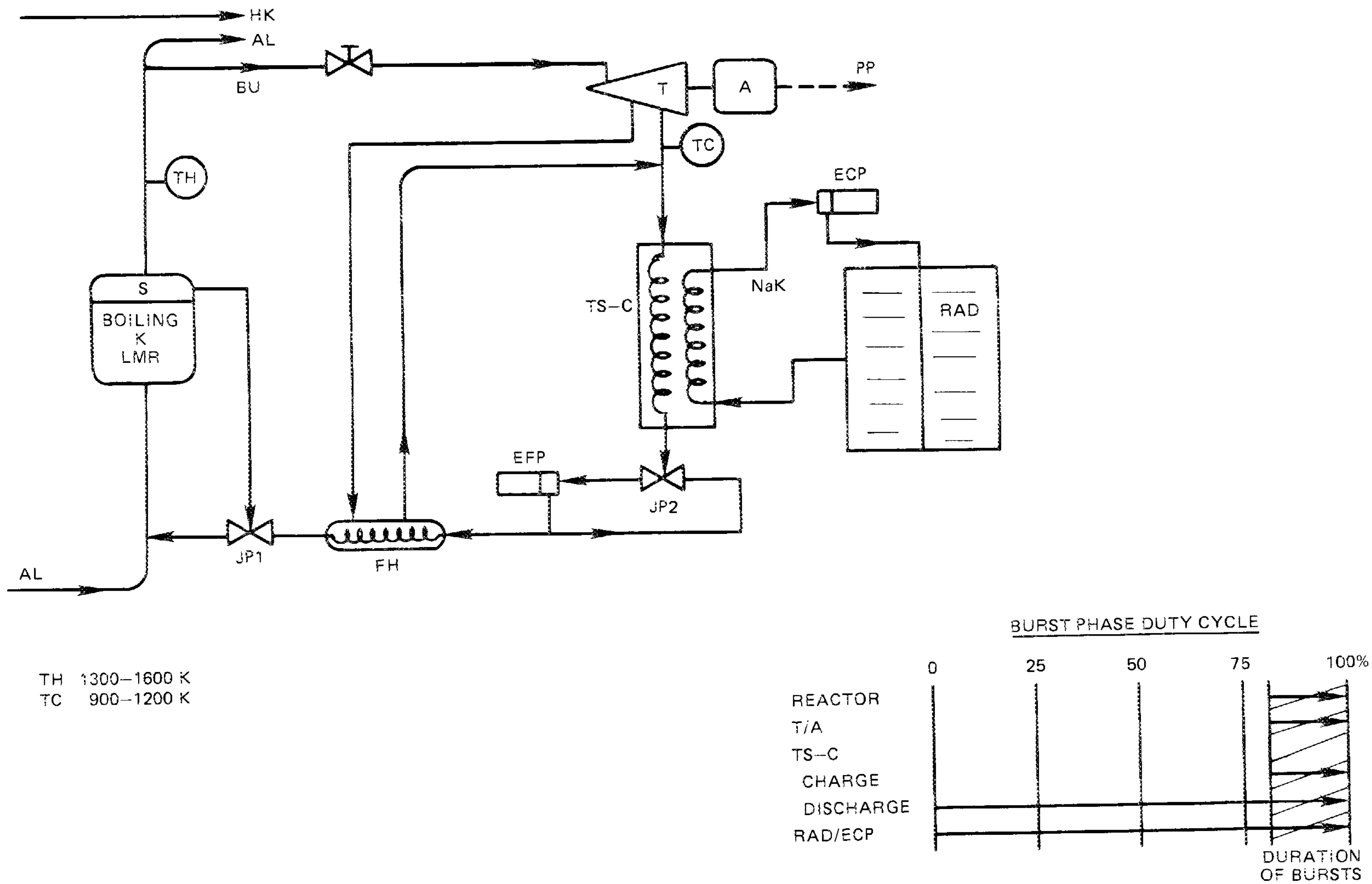


Fig. 2.2. Boiling Potassium Rankine burst system — thermal storage condenser.

radiator which operates for the full orbit cycle instead of only the 20% burst duration. In addition, the radiator is a simpler structure since it does not perform the condensing function, which is instead provided by a thermal storage device. The storage medium may be either a PCM material with a melting point in the 900—1200 K range, or a sensible heat absorber with upper temperature in the 900—1200 K range. Thus, balanced against the advantage of a smaller, and simpler radiator is the weight penalty of the storage unit and the added NaK loop.

Figure 2.3 illustrates a Boiling Potassium system using thermal storage for primary loop energy in addition to a thermal storage condenser. The significant advantage here is that the reactor runs for the full orbit cycle instead of only for 20%, and consequently may be 5 times smaller. In addition, provision for multiple restarts, employing alert phase power for each, are not required. The penalty paid for these benefits is the added mass of the TS-P device and the additional coolant loop. We should note that in this reactor system, the TS-P device performs as a condenser for the primary potassium as well as a boiler for the secondary loop flow. As indicated by the duty cycle legend in Fig. 2.3, the reactor and primary loop operate continuously throughout the active period, as does the heat rejection loop. Only the secondary loop, containing the turbine/alternator and circulating pump are actuated for the burst duration. Therefore in this concept, the primary heat storage reservoir (TS-P) is continually replenished and the heat rejection storage system (TS-C) is continuously being discharged during the active period. Besides a fairly complex TS-P unit, an additional incurred penalty is loss of thermal efficiency due to the ΔT in the primary storage device requiring a somewhat larger energy conversion system for the same net power output.

Figure 2.4 illustrates use of flywheel storage for prime power using a Boiling Potassium Reactor. The unique feature here is that the entire system operates for 100% of the orbit, including the reactor, T/A conversion unit, flywheel and radiator. In particular in comparing Fig. 2.3 with Fig. 2.4, note that the T/A system would be rated at one-fifth the power for the flywheel storage system compared with the case for front-end thermal storage.

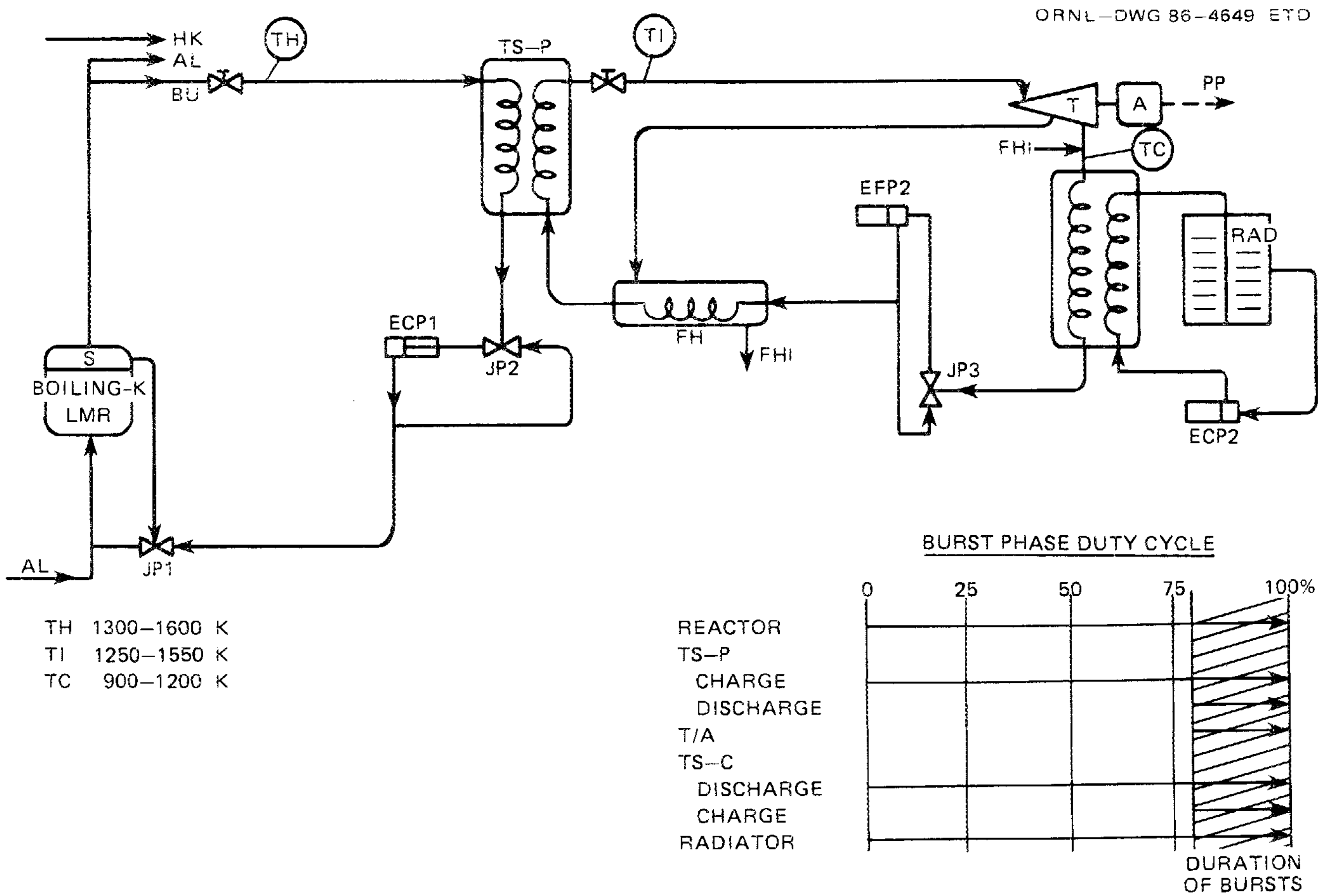


Fig. 2.3. Boiling Potassium Rankine burst system — thermal storage prime and thermal storage condenser.

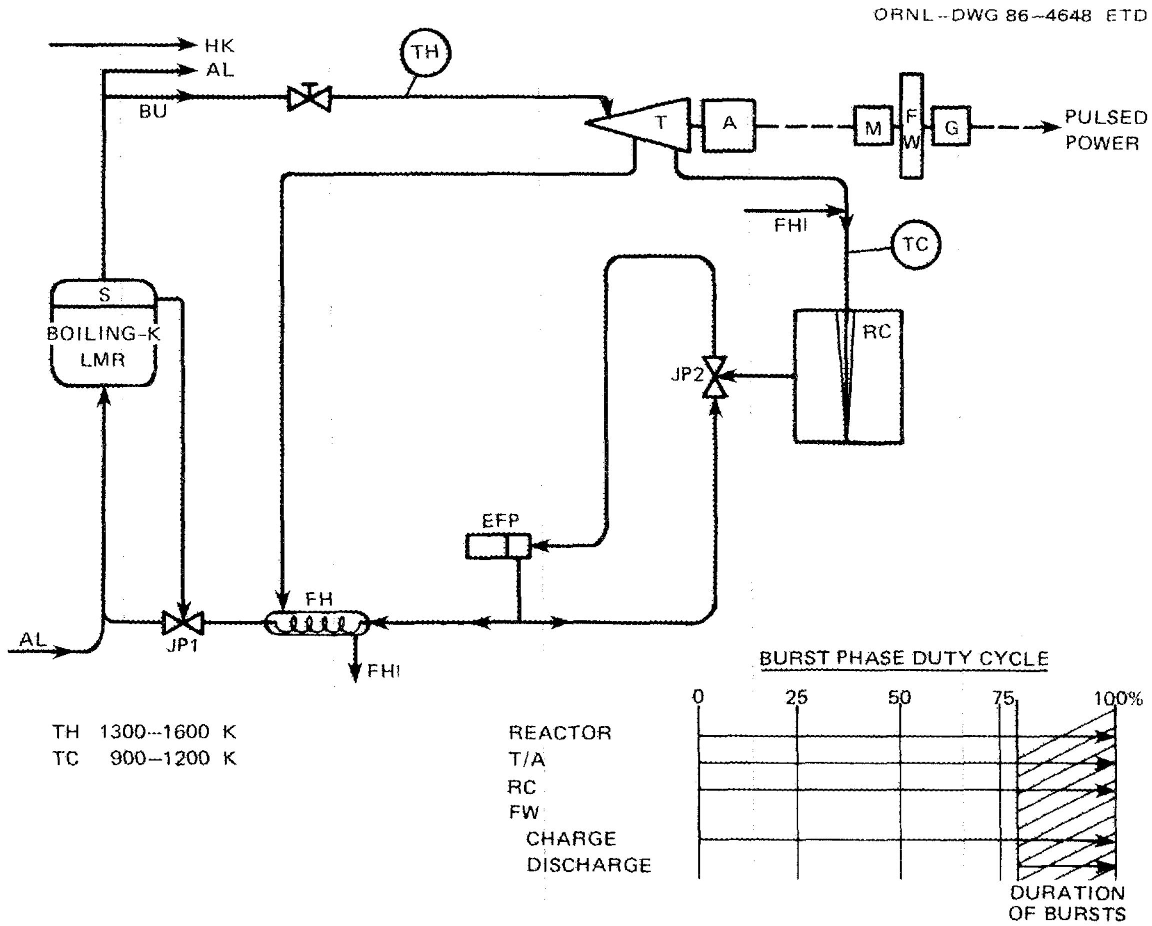


Fig. 2.4. Boiling Potassium Rankine burst system — flywheel storage prime.

An additional benefit of the flywheel storage system accrues if the storage device can unload in pulses, thereby performing a power conditioning role as well as energy storage. The penalty against which these benefits are weighed is the added mass of the flywheel system and the attendant complexity and cost.

2.3 Lithium Cooled LMR

Figure 2.5 illustrates the Lithium Cooled LMR, dual loop concept with no energy storage in burst mode operation. As shown, the primary lithium coolant boils secondary loop potassium in the MHX. The power conversion system employs a potassium vapor turbine and a radiator condenser, approximately equivalent to the conversion and condensing

ORNL-DWG 86-4642 ETD

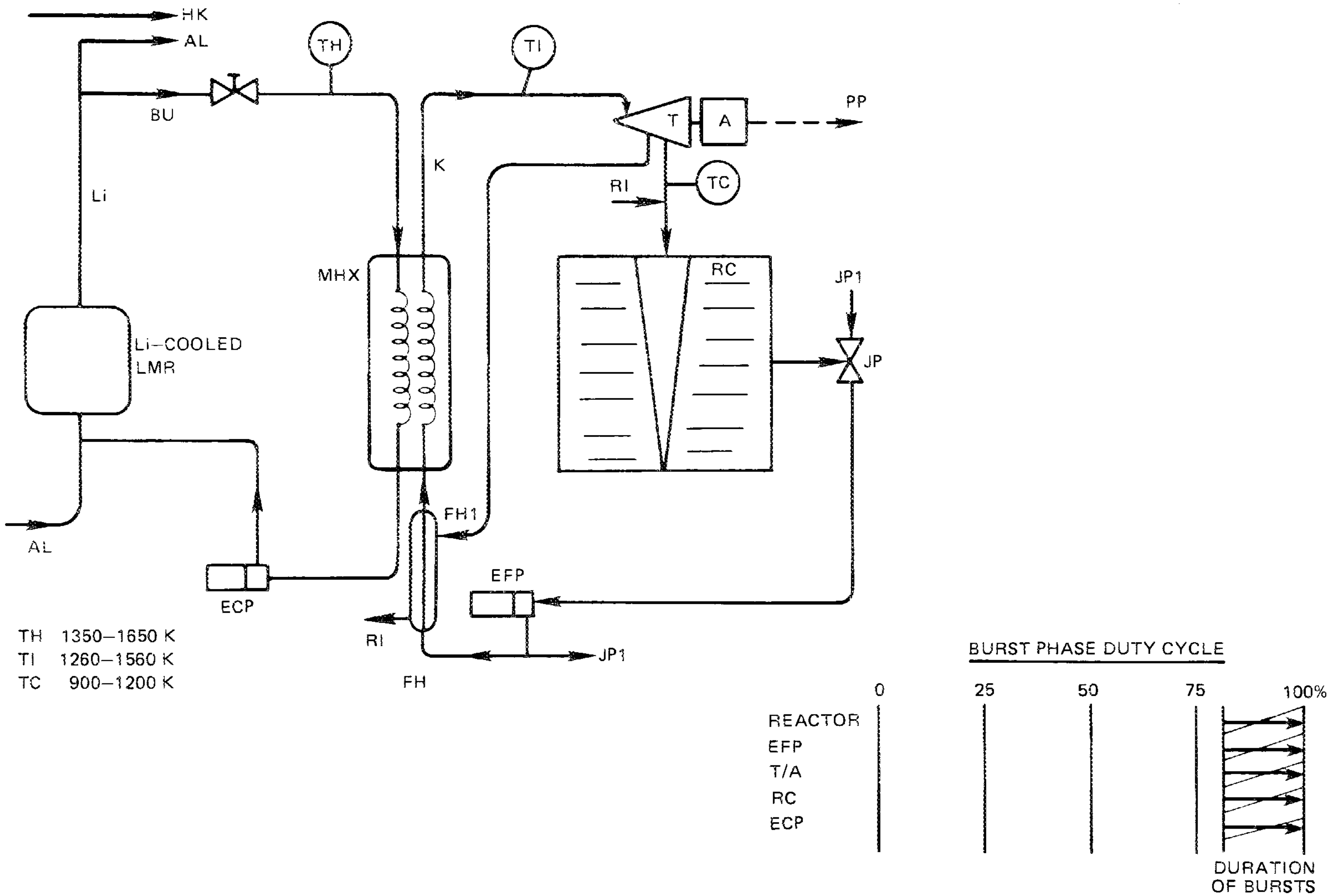


Fig. 2.5. Lithium Cooled Dual Loop LMR burst system — no storage.

units in the non-storage Boiling Potassium Reactor Case (Fig. 2.1). As shown by the duty cycle, all components operate for ~20% of the orbit time. The benefit of simplicity in terms of number of components must be balanced against larger unit sizes (compared with energy storage systems) and the required alert mode power usage for the repeated startups.

Figure 2.6 illustrates a Lithium Cooled LMR with a thermal storage condenser. The storage material is thermally loaded during the burst and unloaded during the entire orbit cycle. The NaK loop heat rejection radiator system operates for the full cycle and thus may be one-fifth size relative to the non-storage case. The radiator for this case does

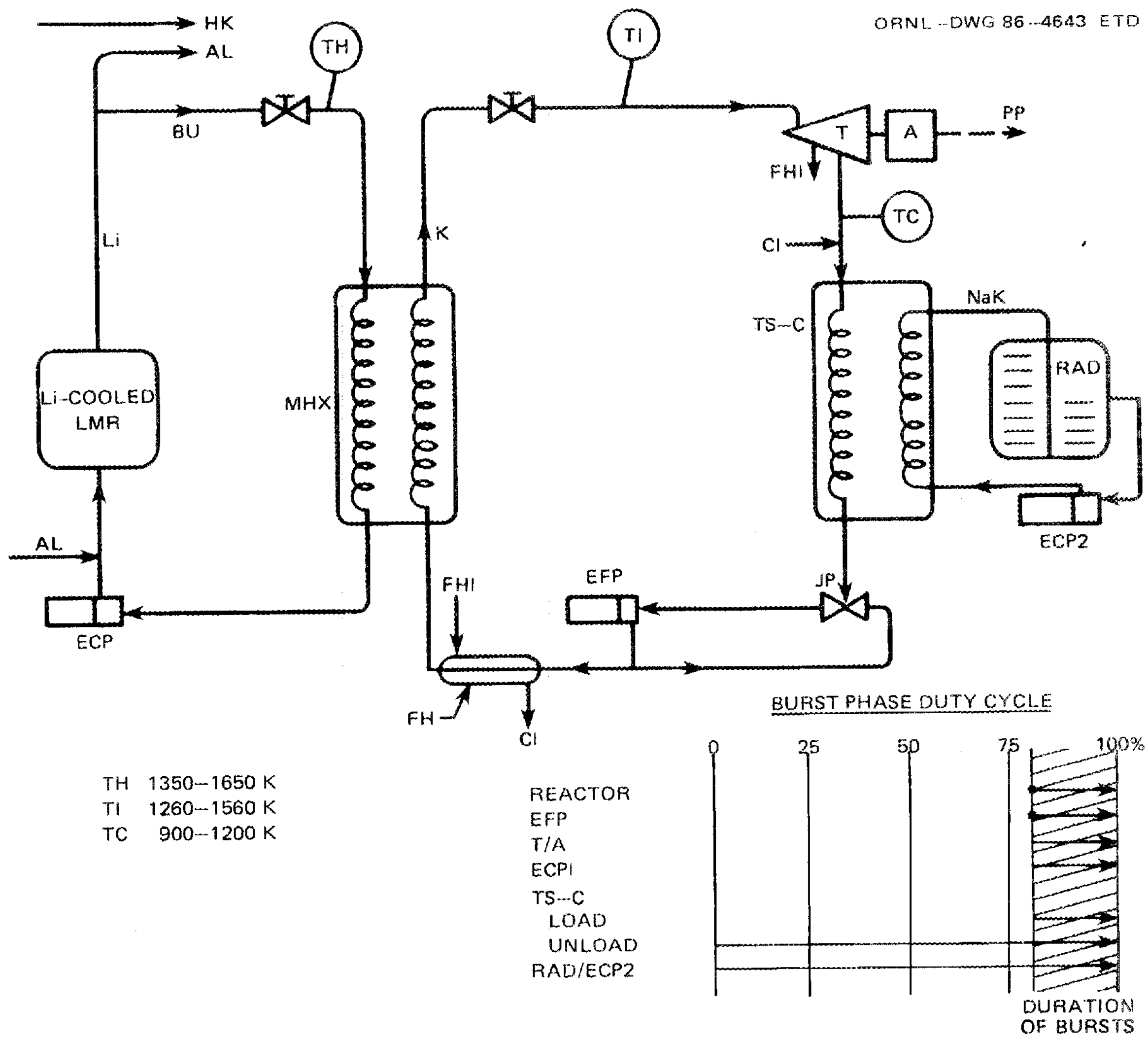


Fig. 2.6. Lithium Cooled Dual Loop LMR burst system — thermal storage condenser.

not perform a condensing function and hence does not operate at constant temperature.

An important subtle benefit common to all back-end thermal storage systems may be higher thermal efficiency for the power cycle. That is, the system may optimize to lower turbine discharge temperature, relative to non-storage, by use of a somewhat larger radiator which would be still substantially smaller than the non-storage case radiator-condenser.

Figure 2.7 illustrates a Lithium Cooled LMR system with both front end and back end thermal storage, the difference between Figs. 2.7 and 2.6 being the replacement of the MHX with a thermal storage device. The

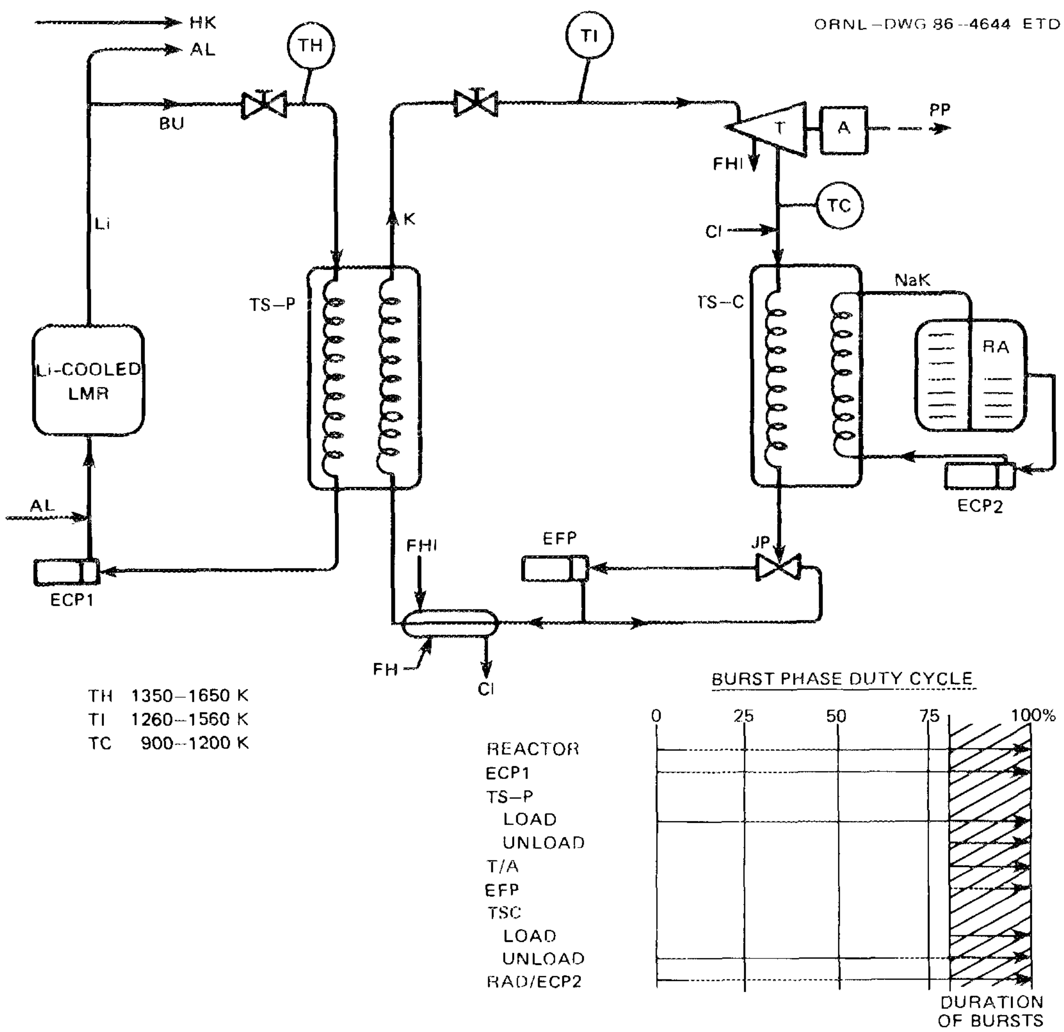


Fig. 2.7. Lithium Cooled Dual Loop LWR burst system — thermal storage prime and thermal storage condenser.

principal advantage, as shown by the duty cycle, is the continuous operation of the reactor over the orbit cycle; thus the reactor size is reduced to about one-fifth relative to the cases shown in Figs. 2.5 and 2.6. The TSP device would be hydraulically simpler and therefore probably smaller than the equivalent device for the Boiling Potassium Reactor (in Fig. 2.3) which functioned simultaneously as a boiler and condenser. In this system arrangement, however, the secondary loop including the turbine-alternator and feed pump, activates only during the burst time, thus there is no size reduction of these components relative to the non-storage case.

Figure 2.8 illustrates the flywheel prime energy storage case for a Lithium Cooled Reactor system. Parallel benefits accrue as already discussed for the Boiling Potassium Reactor, namely, reduced size of all

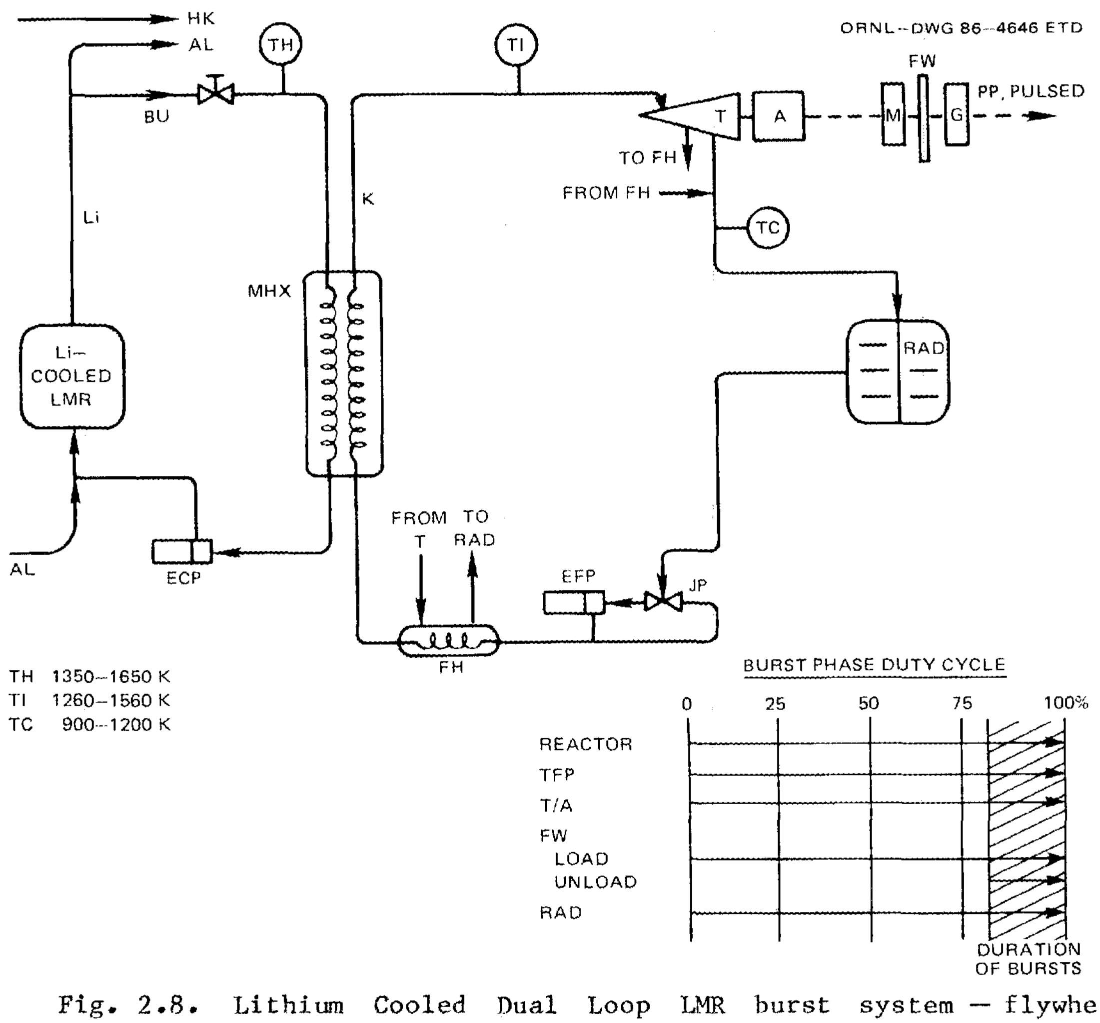


Fig. 2.8. Lithium Cooled Dual Loop LMR burst system — flywheel storage prime.

components relative to the non-energy storage system, including the turbine-alternator; this is shown by the duty cycle legend indicating all components operate for the full orbit cycle. The benefits of small size, continuous operation (no repeated restarts) and possible power conditioning role of the flywheel balance against the added weight and complexity of the flywheel system.

2.4 HTGR Brayton Burst System

An HTGR providing power directly to a Brayton cycle conversion system, with no cycle energy storage, is illustrated in Fig. 2.9. As noted by the duty cycle legend for this non-storage case, the reactor, turbine-compressor-alternator and hence also the radiator operate only for the approximately 20% burst portion of the orbit. A typical HTGR Brayton circuit is shown wherein the primary coolant (helium) drives the turbine and exchanges heat with returning gas in the recuperator before discharging heat by radiation. A single compressor, driven on the turbine shaft, provides all the required primary loop motive power. Also shown is a helium storage reservoir, required for all helium systems for resupply due to continuous leakage and for restart following extended dormancy. The primary loop pressure is controlled by the supply rate from the helium reservoir. We should note that the temperature legend indicates that potentially higher reactor exit temperature are projected for the HTGR compared with liquid metal reactor systems.

Figures 2.10a and 2.10b depict HTGR burst systems employing back-end thermal storage to improve the utilization of the radiator. In Fig. 2.10a, a thermal storage device is placed downstream from the recuperator and therefore would operate at a relatively low temperature. As the duty cycle legend shows, the reactor and turbine systems operate only during the period of the bursts in this version, whereas the radiator coolant loop operates continuously. Therefore, the advantage here, relative to the non-storage case (Fig. 2.9), is a smaller radiator at the cost of providing the thermal storage unit.

It should be noted that both versions 2.9 and 2.10a suffer from requiring thermal radiative discharge at fairly low temperature. This

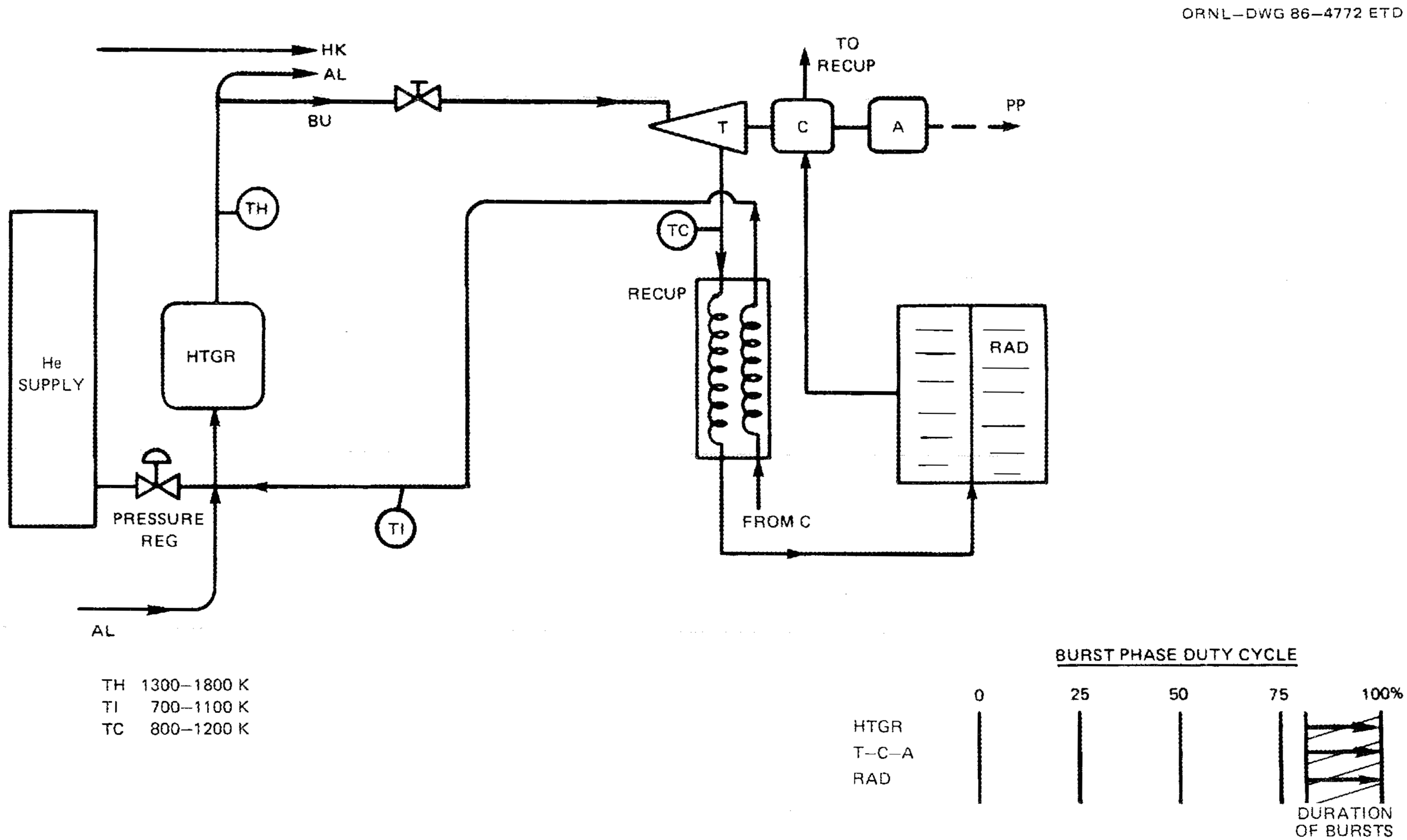


Fig. 2.9. HTGR Brayton burst system — no storage.

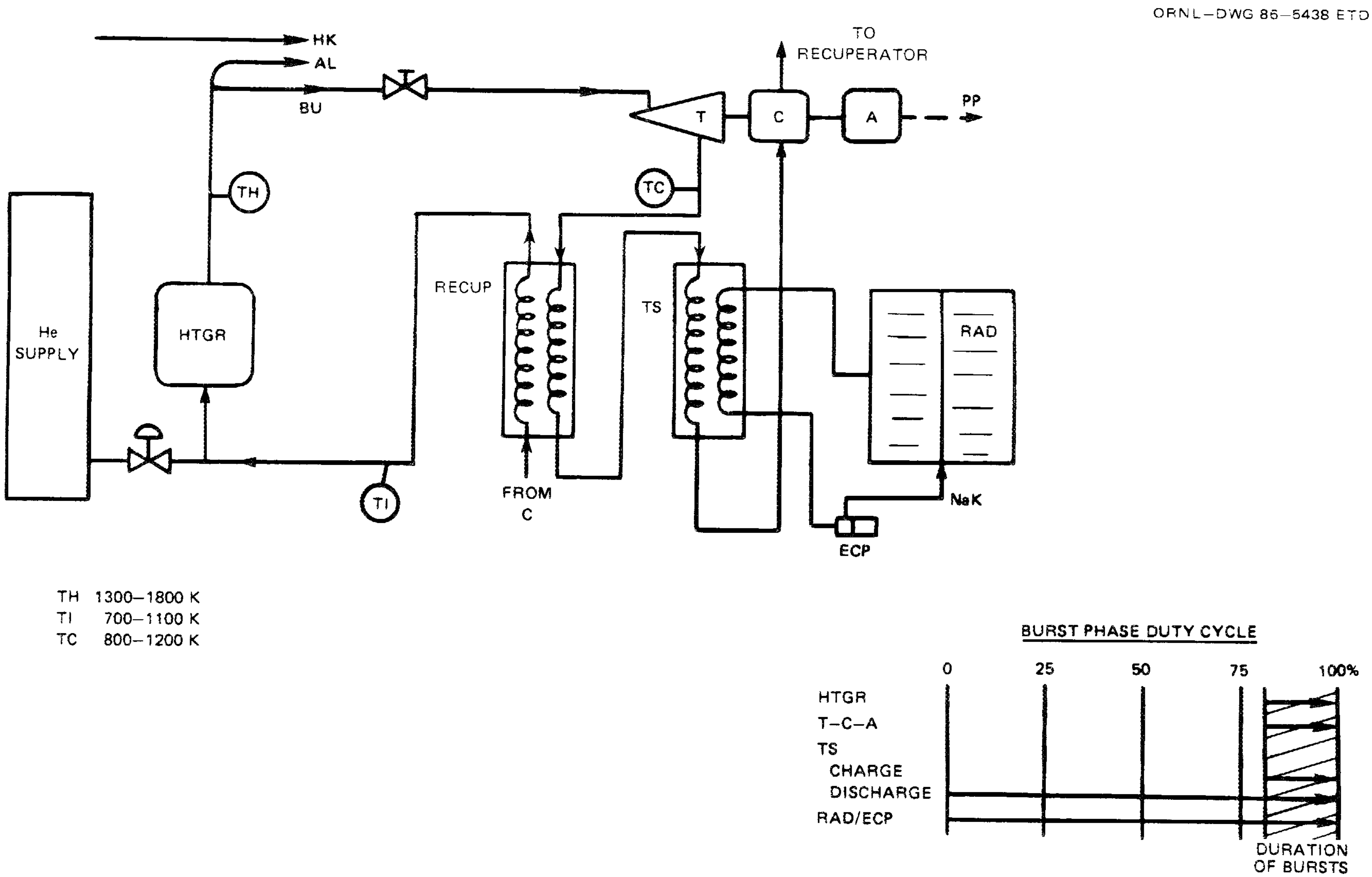


Fig. 2.10a. HTGR Brayton burst system — heat rejection thermal storage.

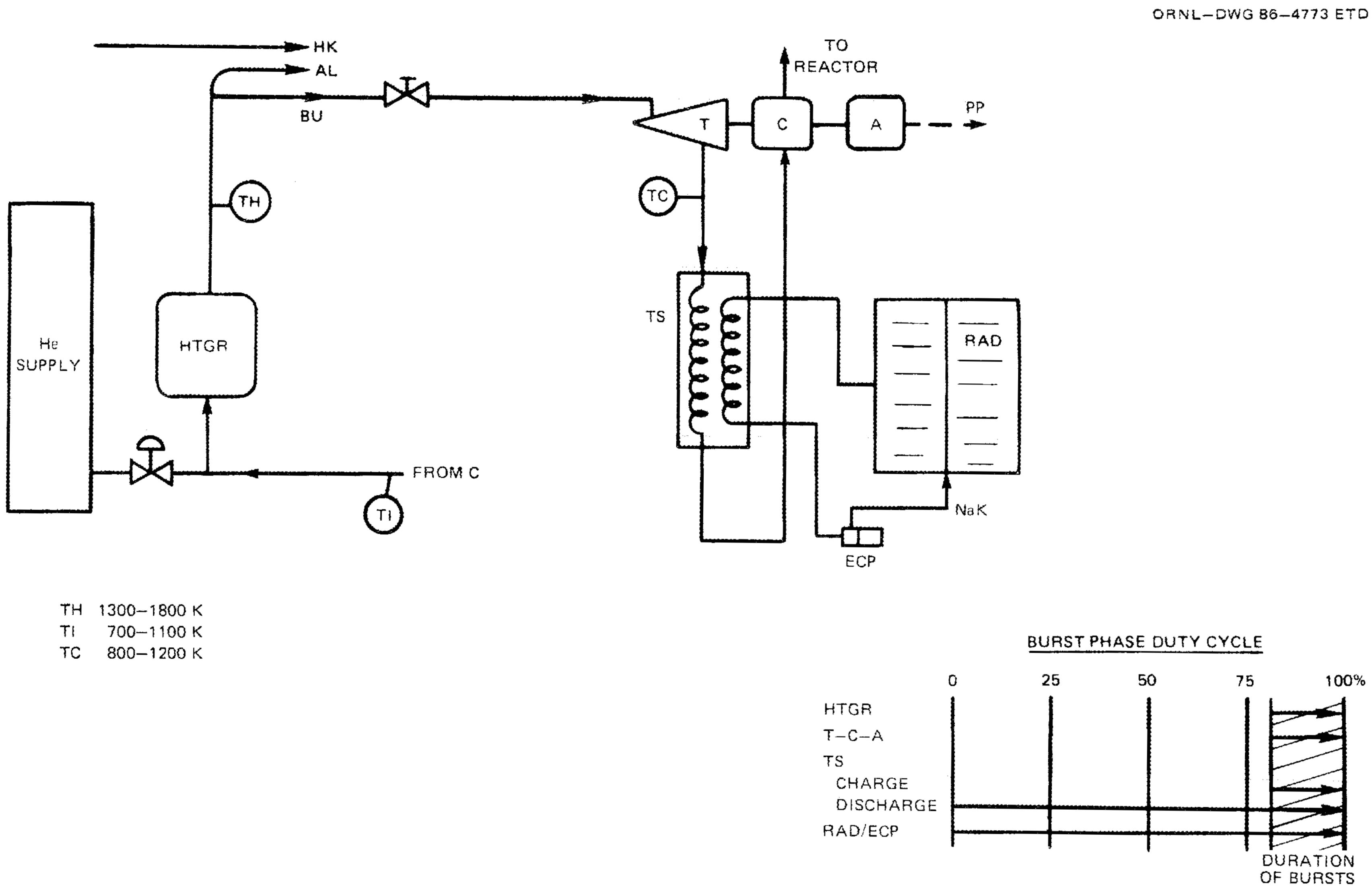


Fig. 2.10b. HTGR Brayton burst system — heat rejection thermal storage.

is caused by the presence of the recuperator which, while it improves thermal efficiency, has the effect of significantly lowering the discharge temperature such that it may burden the radiator. Therefore, one may consider a Brayton cycle system with back-end thermal storage in which the recuperator in Fig. 2.9 is replaced by a thermal storage device, as is shown in Fig. 2.10b. This Brayton cycle version has the advantage, relative to version 2.10a, of requiring a much smaller radiator and one less major component in the primary systems, doing so at a sacrifice of thermal efficiency.

Common to all back-end thermal storage systems are indirect benefits of an overall increase in system hardness and fabricability attendant with the smaller radiator size. In addition there is the likely possibility that the system will optimize to a lower heat reject temperature, by use of a somewhat larger radiator, and thereby gaining an increase in cycle efficiency.

Figure 2.11 illustrates an HTGR Direct Brayton system with flywheel storage of prime power. The potential benefits of flywheel prime energy storage are analogous to that provided for the other reactor systems, namely full cycle operation of all major power components, including the turbine-compressor-alternator and the reactor.

Figure 2.12 shows an HTGR Brayton system employing thermal storage in the primary loop. As shown in the duty cycle legend, so doing enables use of the HTGR for the entire orbit cycle, and hence allows use of a smaller reactor. However, this benefit is weighed against the added weight of the storage device, the need for an additional circulator, the need for electrical power for this additional circulator, and the loss of thermal efficiency on the turbine loop due to temperature degradation relative to the non-storage case (Fig. 2.9).

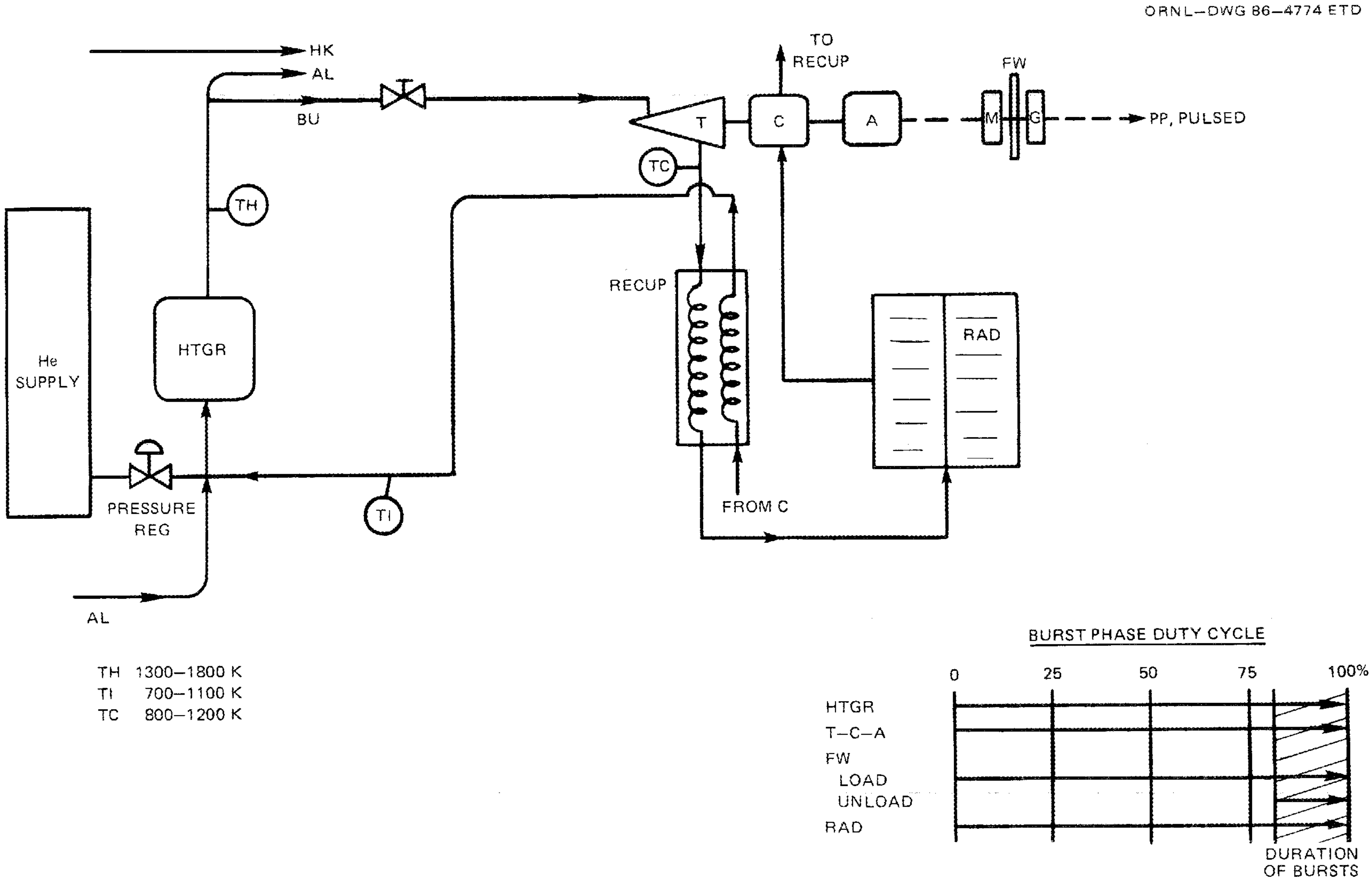


Fig. 2.11. HTGR Brayton burst system — flywheel storage prime.

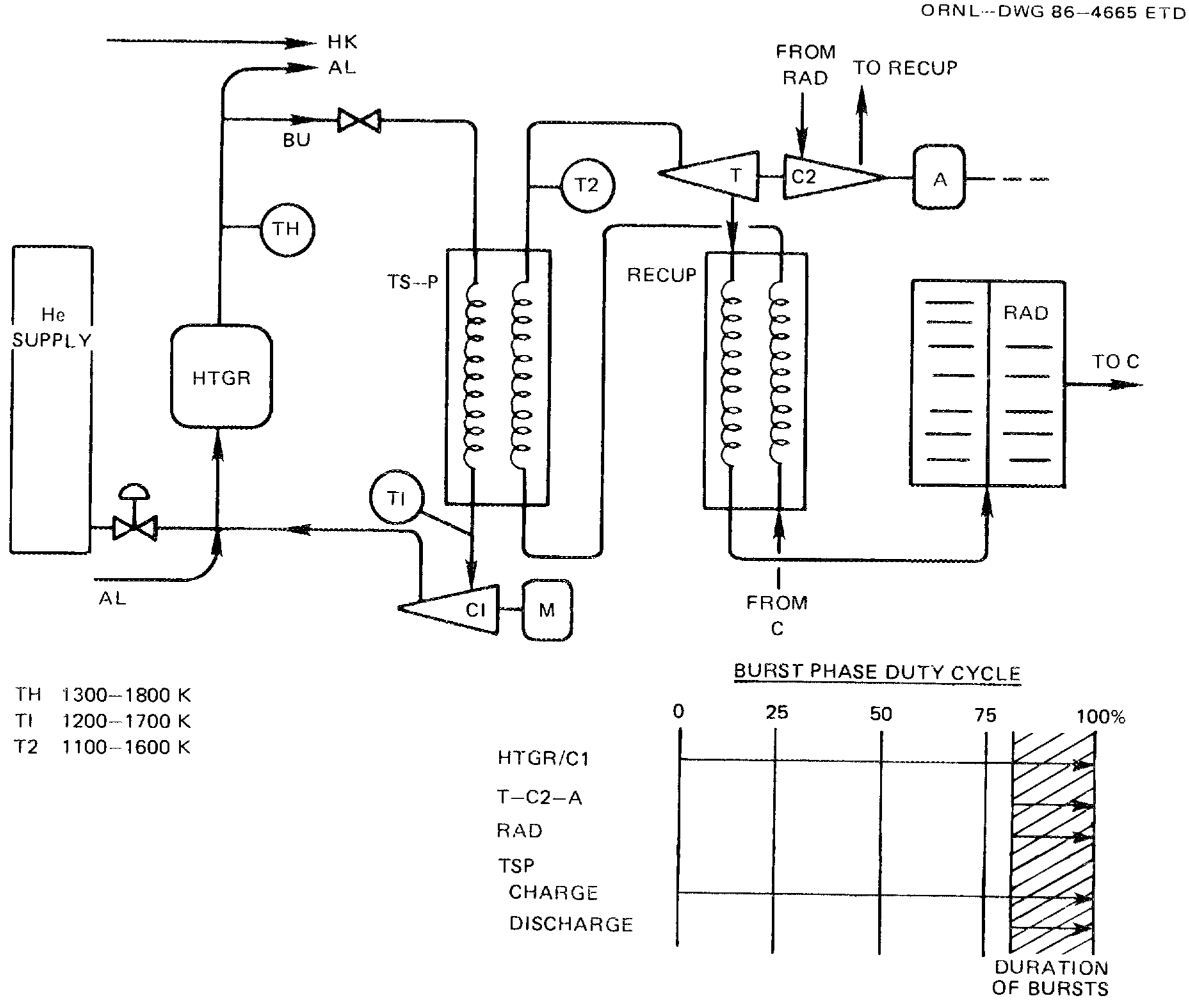


Fig. 2.12. HTGR Brayton burst system — heat supply thermal storage.

3. THERMAL STORAGE R&D PROGRAMS

3.1 Thermal Storage Requirements for Nuclear Systems

3.1.1 Heat supply systems

Temperature range. A front-end heat storage system associated with a Boiling Potassium reactor would accept heat in the temperature range of 1300 to 1600 K, which is a current projection of an upper limit reactor exit temperature, and discharge heat to the turbine working fluid at a somewhat lower temperature. Because of the smaller size and greater simplicity of the primary loop of the Lithium Cooled Reactor, projected upper limit reactor exit temperatures may be ~50 to 100 K higher.

Front end heat storage for the HTGR would require a temperature capability of from 1300 K to 1800 K, the estimated range of upper limit coolant temperatures entering from the HTGR. However, as noted in Sect. 2.4, front end thermal storage does not appear to fit well with an HTGR-supplied burst system due to an expected high ΔT loss in the unit and the requirement for an additional compressor in the primary loop operating at high temperatures.

Thermal storage components. As noted in Fig. 2.3, front-end thermal storage for a Boiling Potassium Reactor requires a device that receives heat from primary loop condensing potassium, and discharges heat by boiling potassium in the secondary loop. As such, it would be well-suited to thermal storage in a phase-change material since both sides of the heat transfer surface would be nearly isothermal.

Front end thermal storage for the lithium-cooled LMR (Fig. 2.7) would require a device which receives heat from a sensible heat drop in flowing lithium and delivers it by boiling potassium on the secondary side. A thermal storage phase change material would thus be required with a melting point less than the lithium outlet temperature. Hence, front end thermal storage for a Lithium Cooled LMR may entail more temperature degradation in the passage of heat energy from the primary to secondary loop than for the Boiling Potassium system. This disadvantage may be alleviated to some degree by use of both phase change and sensible heat storage in a way that will allow the working fluid exit temperature to more closely approach the highest Li temperature.

Thermal storage materials. Front-end thermal storage for the Boiling Potassium Reactor would be best suited to a phase change material with transition in the 1300 to 1600 K range. As noted in Table 1.1, a number of Si eutectics melt in this range and possess high storage capacities in the range 1500 to 1900 kJ/kg. These then would be considered as prime candidates for front end thermal storage, requiring however a resolution of the difficult container compatibility issue common to all molten metals (except the alkali metals).

In addition to the Si eutectics, a few fluoride salts listed in Table 3.1 are also available for consideration in this elevated temperature ranges and with phase change enthalpies in excess of ~500 kJ/kg.

Table 3.1. Fluoride salts with phase change in the 1300 to 1600 K range and heats of fusion in excess of 500 kJ/kg

Salt	Melting point (K)	Storage capacity (kJ/kg)
MgF_2	1536	933
CoF_2	1523	~500
FeF_2	1373	550
CrF_2	1373	~500

Numerous other fluorides are available with melting points in excess of 1400 K, however, these are invariably salts of heavier metals (rare earths, actinides and the heavier alkaline earths) and possess heat storage capacities much below 500 kJ/kg. There has evidently been no compatibility testing with fluoride salts at these elevated temperatures, nor has there been any development of container concepts.

Other potential heat storage materials in the 1300 to 1800 K range are PCMs composed of alkali metal and alkaline earth oxides, a few of which have been listed in Table 1.3. None of these has been tested; however their chemical characteristics are such that compatibility with superalloy cladding material is at least a possibility.

Oxides of other metals and oxygen-bearing salts such as borates, silicates, chromates, etc., with high melting points generally possess storage capacities less than 500 kJ/kg and would likely be incompatible with the refractory metal containers required for these elevated temperatures.

3.1.2 Thermal storage for heat rejection

Temperature range. As noted in Sects. 2.2 and 2.3, the Rankine cycles employed with the Boiling Potassium and Lithium Cooled Reactor concepts require heat rejection systems in the 900 to 1200 K temperature range. The HTGR Brayton system would require a heat rejection system coupled to a turbine exit temperature of from 800 to 1200 K. The PCM used in this device would have to possess a melting point that is less than the He outlet temperature from the thermal storage unit. Precisely what that temperature is would not be known without an optimization study of the entire power cycle, but well may be about 100 K less than the inlet temperature from the turbine exhaust. Therefore, the PCM employed in the HTGR Brayton heat discharge thermal reservoir would require a melting point in the range 700 to 1100 K.

Thermal storage components. The Boiling Potassium and Lithium Cooled Reactor concepts each require similar thermal storage devices for cycle heat rejection. In each case, the storage device accepts heat from potassium vapor at the turbine discharge acting as a condenser, and discharges heat to NaK circulating coolant. As such, it would be nearly isothermal on the high temperature side of the heat exchange surface during thermal charging at which time the PCM is undergoing melting.

The thermal storage device used for HTGR Brayton heat rejection system would affect a heat exchange from hot helium (800 to 1200 K at the inlet during burst operation) to NaK coolant with the heat storage medium as an intermediary. During heat loading, the hot gas inlet would be between 800 and 1200 K with an outlet temperature of perhaps from 700 to 1100 K. The heat storage medium would be cooled by a NaK flow which would operate for the entire charge-recharge cycle.

Thermal storage materials. Candidate heat storage materials for cycle heat rejection may be considered from those being evaluated for the solar dynamic systems planned for NASA's space Station Program. (See Appendix A for a description of the solar receiver development work associated with the Space Station Program and associated discussion in Sect. 1.3.1) Table 1.2 lists some of the PCMs currently being evaluated for use associated with the solar receiver component of the solar dynamic power system. As noted in Appendix A, the PCMs with phase transitions above 1200 K are those being tested for advanced systems; those with lower melting points are being considered for a near term solar Brayton system, while LiOH has been selected for the solar-driven, organic Rankine system.

Also included in Table 1.2 in the 700 to 1200 K melting range, but not being considered for the space station is LiH, which was probably omitted from consideration due to its tendency to dissociate. However, its thermal dissociation tendency is only modest while its heat storage capacity is quite high. Therefore, there is a strong incentive for determining whether or not LiH may realistically be employed in heat reject systems.

Other heat rejection materials may be considered besides the salts listed in Table 1.2, but none appear to have any advantage over them. Some of the Si eutectics fall in low melting range of <1200 K (see Table 1.1), but these possess fairly low heat storage capacity. Some carbonates also fall in this range, but compatibility behavior would be more difficult than for the fluorides, LiOH or LiH, and the degree of heat storage would be lower.

We may summarize the situation relative to potential heat storage materials for cycle heat rejection with the materials listed in Table 3.2.

Table 3.2. Candidate heat storage materials for cycle heat rejection

Heat storage material	Melting point (K)	Heat of fusion (kJ/kg)	Comments
LiOH	746	873	Selected for the solar receiver in the Organic Rankine Cycle Solar Dynamic System. Extensively tested.
Al-12 Si	850	571	Requires encapsulation.
LiH	961	2845	Highest heat of fusion and specific heat. Tendency for dissociation. Some tests planned (DOD).
LiF-14.5 AlF_3	983	721	Being considered in NASA's SSP[a]
LiF-22 CaF_2	1039	~750	Selected for the Closed Brayton cycle solar receiver in NASA's SSP.
NaF-32 CaF_2	1083	~540	
NaF-23 MgF_2	1103	~655	Being tested in NASA's SSP
LiF	1118	1087	
NaF-27 CaF_2-36 MgF_2	1178	520	

[a]Space Station Program.

3.2 Summary of Thermal Storage R&D Programs

3.2.1 NASA-sponsored thermal storage programs

The most active area of thermal storage R&D which could apply to high temperature power systems is currently being conducted by NASA in connection with solar dynamic power for the space station. The role of thermal storage in solar dynamic power systems is to provide heat for the turbine working fluid during periods of orbit shadow, a function which is accomplished in most concepts by incorporating an encapsulated PCM within the solar receiver. Other solar heat storage concepts separate the receiver and storage functions into two devices connected by an intermediate NaK heat transfer loop. At least one concept has been proposed which utilizes a solid sensible heat storage material instead of a PCM with the objective of simplifying the receiver design and avoiding use of an encapsulating metal.

The four NASA programs contributing to thermal storage R&D as described in Appendix A are the following:

1. Corrosion and Compatibility Research for Advanced Solar Dynamic Systems (Appendix A.1)
2. Heat Storage Material Development, conducted for the Space Station Program (SSP)
    2a. Near-Term Solar Dynamic Systems (Appendix A.2.1)
    2b. Solar Dynamic Heat Receiver Technology (Appendix A.2.2)
3. Thermal Energy Storage Tests at NASA Johnson (Appendix A.3)

The three subdivisions shown reflect the administrative units in NASA under which work is being conducted. The first is being performed within the Nuclear and Thermal Systems Office at NASA Lewis. Programs (2a) and (2b) while separate are both conducted within the Space Station Program and are also managed from NASA Lewis. Program (3) is an administratively separate effort conducted within the Propulsion and Power Division at NASA Johnson.

All of the above are similar in two respects - the direction is toward solar dynamic power systems and each places high emphasis on container/PCM compatibility testing. The first program (item 1 above) is directed toward advanced systems and is relatively new; hence the program work scope has not yet been fully developed. The initial, Phase I portion of this program currently in process deals with 100-hr screening tests of NaF-32CaF_2 (T_m = 1083 K) and NaF-23MgF_2 (T_m = 1100 K) eutectic salts with the 27 potential container alloys listed in Appendix A.1. The screening tests involve thermal cycling 25 K above and below each melting point. A visual, preliminary result is reported that only nearly pure elements Fe, Ni and Mo are potentially usable container materials at these temperatures.* This early indication will be verified

*A number of preliminary test results regarding container compatibility with fluoride and LiOH PCMs are in apparent conflict. The reason is believed due to be differences in salt impurity levels.

by subsequent, longer duration controlled testing and post-test metallurigical examination.

Seven additional pure and eutectic salt mixtures are being screened in Phase I of this program; however, no results are yet reported. The current status is summarized in Table 3.3.

Table 3.3. PCMs being tested in phase I of the Corrosion And Compatibility Research Program for Advanced Solar Dynamic Systems

(See Appendix A.1 for potential container alloys)

PCM	Melting point (K)	Latent heat (kJ/kg)
LiF-22 CaF_2	1039	750
NaF-32 CaF_2	1083	~540
NaF-23 MgF_2	1103	~650
LiF	1118	1075
NaF-27 CaF_2-36 MgF_2	1178	520
CaF_2-50 MgF_2	1253	~630
NaF	1268	790
NaF-60 MgF_2	1273	~715
$NaMgF_3$	1303	~710

Phase II of this Advanced Solar Dynamics Materials program is scheduled to begin in the latter part of CY 1986 and will consist of 1000 hr thermal cycle tests for the best combinations of PCM/container alloys selected from Phase I. This program will also begin evaluation of other PCMs of potential use up to 1400 K.

The heat storage technology R&D performed directly within the Space Station Program, as described in Appendix A.2, is being conducted in two parts. The first, currently subcontracted to Rocketdyne, deals with the entire solar dynamic power package. The thermal storage portion, though and important part, is nevertheless subservient to the overall objective. Two types of solar dynamic power systems are being considered in this portion of the SSP - the Closed Brayton Cycle (CBC) with a projected turbine inlet temperature of ~1050 K and an Organic Rankine Cycle (ORC) system with an estimated turbine inlet of 700 K. A choice between the two will be made in Spring of 1987. Up until then, thermal storage material work will be supported for both systems. However, at this time it appears that the following two PCMs are leading candidates for the CBC and ORC solar dynamic systems:

Cycle	Tentatively selected PCM	Melting temperature (K)	Latent heat (kJ/kg)
CBC	$LiF-22CaF_2$	1039	750
ORC	LiOH	747	891

Hastelloy B2 has been demonstrated to be a satisfactory container for $LiF-22CaF_2$ at 1039 K, and both Ni-201 and Inconel 600 alloys were successfully thermal cycled with LiOH between 680 and 780 K.

In addition to the above tentative selections, evaluations work is temporarily continuing on the following PCM materials in a survey-type fashion:

Cycle	Salts evaluated
ORC	LiOH-LiF
	NaF-KF-LiF
	$LiOH-Li_2CO_3$
	$NaCl-MgCl_2$
	$K_2CO_3-Li_2CO_3$
CBC	$LiF-MgF_2$
	$LiF-MgF_2-KF$
	Li, CO_3
	$CaCl_2$
	$LiF-LiBO_2$

A list of potential container alloys tested for compatibility with the above PCMs is given in Appendix A.2.

A second portion of the solar dynamic development work conducted within the SSP, dealing more restrictively with the solar receiver, is described in Appendix A.2.2. In close association with this effort being performed by Boeing Aerospace Division is a NASA LeRC in-house effort focusing on compatibility testing of the PCM/Alloy materials listed in Table 3.4.

Table 3.4. PCM and sensible heat storage materials being evaluated by the NASA LeRC in-house work for the Space Station Program

Cycle	TES material	Melting temperature (K)	Container material
CBC	NaF	1269	Nb
	LiF	1122	Nb
	LiF-29 MgF_2	1019	Ni alloy
	LiF-22 CaF_2	1039	Ni alloy
	Be[a]	1556	
ORC	LiOH	743	Ni 201
	NaF-20 LiOH	700	
	LiF-39 NaF	925	Ni alloy
	Mg[a]	923	Ni alloy
	Zn	693	

[a]Being tested as sensible heat storage materials.

Since this portion of the SSP deals exclusively with the solar receiver component, a number of innovative thermal storage approaches can be evaluated. As noted in Table 3.4, metallic Be and Mg sensible heat storage is being considered for both the CBC and ORC systems, respectively. The original intention was to simplify solar receiver design and fabrication by eliminating the container for the heat storage material. However, it was found that the vapor pressure of Be at ~1100 K was excessive, resulting in mass transport of Be to cooler portions of the loop. Therefore, the original concept has become less attractive as the Be is now known to require cladding. The design strategy was to use sufficiently large Be sensible heat reservoir to allow no more than a 55 K temperature swing in the thermal loading/unloading cycle.

The thermal storage development work at NASA Johnson, described in Appendix A.3, is also directed toward space station solar dynamic power systems. The five PCM salts listed in Table 3.5 are each being exposed to 20 potential cladding materials in thermal cycle tests around their respective melting temperatures. The five week exposures have been completed and have resulted in the elimination of eight potential cladding alloys. The remaining 12 alloys in this testing program are: Armco 18SR, Cabot 214, Hastelloy N and X, Haynes 25, Inconel 600, Ni 201 and SS304, 316, 321 and 347. These will each be tested with the five PCM salts listed in Table 3.5 in 26-week duration thermal cycle tests.

Table 3.5. PCM salts being tested at NASA Johnson

(see Appendix A.3 for container materials)

Cycle	PCM	Melting temperature (K)
ORC	KF-29 LiF-12 NaF	727
ORC	KF-33 LiF	766
ORC	LiOH	746
Intermediate CBC	LiF-33 MgF_2	1012
High temperature CBC	LiF	1121

The results of the 5-week thermal cycle exposures are summarized in Appendix A.3. In summary, it was found that LiOH at 746 K was fairly difficult to contain. Good chemical compatibility was observed only with Ni 200, Ni 201 and Inconel 600, all of which however suffered >20% strength reduction in 5 weeks. On the other hand, 18 of the 20 alloys tested with the ORC fluoride salts showed good compatibility behavior (only two Zr alloys did not) in the 746 and 766 K temperature range.

The higher temperature tests with fluoride salts also showed generally good compatibility behavior for all alloys tested, again except for the Zr alloys and SS347 at the higher test temperature of 1121 K. However, several alloys showed significant strength reduction.

3.2.2 DOD-sponsored thermal storage programs

Currently two DOD-sponsored thermal storage development programs are in process, both supported by the AeroPropulsion Laboratory (APL) of the Air Force Wright Aeronautical Laboratory (AFWAL). The first, described in Appendix B.1, is a new program the scope of which has not yet been fully established. However, a major thrust will be directed toward the feasibility of using LiH as a heat sink material in both a relatively conventional fashion and in an innovative scheme involving direct contact with NaK coolant. The second DOD effort, described in Appendix B.2 involves fluoride salt compatibility testing much like the NASA progress outlined above and in Appendix A.

The four task constituting the DOD program entitled "Energy Storage Concepts for Pulsed Space Power Systems" are described in Appendix B.1. These include:

Task 1. Energy Storage Value Analysis
Task 2. Heat Sink Concepts
Task 3. Heat Source Concepts
Task 4. Property Measurements

Most of the present emphasis is in Task 2 dealing with the feasibility of using LiH as a heat sink material. The incentive is quite high since it possesses the highest specific latent heat of all proposed phase change materials as well as high sensible heat storage capacity (see Table 1.2 and Fig. 1.3). However, its fairly high dissociation pressure at its melting point and the difficulty in dealing with the H_2 overpressure have in the past led to the pressumption that it would be impracticle on a testable, repeat usage basis. Several concepts for coping with the difficult LiH properties will be tested in Task 2 including various containment procedures and one highly innovative procedure in which the LiH heat sink is exposed directly to a NaK coolant.

As noted in Appendix B.1, Task 3 is not scheduled to begin until FY 89 at which time work is projected on use of eutectic Si alloys as heat source materials by use of encapsulation procedures in high melting Si.

A DOD in-house testing program involving fluoride salt compatibility testing with Inconel 617 cladding material is described in Appendix B.2. The following three eutectic salts are being thermal cycled for a planned 10,000 hr duration,

MgF_2-46.9 LiF at 997 K,
MgF_2-39.8 LiF-13.1 NaF at 959 K
MgF_2-42.3 LiF-8.9 KF at 959 K,

where the above compositions are given in weight percent. A total of 18 Inconel 617 capsules, 6 each containing one of the above eutectic compositions are about 50% through the planned 10,000 hr test. Thus far, no failures have been observed. Good metallurigical practice is described for this work involving salt purity verification and specialized container closure procedures to prevent contamination of the salt. High corrosion rates were observed when proper procedures were not followed resulting in air contamination of the fluoride salt.

3.2.3 DOE-sponsored thermal storage programs

A few elements of the fairly extensive DOE thermal storage programs are described only briefly in Appendix C since large areas of application to SDI needs are not anticipated. The reason for this is that the basic thrust of DOE efforts within the Office of Energy Storage and Distribution and the Office of Solar Heat Technologies has been toward commercialization of conservation and renewable energy technologies, e.g., solar thermal electric, waste heat utilization, and for building space heating.

The main effort of the Solar Thermal Technology Division of DOE has culminated in the fabrication and operation of the Barstow Solar Electric Facility. However, nitrate salts, which are not applicable for projected burst power conditions, were selected for thermal storage to provide night-time power.

Though the motivation for the thermal storage program supported by the DOE Office of Energy Storage and Distribution (described in Appendix C.2) differs significantly from SDI requirements, some involve principles or techniques that may potentially be applied with higher temperature materials. The five program elements cited below fall into this category.

1. Composite, High Temperature Media Development,
2. Heat of Mixing Research,
3. Encapsulated Metal PCMs,
4. Slurry Heat Transfer, and
5. Joint NASA/DOE Thermal Storage Research.

Of the above, items 4 and 5 are given second priority in FY 87 and consequently it is doubtful they will be funded. (In addition, funding for Task 3 is now also doubtful.)

The first task, performed at the Institute of Gas Technology (IGT), has developed the concept of containing a PCM within the connected porosity of a non-melting solid matrix. To date, IGT has applied the concept to the containment of carbonate PCMs in oxide ceramics, a material selection not pertinent to SDI. However, the concept has certain desirable features which may find application with other materials. Potentially useful features of this containment concept are (1) enhancement of effective thermal conductance of the storage medium by use of a metallic matrix, and (2) as inherent method of allowing for large phase change volume differences.

Task 2 above, performed by Polytechnic Institute of New York, is directed toward evaluation of the heat of mixing as an energy storage mechanism for low temperature systems. The concept may also apply to higher temperature applications. By itself, the heat of mixing probably does not represent a significant energy storage potential, but metal/salt slurry systems may prove advantageous for other reasons (chemical compatibility, improved thermal conductance), and heats of mixing may enhance heat storage capacities for these dual phase systems.

The use of encapsulated alloy storage material (task 3 above) is directed toward developing ways to encapulate metallic eutectic PCMs within high melting shells. As noted in Sect. 1.3.1.1, a few metals, such as Si (and perhaps only Si), have high latent heat and a series of eutectic alloys with a potentially useful range of melting points, (up to 1685 K for pure Si). Therefore, Si-alloy PCMs may be of direct application to burst power systems, both for heat supply (front end) and cycle heat rejection service. Work at Ohio State University has sought to develop microencapsulation techniques for the Si-Al eutectic (Tm = 850 K) in higher melting Si alloy material by various techniques. These have thus far not proved to be satisfactory. Future work is planned for the higher melting Si-Be system (Tm = 1363 K).

The portion of the DOE Office of Energy Storage and Distribution thermal storage development efforts performed by SERI (Solar Electric Research Institute) or under SDI sponsorship is outlined in Appendix C.2.2. As noted in this appendix, the principal thrust has been toward development of carbonate salt sensible heat storage for solar thermal electric systems and for other potential commercial improvements to these systems.

3.3 Comparison of SDI Program Requirements with Ongoing R&D

SDI Program thermal storage requirements may be assessed by comparison of the projected uses of thermal storage in burst power systems, as outlined in Sect. 2, with current programs and available technology described in Appendices A, B, C and summarized in Sect. 3.2. The evaluation presented below must be regarded as preliminary at this stage due to the currently changing nature of system requirements. Thermal storage program requirements interact strongly with the envisioned types of burst power systems. Thus the elements presented below depend on the presumed nature of these systems described in Sect. 2, i.e., closed cycle nuclear power sources designed for regeneration of burst capability.

1. It is noted that in general incentives for heat supply (front-end) and cycle reject thermal storage exist in the systems described,

but no means is currently available for assessing the cost/benefit ratio. Benefits of thermal storage need to be evaluated against inherent costs by comparisons of system specific power, specific energy and reliability with and without thermal storage for a number of representative cases.

2. The technology for heat supply (front end) thermal storage does not currently exist, nor may it be expected to develop sufficiently rapidly from related NASA, DOD, and DOE efforts. The charter of the NASA Advanced Materials Program (Appendix A.1) extends up to 1400 K and thus may be considered as a contribution. But this is a modest effort, and SDI temperature requirements for the heat source exceed 1400 K. The DOD effort on high temperature Si eutectics is not projected to start before FY 89, if at all. The DOE effort on encapsulated Si eutectics has dealt with the low temperature Si-Al alloy only and is not projected to continue beyond FY 86. Therefore, there is a open technology requirement for heat storage/encapsulating materials for burst cycle heat supply. The required temperature range is 1300 to 1600 K for LMR systems and up to 1800 K for HTGR systems.

3. Currently no program exists for evaluating the use of alkali metal oxides (Li_2O, Na_2O, etc.) and alkaline earth oxides (BeO, MgO, SrO, etc.) as an alternative to the Si eutectics for heat supply (front-end) thermal storage. If a range of eutectics of these oxides exist, they may prove to be potentially attractive for use as high temperature PCMs.

4. Cycle heat rejection storage can utilize heat storage materials developed by NASA for the solar dynamic, space station power system, the heat <u>supply</u> for solar dynamic systems being in the projected heat <u>reject</u> temperature range for burst power systems, i.e., from 900 to about 1200 K. These programs are described in Appendix A and are generally based on fluoride PCM's with storage capacities in the 600 to 800 kJ/kg range.

5. Heat rejection storage capability would be greatly enhanced by the use of LiH in place of fluoride salts as the storage medium. Mass requirements for the thermal storage material could be reduced by as much as a factor of three relative to fluoride salts. There is a small

DOD effort toward LiH thermal storage utilization (Appendix B.1) which, however, is currently directed toward a specific, thermionic power system concept. Additional effort directed toward means for utilization of LiH as a heat reject material would appear to be advantageous to the SDI program.

6. The use of sensible heat to augment latent heat in a rejection thermal reservoir base has been cited as a means for augmenting heat storage capacity. Currently, no program element deals with augmenting PCM thermal storage with sensible heat.

7. The heat transfer dynamics of thermal storage systems form a significant part of the solar dynamic receiver development effort, and a parallel effort for SDI thermal storage units would be required as a means for evaluating system performance. Thermal storage units not only possess an energy storage limitation, expressed by the energy density (kJ/kg) of the particular PCM, but also a specific power limitation, expressed as kW/kg, which depends on the storage configuration, the supply fluid velocities, and condensing or boiling conditions in the heat supply or reject fluid. Until some heat transfer evaluations are performed on projected heat storage components, it is not clear whether thermal storage or heat transfer is the controlling factor on unit mass.

4. FLYWHEEL STORAGE R&D PROGRAMS

Flywheel development programs have been conducted by NASA, DOE and DOD over the past decade. The objectives of these development programs have been different because of the variety in applications concerned. In this section the performance requirements for flywheel energy storage systems for SDI sprint power applications will be delineated. In addition, current and past flywheel development programs sponsored by NASA, DOD and DOE will be summarized and their relevance to the SDI needs detailed. A more complete description of the flywheel programs conducted for the various sponsors is given in Appendices D, E and F.

4.1 Flywheel Storage Requirements for Nuclear Sprint Power Systems

There are two primary measures of performance for flywheel storage systems. Specific energy (or energy density) is determined by dividing the total usable energy stored in the flywheel by the total mass of the flywheel module (this includes the flywheel, motor, generator, containment, suspension system and all other components of the system). Specific power is determined by dividing the output power by the total flywheel module mass.

The mass of the flywheel module is determined by the power or the energy requirements of the specific mission. As an example consider the case illustrated in Table 4.1. As shown, the flywheel module specific energy is assumed to be 360 kJ/kg and the specific power 2.5 kW/kg. These performance levels represent the current capabilities of flywheel systems. For the case where the storage unit must supply 300 MWe for 50 seconds the flywheel system mass is determined by the power requirement. However, when the mission generation time is raised to 300 seconds the flywheel storage module mass is fixed by the stored energy requirement. The general trend implied by this example is illustrated in Fig 4.1. For relatively short generation times the flywheel storage system mass is fixed by the power requirements. As the generation time increases, the system design is governed by the stored energy requirement. There exists a generation time, termed the crossover point, where

Table 4.1. Example of flywheel storage system size

Assumed flywheel performance

Specific power	2.5 kW/kg
Energy density	360 kJ/kg

	Generation time required	
	50 s	300 s
Output power (MW_e)	300	300
Delivered energy (GJ)	15	90
Storage system mass (kg)		
– meet power requirement	120,000	120,000
– meet energy requirement	41,667	250,000

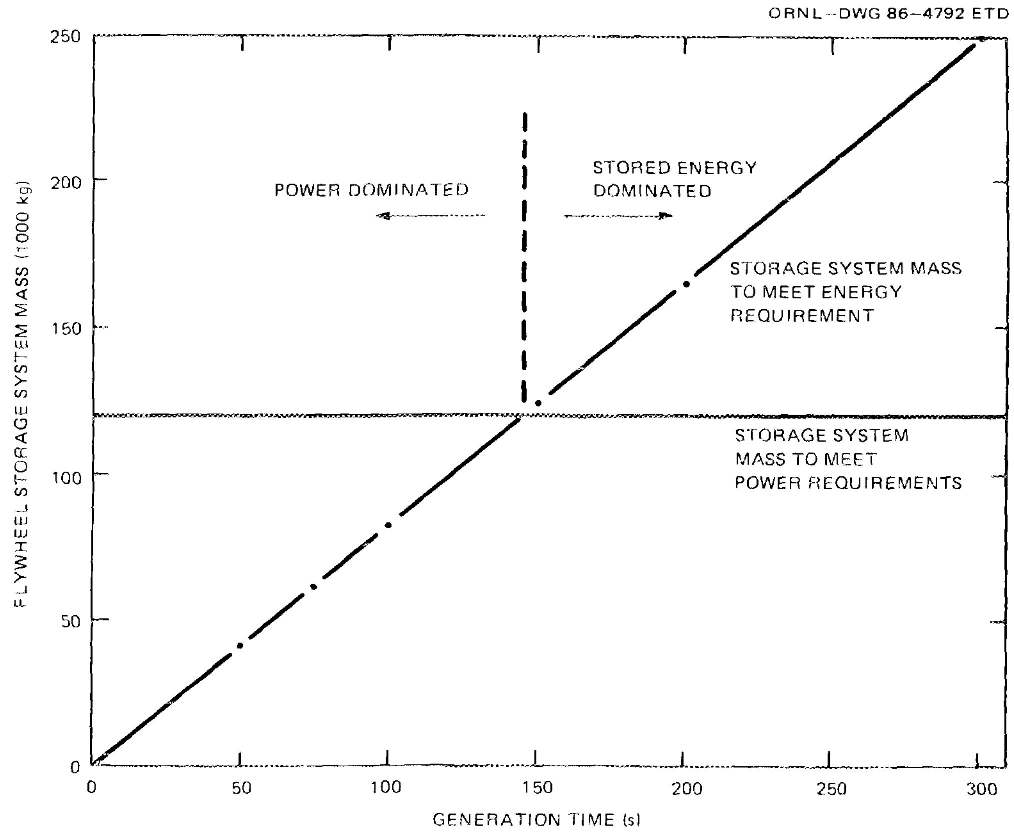


Fig. 4.1. Flywheel mass as a function of generation time for a given concept (Re: Table 4.1).

the energy and power requirements of the mission yield equal storage system masses. Beyond this time the design is dominated by energy storage considerations rather than power needs. The crossover point can be calculated by dividing the specific energy by the specific power. In the example cited above the crossover point occurs at 144 seconds.

As suggested by the discussion above, the mission power level and generation time will be important parameters in determining the required storage performance levels. Within the MMW Space Power program the performance goals set for regenerable energy storage systems include a specific power of 2.5 kW/kg and a specific energy of 450 kJ/kg. As shown in Fig. 4.2, these performance standards result in mass savings for nuclear Rankine cycles for generation times as long as 800 seconds (see Morris, 1986 for details of the analysis). For generation times as long as 550 seconds the total system mass with storage is less than half that of the non-storage system. This indicates that the mass added to the system by including storage is not as great as that deleted by the need for a smaller primary power system.

The results also point to the fact that if benefits are to be extended to longer generation times it will be necessary to improve the specific energy rather than the specific power. Thus the specific power goal is not as critical as the specific energy standard and, research should focus initially on increasing the stored energy density.

Typical SDI mission requirements include output power levels of hundreds of megawatts and delivered energies on the order of tens to hundreds of gigajoules. The total storage system would consist of a number of independent modules to provide for system reliability. This would result in typical module that would be capable of a power output on the order of 100 MWe and would have an energy storage capability on the order of 15 GJ. Since a module contains two counter-rotating rotors, each flywheel must store 7.5 GJ. In addition, each module would meet the performance goals of 2.5 kW/kg for specific power and 450 kJ/kg for specific energy.

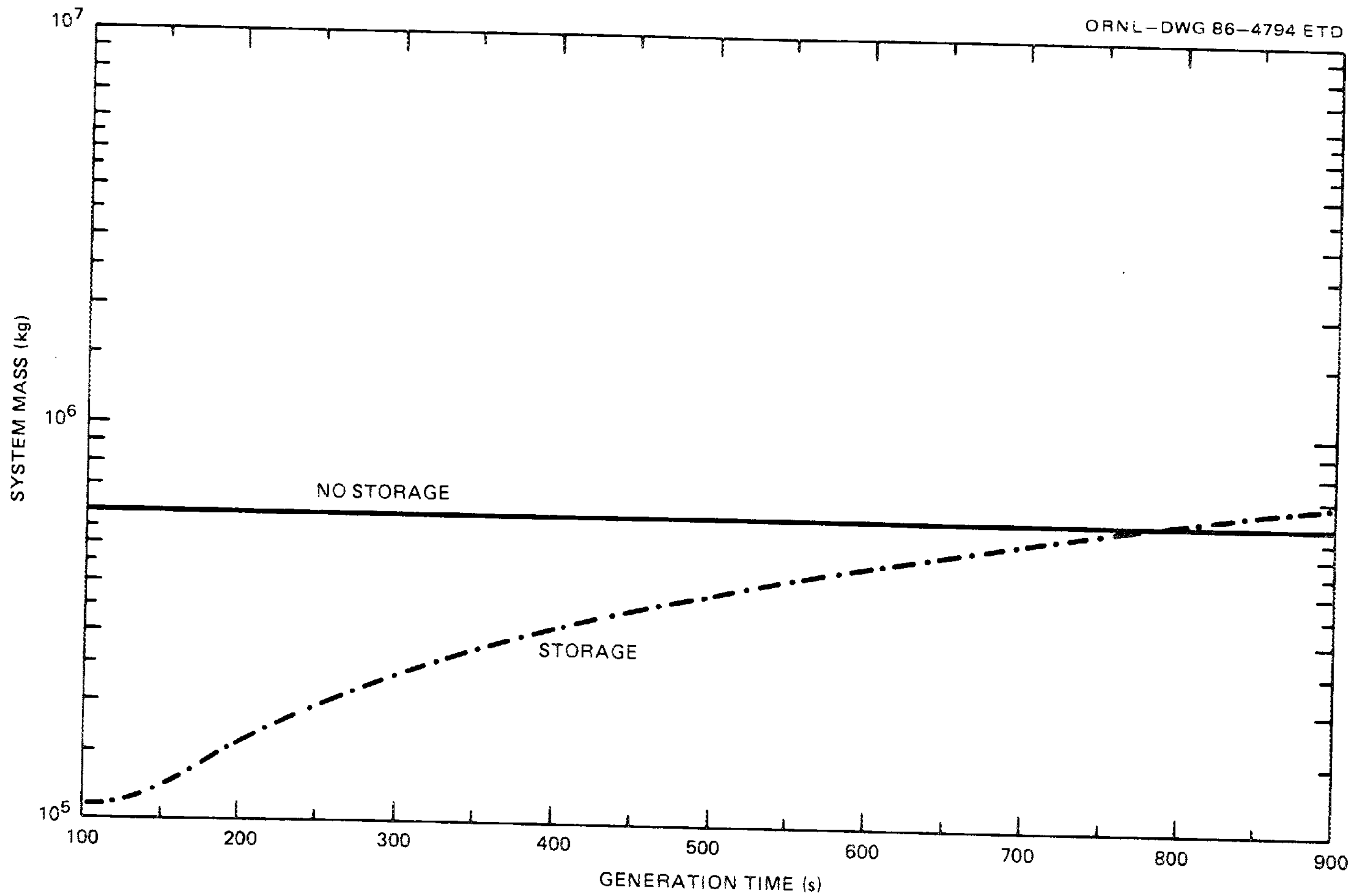


Fig. 4.2. Boiling potassium rankine burst power system mass with and without flywheel energy storage [preliminary results (Morris, 1986)].

4.2 Summary of Flywheel Storage R&D Programs

Over the past decade flywheel development programs have been conducted by NASA, DOD and DOE. As described in Appendices D, E and F, each has had its own application, hence the research goals have been different.

The NASA program (detailed in Appendix D) has been directed at the development of integrated power and attitude control systems (IPACS). Their studies indicate that combining the two functions in a single flywheel package can result in mass savings of 25% or more when compared to the conventional approach using batteries for energy storage and control moment gyros for attitude control. In general, the system requirements are modest compared to those of SDI applications. Power levels are on the order of 2 to 5 kW and total stored energy is on the order of 1.5 MJ. Since the primary application is for power during the dark portion of a vehicle's orbit the charging and discharging time ratios are about three to one. Because requirements are modest, the systems can be designed at relatively low performance levels. Energy storage densities are typically on the order of 100 kJ/kg.

Several programs have been sponsored by NASA in the development of integrated storage and attitude control systems. NASA Langley Research Center sponsored a program in the mid 1970's designated as the Integrated Power and Attitude Control Program (IPACS). This program produced laboratory hardware designed to satisfy the requirements of an advanced solar observatory mission. A titanium constant-stress disc was used in conjunction with a brushless DC motor/generator. The operating speed range was 17,500 to 35,000 rpm. Total usable stored energy of the flywheel system was 5.4 MJ and the storage density was 69 kJ/kg. The delivered power was 2.5 kW.

The combined-function inertial storage system concept was again investigated in 1985 and 1986. This work was sponsored by NASA Goddard Space Flight Center and was designated the Attitude Control and Energy Storage (ACES) concept. This concept envisions the use of a radially thick rotor (having a ratio of internal to external diameter on the order of 0.6). The magnetic suspension system and permanent magnet motor/generator are integrated into the flywheel rotor in the internal bore resulting in a design that is very efficient in terms of volumetric density. The original intent of the program was to demonstrate the feasibility of the integrated flywheel concept by building and testing a prototype. The prototype was to have a usable energy of 1.08 MJ with a power rating of 500 W. The design has been completed but funding is not available to construct the unit. The rotor design was based on the use of Celion 1200 graphite fibers and had a storage density of 72 kJ/kg. In addition to the design activity some limited experimental work was performed on the magnetic suspension system (using a much smaller wheel) and the power electronics.

The DOD flywheel activities have focused on inertial storage for advanced generators (see Appendix E). Typically, these advanced generators are to be used for electromagnetically launching projectiles in tactical weapon systems. This work is being performed by a team consisting of the University of Texas (generator development) and the Enrichment Technology applications Center (ETAC) of Martin Marietta Energy Systems (flywheel development). A development program, funded by DARPA, was initiated in 1985 to develop composite rotors for an advanced homopolar generator. The activities to date include the design and construction (to be completed in January 1987) of a spin testing facility for rotors of up to 76 cm diameter and the development of advanced rotors using the newest high-strength graphite fibers.

The characteristics of the test rims, built as part of the DARPA rotor development activity, are given in Table 4.2 and the test results are given in Table 4.3. As indicated the design was intentionally failed in a test on December 9, 1985. The rim specific energy at failure was 878 kJ/kg. This was double the previous best ultimate energy density level achieved by a flywheel rim. These results provide firm experimental support for the design of flywheels, using the high-strength graphite fiber, which have an operational maximum peripheral speed of 1200 m/s. At this speed the rim specific energy is 663 kJ/kg. This operational specific energy for the rim only gives a firm basis for optimism in meeting the SDI goal of 450 kJ/kg.

Table 4.2. Characteristics of test rims built for DARPA by the Enrichment Technology Research Center

(Olszewski, 1986)

Demo unit	Axial length mm (in.)	Radial thickness mm (in.)	Rim weight (kg)	Rim inertia (kg-m^2)
1A	101.6 (4.0)	38 (1.5)	12.5	1.34
1B	48.3 (1.9)	38 (1.5)	5.8	0.63
1C	48.3 (1.9)	38 (1.5)	5.8	0.63

Table 4.3. Flywheel demonstration test results for rims built as a part of the DARPA effort and tested at the Enrichment Technology Applications Center

(Olszewski, 1986)

1985 Date	Demo unit	Velocity (m/s)	Rim specific energy [kJ/kg (Wh/kg)]	Rim stored energy (MJ)	Results
Oct. 17	1A	1055	495 (138)	6.5	Web failure, small crack. No rim damage.
Nov. 8	18	1173	605 (168)	3.8	Stopped for inspection. No damage.
Nov. 12	1C	1221	663 (184)	4.2	Stopped for inspection. No damage.
Dec. 9	1C	1405	878 (244)	5.4	Intentional failure test.

The emphasis of the DOD program is now shifting and compulsator technology is replacing homopolar generators as the primary emphasis of the program. To match the needs of the compulsator the flywheel will operate at a relatively low peripheral speed (on the order of 500 m/s). Hence high performance flywheels will not be required. This activity is expected to begin in FY 1987.

As indicated in Appendix F, the DOE interest in flywheels began in the late 1970's with the inception of the Mechanical Energy Storage Technology (MEST) Program. The focus of this program was to produce a flywheel for transportation applications that had an energy storage density at ultimate speed (the speed at which failure occurs) of 316 kJ/kg (88 Wh/kg). Program management responsibilities were shifted several times during the course of the program's lifetime. By 1980 the program was managed by ORNL. In addition to overall program management responsibilities, ORNL developed spin testing capabilities and acted as the independent test facility to verify performance characteristics of rotors supplied by industrial firms. The program was phased out by DOE in 1983.

The performance testing was accomplished in two phases. The first phase focused on ultimate speed evaluations. The maximum ultimate storage density achieved was 286 kJ/kg and the maximum stored energy was 3.08 MJ (see Appendix F). In the second testing phase, cyclic fatigue testing was added to the testing regime. The disc and disc/rim designs successfully completed 10,000 cycles and showed no degradation in storage density at ultimate speed.

In FY 1986 the DOE provided technology transfer funding to ETAC to build upon their enrichment technology experience and apply this expertise to generic flywheel development work. The activities undertaken include application of composite structure analysis capability to flywheel design, design and procurement of winding equipment suitable for flywheels appropriate for SDI needs and procurement of assembly tooling for flywheels. This funding is for one year only and will, when combined with the testing facilities built under DOD auspices, represent a unique facility for developing and testing high performance flywheels.

4.3 Relevance of Other Flywheel Development Programs to SDI Needs

The salient features of each of the flywheel development programs is detailed in Table 4.4. Also given in Table 4.4, for purposes of comparison, are the anticipated needs for MMW sprint power applications.

Table 4.4. Summary of flywheel development programs

Program	Sponsor	Status	Application	Performance[a]		Module capability[a]		Cycles complete
				Specific energy (kJ/kg)	Specific power (kw/kg)	Output power (kw)	Stored energy (MJ)	
IPACS	NASA - LaRC	Inactive	Spacecraft Integrated power and Attitude Control System	69	0.03	2.5	5.4	
ACES	NASA - GSFC	Inactive	Spacecraft Integrated power and Attitude Control System	72	0.03	0.5	1.08	
Flywheels for Avanced generators	DARPA	Inactive; awaiting redirection	Develop flywheels for inertial storage for advanced homopolar generators	878[b] (ultimate) 663[b]	NA[c]	NA	6.5[b]	
MEST	DOE - Office of Energy Storage	Inactive	Develop flywheels for transportation applications	286 (ultimate)	NA	NA	3.06 (ultimate)	10,000
Technology Transfer	DOE - Enrichment Technologies	Funded FY 1986 only	Develop capability to apply enrichment expertise to flywheels - Focus is procurement of tasks, rather than flywheel development					
MMW Sprint Power Needs	DOE - DOD	To be funded beginning FY 1987	SDI/Nuclear Sprint Power Sys-Systems	450	2.5	16,000	20,000	<1,000

[a]Unless otherwise noted values are operational performance levels rather than values at ultimate speed.

[b]Rim-only values.

[c]Not available.

The most striking feature of the table is the fact that after FY 1986 there will be no active flywheel development programs being conducted in the United States. Moreover those programs that were conducted are applicable to the SDI sprint power needs in only a limited manner.

As illustrated in the Table 4.4, the performance levels achieved in the NASA flywheel programs are orders of magnitude below those required for SDI sprint power systems. The same is true for the module capability in total stored energy and power. Since the NASA missions have relatively modest needs (in terms of power and stored energy), it is not surprising that the NASA work is not greatly relevant to the SDI needs. Although much of the NASA work is not directly relevant, some portions address issues that are important to the SDI program. Specifically, the magnetic suspension effort that is directed at isolating the flywheel from the spacecraft. This was important in the space observatory mission since platform jitter would have been detrimental to the astronomical objective. It is also important in the SDI sprint power mission since platform jitter will adversely affect aiming accuracy. The experimental work to date has been at too small a scale to be of direct benefit. However, if NASA starts a new program in this area that works with larger scale rotors the technology development results would be of interest.

The MEST Program was also directed to an application that did not require extremely high performance levels. Thus, the program is of only limited value to the SDI needs. The most significant contribution is related to the cyclic lifetime performance of composite flywheels. The MEST program demonstrated that composite flywheel specific energy was not diminished after 10,000 cycles. Since the SDI application will involve on the order of 1000 cycles, materials properties (primarily tensile strength) do not have to be downgraded in the design to account for cyclic fatigue effects.

Taken together the DARPA funded effort and the DOE technology transfer work provide an excellent base for developing the flywheel technology required for SDI sprint power modules. The demonstrated specific energy levels are sufficiently above the SDI requirement to give optimism that the operating goals can be met. Most importantly, through these two programs ETAC has acquired the specialized equipment necessary to develop flywheels for the SDI mission.

This assessment of flywheel programs has shown that there are no existing flywheel development efforts that duplicate the work to be accomplished in the MMW Sprint Power Program. Indeed, the review has demonstrated that it is only through this program that the required technology can be effectively developed. It is also evident that the Enrichment Technology Applications Center is the most logical place to conduct the development program.

5. SUMMARY AND CONCLUSIONS

1. The manner in which heat supply (front end) and heat rejection thermal energy storage and flywheel energy storage may be applied to regenerable, burst power systems based on the Boiling Potassium Rankine LMR, the Dual Loop Lithium Cooled LMR and the Direct Cycle Brayton HTGR reactors is described in Sect. 2. In general, energy storage devices in regenerable systems allow continuous operation of some of the major components (depending on the particular energy storage device) which, in turn, allows smaller component size.

2. A summary of thermal storage conditions required for heat supply (front end) and cycle heat rejection (back end) thermal storage is provided in Table 5.1. Also listed are the principal benefits and disadvantages of each type of thermal storage use. Similarly, the principal benefits and disadvantages of flywheel energy storage are summarized in Table 5.1 as well as the current MMW program flywheel performance goals.

3. Heat supply thermal storage enables reduction in the required reactor size, but does not affect size requirements for the turbine/generator or heat rejection components. Heat supply thermal storage fits well with the Boiling Potassium Rankine LMR system where condensing potassium on the hot side and boiling potassium on the working fluid size enable near isothermal operation. A heat supply thermal storage unit for a Lithium Cooled LMR would be loaded by a sensible heat drop in the primary fluid and unloaded by boiling potassium on the working fluid side. Front end heat storage devices may not be well suited for Direct Cycle Brayton HTGR systems primarily because an additional compressor would be required to circulate the primary loop helium.

4. Heat supply thermal storage for LMR-based systems would require heat storage materials approximately in the 1200 to 1600 K temperature range. HTGR-based systems may require heat storage materials effective over a wider range due to the higher projected reactor outlet temperature and larger temperature drop of the helium in the storage unit. The technology for heat storage in these temperature ranges does not currently exist.

Table 5.1. Energy storage conditions and advantages/disadvantages

Heat supply (front-end) thermal storage	
Temperature Range	
Boiling Potassium and Li-Cooled Reactor systems	1200-1600 K
HTGR Brayton systems	1200-1800 K
Advantages	
(1) Allows continuous reactor operation	
(2) Reduces reactor size	
(3) Probably reduces total system mass	
(4) Fits well with Boiling Potassium Rankine systems	
Disadvantages	
(1) Added mass of storage unit	
(2) Reduced cycle efficiency due to ΔT's in the storage unit,	
(3) For the HTGR Brayton system — requires additional motor-driven compressor	
(4) For the HTGR Brayton system — difficult design of the thermal storage unit due to large sensible ΔT's	
(5) Requires development of heat storage systems (i.e., the storage medium plus container)	
Heat rejection (back-end) thermal storage	
Temperature Range	
Boiling Potassium Rankine and Lithium LMR systems	900-1200 K
HTGR Brayton systems	700-1200 K
Advantages	
(1) Reduced radiator size (therefore also, lower drag, easier assembly, hardened system) and total system mass	
(2) Possibly higher optimum cycle efficiency	
(3) Can apply existing technology	
Disadvantages	
(1) Added mass of storage unit	
(2) For the HTGR Brayton system — difficult design of the thermal storage unit, due to large sensible heat ΔT's	
Flywheel energy storage	
MMW Performance Goals	
Specific energy (kJ/kg)	450
Specific power output (kW/kg)	2.5
Advantages	
(1) Permits continuous operation of the reactor, turbine/alternator and heat rejection systems during period of generation of bursts	
(2) Permits smaller reactor, turbine/alternator and radiator, relative to non-storage case	
(3) May contribute a power conditioning function	
Disadvantages	
(1) Added weight	
(2) Mechanical complexity; additional failure modes	

5. The only active development work contributing directly to heat storage materials required for front end heat storage is NASA's Advanced Thermal Storage Systems program described in Appendix A.1. However, this program is directed toward solar dynamic power, and its charter extends from 1050 to only 1400 K which is in the lower end of the needed temperature range. High temperature thermal storage material development may be included in the DOD-sponsored program described in Appendix B.1 beginning in FY 1989, but this is not assured and the support level would be modest. No DOE-sponsored work was found contributing directly in this area.

6. The following approaches appear to offer the best chance for development of heat supply storage capability in the 1300 to 1600 K range:

a. High melting fluoride salts, most notably MgF_2 with a 1536 K melting point and 933 kJ/kg energy storage capacity. However, the fluoride salt options in this temperature range with energy storage capacities in excess of 500 kJ/kg are not large. Fluoride salts have good inherent compatibility behavior but require tight impurity control of organics, moisture, and oxygen. High temperature fluoride salts may be rendered more attractive by addition of a metallic phase to enhance thermal conductance and to mitigate the effects of high volume change on melting.

b. A range of silicon eutectics are available in the 1300 to 1683 K range. These have the advantages of high heats of fusion, high thermal conductance, and low volume change on melting. The technology for employing these in contact with liquid metal or gaseous heat transfer media does not currently exist.

c. Some metal oxides such as Li_2O and Na_2O are highly stable and therefore may be compatible with container materials in this temperature range, perhaps aided by the presence of an alkali metal oxygen getter. However, it is not clear if convenient eutectics of these highly stable metal oxides exist.

d. At this stage, one should not eliminate consideration of sensible heat reservoirs which may find advantage due to mechanical simplicity, especially for use with helium-cooled systems. In this regard, sensible heat reservoirs consisting of boron or graphite may be considered.

7. The principal advantage of heat storage for cycle heat rejection (back-end heat storage) lies in allowing smaller radiators, as storage would allow operation over the entire burst plus regeneration time periods. This may result in lower total system mass. Other advantages may accrue which have not been quantitatively assessed: (a) lower system vulnerability (due to a smaller radiator), (b) lower system drag (again due to the lower profile area from the smaller radiator), (c) the requirement for in-orbit assembly may be reduced due to the more compact nature of thermal storage relative to the radiator, and (d) use of thermal storage for heat rejection may allow higher thermal efficiency for the power cycle by lowering the effective heat rejection temperature.

8. Cycle heat rejection storage would require similar devices for both the Boiling Potassium Rankine and Lithium Cooled LMR concepts; i.e., heat loading by condensing potassium from the turbine exhaust in the 900 to 1200 K temperature range and heat discharge to a radiator by means of a pumped NaK loop. Back end thermal storage for the HTGR Brayton system would accept helium turbine exhaust in 700 to 1200 K range and also unload to a continuously operating NaK loop.

9. Heat reject materials technology is available from NASA's Space Station Program in configurations appropriate for solar heat receivers for the Closed Brayton Cycle (CBC) system, which requires heat storage in the 1050 to 1100 K range (see Appendix A.2). In addition, NASA's Advanced Thermal Storage Systems program (Appendix A.1), whose range of interest extends from 1050 to 1400 K, will provide useful information. The Space Station Program has focused on $LiF-22CaF_2$ eutectic melting at 1039 K, whereas the NASA Advanced Materials Program is relatively new and will examine fluoride/metal slush systems and silicon eutectics as well as fluoride salts.

10. Heat storage for cycle heat rejection (back-end) may be significantly improved if LiH proves to be a feasible heat storage material. With a heat of melting of 2845 kJ/kg at 961 K, it has more than

three times the heat storage capability of many of the fluoride salts being considered. In addition, it possesses a high specific heat, such that thermal storage units taking advantage of both latent and sensible heat storage may prove even more advantageous. An investigation regarding the practicality of so using LiH is being undertaken within a DOD-sponsored program outlined in Appendix B.1. However, the principal thrust of this effort is currently directed towards a specialized application for a thermionic system in which the LiH and NaK heat transfer media are brought into direct contact.

11. The principal problem in use of LiH as a heat reject material relates to its long-term stability. It possesses a significant dissociation pressure at its melting point, and consequent loss of hydrogen by diffusion gradually converts the material to Li. Therefore, means for adequate H_2 containment over the projected utilization lifetime is a development issue. In addition, a fairly low thermal conductance and high volume change on melting present practical problems in LiH utilization. These negative aspects of LiH may to some degree be mitigated by addition of an adequate amount of Li metal as a second phase.

12. Besides the well-tested LiF-22CaF_2 salt and the speculative LiH, there exist numerous fluoride salt combinations in the melting range anticipated for cycle heat rejection (see Appendix A and Tables 1.2 and 3.2). Numerous container materials have been tested for compatibility with these fluoride salts within NASA programs, currently up to about 1100 K. There exist no container compatibility tests with fluoride salts above 1100 K at this time.

13. Table 5.2 summarizes the above considerations and presents four heat storage development areas which would likely be of near-term benefit to nuclear-based MMW systems. Included here are the clearly advantageous series of Si-alloys with congruent melting temperatures higher than 1239 K (see Table 1.1) for cycle heat supply, and lithium hydride-based systems for cycle heat rejection. Since the feasibility of neither of these systems is assured, some development effort along more conventional directions, e.g., high temperature fluorides and fluoridal metal "slush" systems, appears prudent. In addition to the cited material development areas, work is required on defining the

Table 5.2. Thermal storage — key development areas and issues

Development area	Key issues
1. Advanced heat storage systems (i.e., storage media plus containment) for T > 1100 K	1. Evaluation of candidate systems in the 1100—1800 K range; fluorides, metal/fluoride, oxide, metallic systems 2. Optimization of heat storage medium mass per system mass 3. Behavior through phase change in 1-g and microgravity
2. Silicon eutectic alloy systems	1. Development of high melting alloy systems ($T_m \geq 1239$ K) for cycle heat supply. See Table 1.1. 2. Containment procedures; passivated metals vs ceramics 3. Thermal and mechanical design properties 4. Chemical compatibility
3. Evaluation of lithium hydride based storage systems	1. Degree of dissociation and hydrogen containment 2. Optimum container material 3. Container configurations for accommodating large volume change; effect of void formation 4. Behavior in microgravity 5. Effective design properties over unit life 6. Thermal conductance enhancement
4. Thermal and mechanical design	1. Minimum system mass configurations 2. Mitigate effects of void formation in storage medium 3. Means for accommodating sensible heat ΔT's 4. Heat exchange configurations for boiling/condensing and latent heat energy transport

configurations for affecting the heat transfer to and from the heat storage media. These configurations require careful evaluation in order to minimize the mass ratio of structure to heat storage media. This is especially true for the more complex thermal hydraulic situations involving large ΔT's resulting from heat transfer from a fluid with large sensible heat change.

14. The use of flywheel energy storage in regenerable, nuclear-based, burst power systems allows continuous operation of all the major power supply components, including the reactor, turbine-generator and heat rejection components. This feature is illustrated by the legends labeled "Burst Phase Duty Cycle" associated with flowsheets shown in Sect. 2. Therefore, flywheel energy storage permits a size reduction of these components by a factor approximately equal to the ratio of the duration of the burst pulses relative to the total cycle time including regeneration.

15. Projected sprint power applications require flywheel modules with an energy storage capability of about 15 GJ with a power output of about 100 MW(e). In addition, each module would be required to meet performance goals of 2.5 kW(e)/kg specific power and a specific energy of 450 kJ/kg.

16. Over the past decade, flywheel development programs have been conducted by NASA, DOD, and the DOE. The critical features of these programs are illustrated in Table 5.3. Also provided in Table 5.3 are the anticipated needs for MMW sprint power applications. From the table it is clear that the only active flywheel development program in FY 1987 will be that associated with the MMW SDI program.

17. As illustrated in Table 5.3, the performance levels achieved in the NASA flywheel programs are orders of magnitude below those required for SDI sprint power systems. The same is true for the module capability in total stored energy and power. Since the NASA missions have relatively modest needs (in terms of power and stored energy), it is not surprising that the NASA work is not greatly relevant to the SDI needs. Although much of the NASA work is not directly relevant, some portions address issues that are important to the SDI program. Specifically, the magnetic suspension effort that is directed at isolating the

Table 5.3. Summary of flywheel development programs

Program	Sponsor	Status	Application	Performance[a] Specific energy (kJ/kg)	Performance[a] Specific power (kw/kg)	Module capability[a] Output power (kw)	Module capability[a] Stored energy (MJ)	Cycles complete
IPACS	NASA - LaRC	Inactive	Spacecraft Integrated power and Attitude Control System	69	0.03	2.5	5.4	
ACES	NASA - GSFC	Inactive	Spacecraft Integrated power and Attitude Control System	72	0.03	0.5	1.08	
Flywheels for Avanced generators	DARPA	Inactive; awaiting redirection	Develop flywheels for inertial storage for advanced homopolar generators	878[b] (ultimate) 663[b]	NA[c]	NA	6.5[b]	
MEST	DOE - Office of Energy Storage	Inactive	Develop flywheels for transportation applications	286 (ultimate)	NA	NA	3.06 (ultimate)	10,000
Technology Transfer	DOE - Enrichment Technologies	Funded FY 1986 only	Develop capability to apply enrichment expertise to flywheels - Focus is procurement of tasks, rather than flywheel development					
MMW Sprint Power Needs	DOE - DOD	Minimal funding in FY 87	SDI/Nuclear Sprint Power Sys-Systems	450	2.5	16,000	20,000	<1,000

[a]Unless otherwise noted values are operational performance levels rather than values at ultimate speed.

[b]Rim-only values.

[c]Information not available.

flywheel from the spacecraft. This was important in the space observatory mission since platform jitter would have been detrimental to the astronomical objective. It is also important in the SDI sprint power mission since platform jitter will adversely affect aiming accuracy. The experimental work to date has been at too small a scale to be of direct benefit. However, if NASA starts a new program in this area that works with larger scale rotors the technology development results would be of interest.

18. The MEST Program was also directed to an application that did not require extremely high performance levels. Thus, the program is of only limited value to the SDI needs. The most significant contribution is related to the cyclic lifetime performance of composite flywheels. The MEST program demonstrated that composite flywheel specific energy was not diminished after 10,000 cycles. Since the SDI application will involve less than a 1000 cycles, materials properties (primarily tensile strength) would probably not have to be downgraded in the design to account for cyclic fatigue effects.

19. Taken together, the DARPA funded effort and the DOE technology transfer work provide an excellent base for developing the flywheel technology required for SDI sprint power modules. The demonstrated specific energy levels are sufficiently above the SDI requirement to give optimism that the goal can be met. Most importantly, through these two programs ETAC has acquired the specialized equipment necessary to develop flywheels for the SDI mission.

20. This assessment of flywheel programs has shown that there are no existing flywheel development efforts that duplicate the work to be accomplished in the MMW Sprint Power Program. Indeed, the review has demonstrated that it is only through this program that the required technology can be effectively developed. It is also evident that the Enrichment Technology Applications Center is the most logical place to conduct the development program.

REFERENCES

AFWAL (1980), *Advanced High-Power Generator for Airborne Applications*, Report AFWAL-TR-80-2130, study by Rockwell International for Air Force Wright Aeronautical Laboratories.

Ananthanarayanan, V., Gallo, R., Ravi, V., Thacker, W., Varol, I., Mobley, C., and Rapp, R., *Hypereutectic Heat Storage Shot*, Annual Report on Contract No. 19X-43394C, The Ohio State University Research Foundation, Columbus, Ohio, Jan. 15, 1985.

Birchnell, C. E., and Riechman, A. F., "Heat Storage in Eutectic Alloys," *Met. Trans. A*, Vol. 11A, pp. 1415—1420, (1980).

Farkas, D., and Birchnell, C. E., *Met. Trans. A*, Vol. 16A, pp. 323—328, (1985).

Fee, D. C., *Fuel Cell Development for SDI Applications*, Argonne National Laboratory Report, to be published.

GE Technical Bulletin (1983), "Electric Motor Drive Subsystem," FS-69(500) 3-83, Ordinance Systems-Electronic Systems Division, Pittsfield, MA.

Gully, J. H., Estes, E. G., Walls, W. A., and Weldon, W. F. (1984), "Compact Homopolar Generator Developed at CEM-UT," IEEE Trans. on Magnets, MAG-20:20-3-206.

Hoffman, H. W. et al., "Energy Storage Options for Space Power," *Proceedings of 2nd Symposium on Space Nuclear Power Systems, Albuquerque, NM, Jan. 9-11, 1985.*

Janz, G. J. et al., *Physical Properties Data Compilations Relevant to Energy Storage, I. Molten Salt Eutectic Data*, NSRDS-NBS 61, Part 1, March 1978.

Kaufmann, K. W., and Lorsch, H. G., *Preprint 76 WA/HT-34 ASME*, December 1976.

Mahefky, J. Beam, "Spacecraft Thermal Power Systems for Cryocooler Applications", AIAA Conference on the Future of Aerospace Power Systems, St. Lewis, MO, March 1977.

McCulloch, W. H., Letter to R. J. Sovie, May 5, 1986, "MMW Power Systems Requirements Guidelines".

Mobley, C. E. and R. A. Rapp, "Hypereutectic Heat Storage Shot," The Ohio State University Project Proposal No. 17062-55-00, The Ohio State University, Columbus, Ohio, August 1986.

Morris, D. G., Hoffman, H. W., and Olszewski, M. O., *Energy Storage Concepts for Pulsed Space Power Cycles, Annual Report for Period May 1985-June 1986* (to be published).

O'Connell, L. G. et al., *Energy Storage Systems for Automobile Propulsion: Final Report, Vol. 2: Energy Storage Devices*, UCRL-53053-80, Dec. 15, 1980.

Olszewski, M. and O'Kain, D. V., "Advances in Flywheel Technology for Space Power Applications," *Proceedings of 21st Intersociety Energy Conversion Engineering Conference, August 25-29, 1986, San Diego, CA.*

Project Staff, "SDI, Multi Megawatt Space Nuclear Power Program," April 1986.

Smith, John et al., "NASA LeRC/Sandia Briefing on Nuclear Burst Power Systems", March 1986.

Weldon, W. F., M. D. Driga, W. L. Bird, K. M. Tolk, H. H. Woodson, and H. G. Rylander, "Compulsator - A High Power Compensated Pulsed Alternator," in *Proceedings of Second International Conference on Energy Storage, Compression, and Switching, held in Venice, Italy, December 5-8, 1978*, pp. 124-138.

Appendix A

THERMAL STORAGE R&D SPONSORED BY NASA

A.1 Corrosion and Compatibility Research for Advanced Solar Dynamic Systems

Administrative. This is a relatively new, largely in-house NASA Lewis program conducted within the Material Division. On some documents it appears with the shorter title "Advanced Thermal Energy Storage Systems." Programmatically, this work appears within the Nuclear and Thermal System Office (NTSO) at LeRC, R. J. Sovie Office Manager. The program is managed by T. Mroz, Head of the Advanced Solar Dynamics group in the NTSO.

This program is closely related to but administratively separated from the design and development of solar dynamic power systems conducted within the Space Station Program (SSP) (see A.2). Although the SSP conducts some similar material development as this program, the intention here is to provide higher temperature capability and more extensive R&D than possible within the SSP.

Objective

The objective of this program is to develop thermal energy storage systems for advanced, high temperature solar dynamic space power systems. Specifically, to identify combination of energy storage media and containment alloys for use in space at temperatures between 1025 and 1400 K.

Work description

The work plan is arranged into the following four phases:

Phase I consists of a literature review and identification of potential storage media in the 1025 to 1400 K range. Screening tests for salt/metal combination at T_m + 25 K are in process and are planned for 100 h duration. As a part of the screening process, corrosion and microstructure examination will be performed.

In Phase II, 1000 h exposures of salt/container alloy combination will be performed on materials identified by Phase I. Phase II will also include metallographic examination of containers and welds and tensile strength measurements, using the as-received alloy as control. In other words, Phase II is essentially a continuation of the screening program using longer tests, with added room temperature tensile strength change and microstructure alteration measurements.

Phase III will involve in-situ tensile tests of container alloys specimens in salts at T_m + 25 K. Exposure times of 2500 h in liquid salt and salt vapor are included. In addition, tensile and measurements will be performed up to T_m + 300 K and creep measurements from T_m − 50 to T_m + 50 K, with the as-received alloy used as control.

Phase IV will continue the screening process with 10,000 h tests at T_m + 25 K plus some accelerated corrosion tests at T_m + 125 K. Tensile tests at T_m + 300 K and creep measurements at T_m ± 25 K will be used in the evaluation, with the as-received alloy as control.

Level of Effort (proposed)

FY	$ (k)
86	325
87	350
88	500
89	500
90	500

Status and Schedule

As the schedule shown in Table A.1 indicates, the initial screening phase (phase I) was begun in FY 86 and is currently in progress. The work emphasizes fluoride salts in this initial phase; later, consideration will be given to non-fluoride salts and ceramic heat storage materials.

The 100-h screening tests at T_m + 25 K have been started, with initial results reported for the NaF-32 CaF_2 (T_m = 1083 K) and NaF-23 MgF_2 (T_m = 1100 K) eutectics. Twenty-seven alloys have been exposed to the former; visual, preliminary indication is that only the pure elements Fe, Ni, and Mo have the potential for satisfactory container material at this temperature.

The container materials being tested in Phase I are:

Table A.1. Schedule and status - Advanced Solar Dynamic Program

Phase	Year	'86				'87				'88				'89				'90			
	Quarter	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
I. Identify possible combinations via ~100 h exposures @ T_M + 25 K		←	—	—	—	—	—	—	—	—	—	—	—	—	—	—	→				
II. Refine choices by ~1000 h testing @ T_M + 25 K					←	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	→
III. Demonstrate feasibility with ~2500 h exposures @ T_M + 75 K								←	—	—	—	—	—	—	—	—	—	—	—	—	→
IV. Proof of long term life at T_M + 25 K with goal of no loss in mechanical properties after 10^4 h of exposure										←	—	—	—	—	—	—	—	—	—	→	

Nearly Pure Metals

Ni (Ni-200)
Fe (mild steel)
Ti (A30)
Mo
Nb
Ta
W

High Temperature Alloys

Co-based H25 and HS-188
Fe-based austenitic alloys (304, 316, and 347 stainless steels and high Ni alloys A286, N155, RA330, and 310)
Ferritic alloy 185R
Ni-based - several Hastelloys
High Ni, Superalloys 702, K-Monel, 600, 718, and Nimonic 75

In addition to the above two salts, the following seven are being screened in Phase I: LiF-22 CaF_2, LiF, NaF-27 CaF_2-36 MgF_2, CaF_2-50 MgF_2, NaF, NaF-60 MgF_2, $NaMgF_3$. All possess latent heats in excess of 500 kJ/kg, which is one of the selection criteria.

A report was written [Misra and Whittenberger (1986)] on estimating heats of fusion of fluoride salt eutectics.

Application to SDI Nuclear

The temperature range of direct examination in this program, 1025 K to 1400 K, is of direct interest for SDI nuclear applications. (SDI-nuclear would probably consider heat rejection at $T < 1200$ K and front end supply at temperatures between 1200 and 1800 K. Therefore, the particular salt/container combinations surviving this program of careful screening and testing would probably not be used for SDI-nuclear.

However, the extensive information being developed on fluoride melt/container alloy compatibility would be supportive of material selection efforts for SDI-nuclear.

A.2 Heat Storage Material Development Conducted Within the Space Station Program (SSP)

Administrative. The space station concept developed by the Space Station Program (SSP), which is currently NASA's highest priority effort, is envisioned as an essentially planar structure, ~140 m by

110 m wide, assembled in space and placed in permanent orbit for the support of 4 habitats housing 8–12 people and several experimental modules. Initially, the space station will be provided with 25 kW(e) of power from a photovoltaic bank. Plans call for augmenting power in later phases (beginning in June 1994) in steps of 50 kW(e) with solar dynamic systems [two units of 25 kW(e) each], ultimately growing to total supplied power of about 300 kW(e) for the space station. The SSP is being coordinated from NASA Headquarters in Washington; responsibility for the development and construction of the power systems rests with NASA Lewis, with the NASA Johnson center having the responsibility for the structure.

The overall schedule for the power system development work is planned as follows:

	Begin	End
Phase B Definition and preliminary design		December 1986
Phase C/D Final design and fabrication	May 1987	Through the PMC[a] phase
Preliminary design review	May 1988	
First SS launch	~1993	
First SS launch with solar dynamic power	~1994	

[a]Permanent manned capability.

Currently, two options for the solar dynamic system are still being considered — an Organic Rankine Cycle (ORC) with a turbine inlet temperature of ~700 K and a Closed Brayton Cycle (CBC) with turbine inlet at ~1090 K. Selection between these two options will be made early in phase C/D.

Solar dynamic systems require energy storage for shadow power during the ~30% of the 100 min orbit with no isolation. Usually, this is designed as thermal storage within the receiver provided by a PCM. The

SSP is considering thermal storage via PCM material for the near term system: use of sensible heat storage to augment or even replace the PCM is being considered for advanced systems.

The power systems development work for the SSP has been organized at NASA LeRC by Steve Cohen, Solar Dynamic Subsystems manager, into two parallel efforts:

(1) Design and fabrication of the power systems.

This is a ~$6 M/y effort dealing with the entire power systems package. Rocketdyne is the primary contractor for Phase B and also appears to be the leading contender for phase C/D. Subcontract work at Garrett deals with the CBC system; subcontractor Sandstrand focuses on the ORC system.

(2) Advanced Systems Work

It was intended that this effort funded at ~$3 M/y, would focus on a few critical areas, primarily the receiver, and lead the design and fabrication work. However, the demands of a rapid schedule have somewhat blurred those respective roles. The Advanced Systems work has been contracted to Boeing, with NASA LeRC contributing in the area of material compatibility at a ~$200 K/y level. Barber-Nichols, under subcontract to Boeing, is concentrating on ORC materials and receivers.

As one may surmise, TES considerations are an important part of the power systems work in the SSP, but are more or less folded into the overall effort to deliver a complete system on a fairly tight schedule. An extensive search was conducted for the optimum TES system for each of the power systems being considered — the ORC with turbine inlet at ~700 K and the CBC with ~1050 K turbine inlet.

A.2.1 TES work for the design and fabrication of the near term solar dynamic system for the SSP

As noted above, Rocketdyne is the prime contractor for Phase B of the work, which is scheduled for completion December 1986. The scope of the TES survey and testing work performed by Rocketdyne and its subcontractors has been outlined in the proceedings of a recent meeting [Lee (1985)].

Rocketdyne (Prime Contractor, Phase B)

Initially, a survey of salt properties was conducted covering the following materials.

Cycle	Salts evaluated
ORC	LiOH
	LiOH-LiF
	NaF-KF-LiF
	LiOH-Li_2CO_3
	NaCl-$MgCl_2$
CBC	LiF-MgF_2
	LiF-MgF_2-KF
	Li_2CO_3
	$CaCL_2$
	LiF-$LiBO_2$
	NaF-CaF_2-MgF_2

The salts were evaluated according to the criteria in the following order:

Thermal capacity
Thermal conductivity
Volume change on melting
Compatibility
Stability
Experience

As a result of this survey and the subsequent testing program the following salts were chosen for the ORC and the CBC.

Cycle	Selected PCM	T_m
ORC	LiOH	747 K
CBC	LiF-21 CaF_2	1039 K

Corrosion Tests. The objective of the corrosion tests are to verify the integrity of the salt containers under thermal cycling and duration condition to be experienced in the solar receivers. A portion of the work on fluoride salts was subcontracted to Arizona State University.

Test Parameter Range

Salt	Temperature	Metal
LiF	850-1444 K	Hastelloy B2 316 SS, Nb-1%Zr
LiF-33 MgF_2	1022 K	Haynes 25, Hastelloy B2, 316 SS
LiOH	683-783 K	Ni 201, Inconel 600
LiF-MgF_2-KF	300-1025 K	I617, 304 SS

These tests included both isothermal coupons immersed in the melt and canisters thermal cycled through the phase change temperature. The tests indicated the following:

- Nb-1Zr, Hastelloy N and B2, and Haynes 25 possess satisfactory corrosion resistance to the fluoride salts in the temperature regime of the tests. Hastelloy B2 showed a corrosion rate of <0.01 mpy with LiF-33 MgF_2 at 1022 K.
- Ni-201 and Inconel 600 was resistant to attack from LiOH. A Ni-201 canister was successfully thermal cycled >900 times between 683 K and 783 K.
- Salt purification is beneficial from a corrosion point of view.
- Exposure of LiOH(ℓ) with Na(ℓ) liberated H_2 according to the reaction:

$$2\ LiOH + 2\ Na \rightarrow Li_2O + Na_2O + H_2$$

These tests were performed in support of a concept in which the TES and receiver are physically separated, the TES receiving heat by means of a pumped NaK loop.

Sandstrand (Subcontractor to Rocketdyne)

Some Phase B work (within the SSP) dealing with the development and design of the ORC solar dynamic system was subcontracted to Sandstrand by Rocketdyne. The following candidate PCM's were considered by Sandstrand for the ORC,

	TM (K)	Heat of fusion (kJ/kg)
LiOH	747	~904
K_2CO_3-47 Li_2CO_3	761	~302
KF-33 LiF	766	~381
KF-29 LiF-12 NaF	727	~435

and subjected to the following screening activities:

Thermophysical property survey,

300 h screening tests,

4000 h capsule/coupon corrosion tests.

The subcontract schedule called for completion of the corrosion tests and the receiver conceptual design by approximately June 1986. As a result of this work and a parallel effort at Rocketdyne, LiOH was selected as the PCM and Ni-200 alloy as container material for the ORC solar dynamic system.

The following corrosion tests were performed:

LiOH

Two Ni-200 capsules at 756 K for 500 h.

K_2CO_3-47 Li_2CO_3

Nine type 321 and one type 316 stainless steel capsules at 778 K for up to 4000 h.

KF-33 LiF

Four type 316 stainless steel capsules at 778 K for 4000 h.

Further compatibility testing of LiOH with 26 alloy materials was sub-subcontract by Sundstrand to Argonne National Lab. These consisted of 300 h tests of LiOH at 773 K with 20 Ni-based alloys (Cabot 214, 7 Hastelloys, 2 Incoloys and 4 Inconels, Monel 400, Multimet N-155, Ni 200, Ni 270, and 2 Rene's), and pure Fe, Haynes 188, pure Ag, pure Ti, Ti-8Al-MoV, Zircaloy 2, and Zr-702. These extensive screening tests with LiOH come to the following conclusions:

- Pure metals (Ni, Zr, Ti, Ag) showed superior corrosion resistance to LiOH than the various Ni-Cr-Fe-Mo-Co alloys tested, with pure Ni showing the least corrosion.

- Pure Fe showed significant reaction.
- Cr addition to Ni-based alloys was detrimental; Fe-addition improved Ni-based alloys.

Garrett (Subcontractor to Rocketdyne)

Garrett was a Phase B subcontractor to Rocketdyne within the SSP in areas dealing with the CBC solar dynamic system, including the receiver design and selection of the TES material. The work at Garrett in the TES area has included:

(1) A survey phase, in which the properties of several carbonate, chloride and fluoride salts were evaluated. This survey selected the LiF-32 MgF_2 salt (later charged to LiF-22CaF_2) as being the best choice in the desired temperature range. The thermal capacity of fluorides were found to be 50 to 100% higher than carbonates in the temperature range (~1100 K), and were compatible with "superalloy" cladding materials. In addition, the carbonates displayed a tendency to form gases.

(2) A physical chemistry measurement program, including verification of the reported heats of fusion and composition of the Li-32 MgF_2 eutectic.

A.2.2 Solar Dynamic Heat Receiver Technology Program

This contributing effort to the SSP is funded at ~\$3M/y with Boeing Aerospace Company as the prime contractor accompanied by a NASA LeRC in-house effort at ~\$200 K/y. The Boeing work consists of the following seven tasks:

Task 1: Tradeoff studies between various solar receiver conceptual designs,

Task 2: Identification of testing requirements for concept verification,

Task 3: Tooling and fabrication

Task 4: Detailed design

Task 5: Hardware tests

Task 6: Demonstration tests

Task 7: Hardware delivery

Boeing has subcontracted work related to the ORC receiver to Barber-Nichols and some CBC salt compatibility work to IGT. The schedule for the Solar Dynamic Heat Receiver Technology Program (SDHRTP) is planned as follows:

Task	Completion date
1	July 1986
2	July 1986
3	October 1986
4	January 1987
5	July 1987
6	January 1988
7	June 1988

Within Task 1, Boeing has developed seven conceptual receiver designs for the CBC, and through its subcontractor, Barber-Nichols, seven receiver conceptual designs for the ORC, to be used for tradeoff studies.

The designers, Boeing and Barber-Nichols, are primarily accumulating and evaluating TES material properties for use in or associated with each receiver concept. TES material property testing in support of this conceptual design activity in being performed (in large part) by the associated NASA LeRC in-house effort and, for CBC salts, by IGT under subcontract to Boeing.

The TES materials being considered in phase 1 receiver evaluations and being tested by LeRC in-house are listed in Table A.2.

Note that this program is considering a number of different TES approaches for the solar dynamic receiver from that being considered by Rocketdyne and Sundstrand under the near-term SSP effort (Section A.2.1).

- Boeing is considering a metallic Be sensible heat TES unit in one of their concepts. The original intention was to omit the cladding and have direct contact of the working fluid with the Be. However, the vapor pressure of Be at ~1100 K proved to be too high and this

Table A.2. PCM materials being evaluated by the NASA LeRC In-house program

Cycle	TES material	Melting temperature (K)	Container material
CBC	NaF	1269	Nb
	LiF	1122	Nb
	LiF-29 MgF_2	1019	Ni alloy
	LiF-22 CaF_2	1039	Ni alloy
	Be	1556	
ORC	LiOH	743	Ni 201
	NaF-20 LiOH	700	
	LiF-39 NaF	925	Ni alloy
	Mg	923	Ni alloy
	Zn (?)	693	

approach now is recognized to require cladding with an alkali metal buffer between the cladding and the Be. Thus, the attraction of this approach has diminished. The design objective was to allow no more than a 55 K temperature drop during energy unloading in the solar shadow by use of a sufficiently large Be mass. Thermal calculations showed that this could be achieved. The objective of this approach was to achieve an easily fabricable receiver concept.

- The same concept has been considered at ORC temperatures by Barber-Nichols using Mg sensible heat storage instead of Be.
- The TES materials that appear to be the leading candidates in the Boeing CBC concepts are the LiF-29MgF_2 and LiF-22CaF_2 eutectic salts and metallic Be. The leading TES candidates for the ORC appear to be LiOH and metallic Zn, the latter involving a novel approach being considered by Barber-Nichols.
- Boeing is testing an LiF/metallic mesh TES material in which the metallic mesh provides an enhanced composite thermal conductivity. In addition, the metallic mesh to a degree controls the void formation location by a "wicking" behavior of the liquid LiF on the mesh.

A.3 TES materials tests at NASA Johnson

Administrative

A fairly extensive program of PCM/container alloy compatibility testing is being conducted at NASA Johnson within the Propulsion and Power Division in the Engineering Directorate. Although there is no direct administrative connection, the work scope is in technical support of the two solar dynamic power systems being considered for the Space Station Program — the Organic Rankine Cycle (ORC) requiring heat supply at 700 K and the Closed Brayton Cycle which operates at a turbine inlet temperature of ~1100 K. The project manager is Nanette M. Faget.

The work is funded by the Advanced Technology Program at NASA-Johnson at a level of ~\$160 K/y in FY 1985 and FY 1986, and is projected to continue at this level through CY 1986 at which time the initial, scoping phase would be completed. Follow-on work would deal with a few selected PCM/container systems; however, these would be subjected to a more extensive range of thermal and mechanical tests.

Objective

The objective of this test program is to determine which PCM/container alloy combinations would yield satisfactory service for the life of the space station for each of the two solar dynamic systems currently being considered (the ORC and the CBC).

Scope and work description

The scope of work and test results through approximately April 1986 have been described by Faget (1986). The following PCM salts and container materials are being tested:

Phase Change Materials

PCM	Melting Temperature (K)	Cycle
KF-29 LiF-12 NaF	727	ORC
KF-33 LiF	766	ORC
LiOH	746	ORC
LiF-33 MgF_2	1012	Intermediate CBC
LiF	1121	High-T CBC

Container Alloy Materials (20)

Armco 18 SR, Cabot 214, Hastelloy B, B-2, N and X, Haynes 25, Inconel 600, 617 and X750, Incoloy 800, Nickel 200, 201, SS 304, 310, 316, 321, 347, Zirconium 702, 705.

Each PCM is tested with each of the 20 container alloys, resulting in 100 salt/alloy combinations. Isothermal exposures are planned for 5, 12, and 26 weeks. The results of the 5 week exposures will be used to select the most promising salt/alloy pairs for the subsequent tests.

Work status

The 5-week exposures have been completed and reported by Faget (1986). In summary those test results show the following:

Only Ni 200, Ni 201 and Inconel 600 was compatible with LiOH at 746 K, and these showed significant strength reductions (20-30%) in 5-weeks.

All of the container alloys showed corrosion rates <0.5 mils/yr with the ORC fluoride salts at their respective temperatures, 727 K and 766 K, except the two zirconium alloys which were significantly corroded.

The intermediate CBC salt (LiF-33 MgF_2 at 1012 K) showed corrosion rates of <0.5 mils/yr for all tested alloys except the two zirconium alloys and Incoloy 800, for which the corrosion rate was 0.6 mils/yr.

The following alloys showed weight changes (both positive and negative) in excess of 0.5 mils/yr in LiF at 1121 K: Hastelloy N, Inconel 600 and 617, Nickel 200 and 201, SS 316 and 347, and zirconium 702 and 705. Significant yield strength loss occurred for all of the other alloys except Cabot 214, Hastelloy B, Hastelloy X, Haynes 25, Incoloy 800, SS 309 and SS 310. These alloys showed yield strength reductions of <15%.

Schedule and Status

The 5-week, isothermal coupon tests have been completed and the down-selection for the follow-on 12 and 26 weeks tests have been made. The following 12 alloys have been selected for further tests: Armco 18 SR, Cabot 214, Hastelloy N and X, Haynes 25, Inconel 600, Ni 201, and SS 304, 316, 321 and 347.

Following the 26 weeks tests, one ORC and one CBC salt will be selected for more intensive study which will include metallography, thermal and stress cycling and performance verification under zero-g conditions.

Applications to SDI-Nuclear

1. The PCM/container compatibility tests relating to the ORC solar dynamic system could apply directly to heat reject thermal storage for the nuclear supply system. (At this stage, however, it is not clear what the optimum heat reject temperature would be for the LMR and HTGR heat sources.)

2. The extensive testing of the four fluoride salts with the twenty container alloys at temperatures from 727 to 1121 K adds significantly to the data base on use of fluoride PCMs.

A.4 References for Appendix A

Faget, N. M., 1986, "Material Compatibility Issues Related to Thermal Energy Storage for a Space Solar Dynamic System," *Proc. of the 21st Intersociety Energy Conversion Conference, San Diego, August 1986.*

Lee, W. T., ed., 1985, *Proceedings of a Seminar on Recent Advances in Thermal Energy Storage Materials,* held at Rocketdyne, Canoga Park, CA, July 1985.

Appendix B

TES RESEARCH AND DEVELOPMENT SPONSORED WITHIN THE DOD

Currently the authors are aware of only two thermal storage R&D efforts being sponsored by the DOD; both originate within the Aero-Propulsion Laboratory (APL) at the Air Force Wright Aeronautical Laboratory (AFWAL).

B.1 Energy Storage Concepts for Pulsed Space Power Systems (Preliminary)

This is a new program sponsored by the Power Technology Branch of the Aerospace Power Division in AFWAL/APL. Since this effort is still in an early formative phase, all descriptive comments that follow must be regarded as preliminary pending completion of the planning effort. A program with the following four elements has been proposed.

Task 1: Energy Storage Value Analysis

This task will define the burst power missions, for which energy storage technologies may be applied. Subsequently a computer program will be developed for evaluating the benefit of adopting thermal, flywheel, or chemical storage features to the burst power systems. It is not intended to develop a comprehensive and definitive study in this area, but rather to provide some administrative guidance for the experimental tasks. This in borne out by the schedule and level of effort shown in Table B.1.

Task 2: Heat Sink Concepts

The immediate objective of this task is to explore the feasibility of using the highly advantageous heat storage properties of LiH for power cycle heat rejection. Three approaches will be investigated.

Task 2.1: Direct Contact with NaK

In this advanced and speculative concept, the LiH heat sink is in direct contacted with NaK, which is presumed to be an intermediate heat transport medium. Exploration of this heat sink concept will proceed through the following three phases.

Table B.1. Multiyear budget – FY 1986 through FY 1988 –
Energy Storage Concepts for Pulse Power Systems (DOD)

Activity		Budget ($1000)		
		FY 1986	FY 1987	FY 1988
Task 1.	Energy storage value analysis			
	1.1 Defined missions	125	10	
	1.2 Novel systems		35	25
Task 2.	Heat sink concepts			
	2.1 direct contact systems	120	275	275
	2.2 Packed bed systems	200	215	250
	2.3 Tube and shell	20	20	10
	2.4 System concept analysis	30	20	10
Task 3.	Heat source concepts			
	3.1 Encapsulated silicon alloys			
	3.2 Open composite systems			
	3.3 System concept analysis			
Task 4.	Material properties and compatibility			
	4.1 Properties database	2	15	15
	4.2 Materials compatibility		10	15
	Total	497	600	600

Phase 1: Scoping experiments. These are planned to be initial, small-scale tests to determine whether or not LiH may be frozen out of a Li-H-Na-K melt to regenerate the original LiH heat sink material. In addition, the behavior of hydrogen in the melt-freeze cycle will be observed.

Phase 2: Feasibility tests. If the phase 1 scoping experiments are successful, larger scale tests will be initiated involving a small-scale pumped loop. The loop tests will seek to demonstrate the nature of LiH freezing from a Li-H-Na-K melts, the degree of H_2 evolution, and means for avoidance of unwanted LiH precipitation in cool zones and material compatibility.

Phase 3: System development. Following successful completion of the smaller scale tests, a larger scale heat loop will be fabricated.

Phase 4: Prototype system.

Task 2.2: LiH Packed Bed Systems

The objective of this task is the development of encapsulation techniques for LiH for use in packed-bed configurations.

Phase 1: Ecapsulation technique screening. The following concepts for encapsulating LiH will be explored in short-term, small scale tests: cylindrical bellows, spherical capsules, shells with internal deformable foil to accommodate volume change experienced on phase change, and flexible shell capsule. These capsules need to overcome three troublesome physical features of LiH, namely, its 20% expansion on melting, its tendency to evolve H_2, and its strong adhesion to capsule surfaces.

Phase 2: Feasibility development. The more promising encapsulation procedures observed in the phase 1 scoping tests will be more extensively studied. The studies will include measurement of H_2 retention, capsule durability, fabrication techniques.

Phase 3: Packed bed tests. Following successful completion of phase 2, an encapsulation procedure will be selected for tests in a bench scale packed bed system. Thermal performance of the bed and capsule integrity will be monitored.

Phase 4: Prototype packed bed tests.

Task 2.3: Shell and tube containment of LiH

In this task, more conventional types of LiH containers will be tested involving larger scale metal tubes with either expansion volumes or flexible boundaries to accommodate the large volume change on phase transition.

Phase 1: Configuration assessment

Phase 2: Feasibility tests

Phase 3: Prototype tests

Task 2.4: Heat Sink Concept Analysis

Thermal and stress analyses will be performed in this task in support of the development tests conducted in tasks 2.1, 2.2, and 2.3. The analyses will include hydrogen loss calculations, size optimization of LiH capsules, heat transfer enhancement, prediction of variable gravity effects and thermal stress modeling.

Task 3: Heat Source Concepts*

As noted in Table B.1, this task is currently inactive; initiation is being project for FY 89. Initially, this task will be directed toward use of Si-based eutectic PCMs in the 1200 to 1675 K melting range. These have the advantages of high energy storage density (1500 to 2000 KJ/kg), good thermal conductivity and smaller volume change on phase transition than the molten salts.

Task 3.1: Heat Source Concepts

This task will develop methods for using Si-alloys as PCM's by development of satisfactory encapulation techniques. Conventional containment of Si-alloys in metallic materials is not feasible due to compatibility problems.

Phase 1: Encapsulation techniques screening. A few samples of a number of encapsulation techniques will be tried and evaluated. Initial tests will focus on the Be-Si eutectic (Tm = 1363 K) employing a $MoSi_2$ shell applied by a number of possible methods including chemical vapor deposition, surface reaction, anodizing, or plasma spraying.

Phase 2: Feasibility experiments. Tests on single spheres will be performed to determine the useful life and thermal performance.

Phase 3: Prototype tests. An encapsulation procedure will be selected and used to fabricate a bench scale packed bed. The thermal and mechanical performance of the packed bed will be tested.

Task 3.2: Open Composite Systems

In so-called open composite systems the molten PCM is contained within the connected porosity of a metallic or ceramic matrix material by surface tension forces. The systems tested thus far have consisted of molten salts held in metallic sponge. The principal advantages of this method of PCM containment are a possible resolution of the volume change problem of molten salts and providing a high thermal conductance matrix.

---

*Refers to "front end" storage, i.e., storage of heat from the reactor source for subsequent delivery to the power cycle working fluid.

Phase 1: Selection of high temperature open composite systems

Phase 2: Feasibility tests

Phase 3: Prototype tests

Task 4: Material Property Measurement and Compatibility

This task will collect, evaluate properties of PCM's, container materials and heat transfer media used in thermal storage systems.

Table B.1 provides a current tentative projection of program costs from FY 86 through 88. We note from this table that as currently planned, this program is largely devoted to development of LiH heat sink technology, as outlined in Task 2. Table B.2 outlines the current version of the work schedule.

Application to SDI Nuclear. This program's current emphasis is on the application of LiH heat sink material in a specific thermionic concept involving direct contact with NaK intermediate coolant. If this proves to be feasible, a similar application may be used in nuclear burst power heat rejection systems as shown in Figs. 2.3, 2.6 and 2.10.

If this advanced technique proves not to be feasible, the information developed in this program on LiH encapsulation and containment techniques and the analytical and modeling techniques developed may still be useful to the SDI effort in demonstration of possible approaches to the use of LiH as a heat reject material. However, the scope of the effort on LiH containment and properties does not appear to be sufficient in the program (in the judgement of the authors) to settle the feasibility question regarding use of LiH for burst power cycle heat rejection.

The currently inactive portion of the program involving Si-alloy eutectics for front-end heat supply also could be a direct input to SDI program requirements. If encapsulation techniques can be developed, several Si-alloy eutectics possess congruent melting points in the range of potential use for nuclear burst power systems, i.e., at temperatures between 1300 and 1650 K for Boiling Potassium and Lithium Cooled Reactor concepts. The alloy selected for initial study, Be-Si, with melting point at 1363 K, is at the lower end of the range of interest, and hence may apply directly. Front end heat storage systems in the 1300 to

Table B.2. Program schedule –
Energy Storage Concepts for Pulsed Power Systems (DOD)

Activity	Schedule				
	FY 1986	FY 1987	FY 1988	FY 1989	FY 1990
Task 1. Energy Storage Value Analysis					
1.1. Defined Missions	———	——			
1.1.1. Mission description					
1.1.2. System description					
1.1.3. Value analysis					
1.2. Novel Systems		———	———		
1.2.1. Scoping study					
1.2.2. System analysis					
Task 2. Heat Sink Concepts					
2.1. Direct Contact Systems	——	———	———	———	———
2.1.1. Scoping experiments					
2.1.2. Feasibility tests					
2.1.3. System development					
2.1.4. Prototype system tests					
2.2. Packed Bed Systems	——	———	———	———	———
2.2.1. Encapsulation technique screening					
2.2.2. Feasibility development					
2.2.3. Packed bed tests					
2.2.4. Prototype system tests					
2.3. Shell and Tube Systems	——	———	———	—	———
2.3.1. Configuration assessment					
2.3.2. Feasibility tests					
2.3.3. Prototype tests					
2.4. Heat Sink Concept Analysis	——	———	———	———	———
2.4.1. Concept evaluations					
2.4 2. Heat transfer enhancement					
2.4.3. Variable gravity effects					
2.4.4. Thermal/stress modeling					
Task 3. Heat Source Concepts					
3.1. Encapsulated Silicon Alloys				——	———
3.1.1. Encapsulation technique screening					
3.1.2. Feasibility experiments					
3.1.3. Prototype test					
3.2. Open Composite Systems					
3.2.1. Composition and configuration screening					
3.2.2. Feasibility tests					
3.2.3. Prototype tests					
3.3. System Concept Analysis					
3.3.1. Concept evaluation					
3.3.2. Thermal-mechanical model development					
Task 4. Materials Properties and Compatibility		———	———	—	———
4.1. Properties database					
4.1.1. Lithium hydride					
4.1.2. Alkali metals					
4.1.3. Containment					
4.2. Materials Compatibility					
4.2.1. Li-NaK-LiH system					
4.2.2. Structural materials					
4.2.3. Additive effects					

1800 K range may be considered for HTGR burst power systems; Si-alloy eutectics are available up to 1685 K (pure Si) and thus may apply as well to HTGR TES systems.

B.2 AeroPropulsion Laboratory In-House Thermal Energy Storage Tests

Administrative. This effort is supported by in-house funds within the Aerospace Power Division of the AeroPropulsion Laboratory of the Air Force Wright Aeronautical Laboratory (AFWAL) at a level of ~$200 K/y. The program is administered by the Power Technology Branch, which has subcontracted portions of the test program (salt and capsule preparation and the thermal cycling tests) to Universal Energy Systems, Inc. of Payton, OH, and conducts other related tests in-house.

The current purpose of this program appears to be a general support of advanced heat storage systems coupled to heat pipes operating at about 1000 K. Originally, this program was directed toward development of an integral thermal storage/heat pipe device to provide orbital eclipse power for cryogenic refrigerators. Subsequently, the cryogenic refrigerator aspect was dropped.

Objective. Specifically, this program seeks to develop a 1000 K thermal storage capability coupling to a heat pipe heat transfer system. After screening tests for salt and container material selection, the program will culminate in a full-life, 10,000 h (417 d), thermal cycle test followed by post-test metallographic and corrosion rate measurements.

Work description, up to the point of initiation of the final 10,000 h thermal cycles, is described by Ponnappan (1985).

An initial work phase consisted of test of eutectic mixtures of LiF, MgF_2, NaF and KF salts held in Inconel 617 steadily for 10,000 h at a temperature just above melting. These tests were completed satisfactorily, i.e., good salt/container material compatibility was observed. In addition, thermal cycle tests were performed involving 500 cycles at $\pm 50°C$ of the melting points of these salts in Inconel 617. These also proved good material compatibility.

A second test phase involved use of Inconel 600 instead of 617. In these tests the capsules failed and the salt leaked. Post-test analyses ascribed the failures to:

1. Welding of the capsules in air rather than vacuum, consequently contaminating the salt which lead to accelerated corrosion;

2. The Inconel 600 bar stock was found to contain pin-hole defects;

3. In addition, the Inconel 600 was found to contain excessive Ca impurity which could have accelerated corrosion.

From its inception, the experimental work in this program has been conducted with careful and sound metallurigical techniques. Salt purity has been verified and maintained. Melting points of pure and eutectic mixtures have been checked against literature values. Container alloy compositions were verified, and capsules were closed using electron beam welding in a vacuum enclosure. When all of these procedures were not followed, as with the Inconel 600 capsule tests, failures occurred.

Current tests focus on the following three fluoride eutectics in Inconel 617 capsules:

Salt*	Melting point (K)
MgF_2-46.9 LiF	997
MgF_2-39.8 LiF-13.1 NaF	959
MgF_2-42.3 LiF- 8.9 KF	959

*Eutectic compositions in weight-%.

The thermal cycling tests for the final phase of the program are conducted using a 4-h period involves a 2 h heating and a 2 h cooling phase. About 30 min are required for phase transition, both melting and freezing. The salt exists about 1.5 h each as a liquid and a solid during the 4 h thermal cycle.

Schedule and status. The final phase of this program involving the 10,000 h thermal cycle tests are currently in progress; the tests are ~50% complete as of Sept. 1, 1986. The tests are planned to be ended upon observation of the first capsule failure.

A total of 18 Inconel 617 capsules are in this final phase, 6 each containing the eutectic mixtures shown above. Thus far no failures have been observed.

Following test completion, the capsules will be metallographically examined; the degree of corrosion and the corrosion mechanism will be determined.

Application to SDI Nuclear. This program provides both general and possibly specific information useful to SDI burst power systems. The information with regard to fluoride salt corrosion of Inconel 617 and Inconel 600 alloys may apply generally to Ni-based alloys. Also of general value are the techniques developed for salt preparation and capsule fabrication described by Ponnappan (1985) and earlier reports by Davison (1975), Beam (1977) and Ponnappan (1983). These preparation techniques demonstrate what is required for the fluoride/container unit to behave in the compatible fashion that theory predicts.

Specifically applicable information relates to the possible use of any of the three fluoride eutectics currently being tested in Inconel 617 containers to burst power heat rejection systems. As noted in Sect. 2, both the Boiling Potassium and Lithium cooled Reactor burst power systems may advantageously utilize capacitive heat rejection in the 900 to 1200 K range.

B.3 References for Appendix B

Beam, J. E., 1977 *Evaluation of Eutectic Fluoride Thermal Energy Storage Unit Compatibility, Part II — Test Procedures and Post-Test Results*, AFAPL-TR-75-92-Part II, AFWAL, March 1977.

Davidson, J. E., 1975, *Evaluation of Eutectic Fluoride TES Unit Compatibility, Part I*, WPAFB, October 1975.

Lee, W. T., 1975, *Proceedings of a Seminar on Recent Advances in TES Materials*, held at Rocketdyne, Canoga Park, CA, August 1975.

Ponnappan, R., 1975, *High Temperature TES Experiment*, in Lee, W. T. (1975).

Appendix C

THERMAL STORAGE RESEARCH AND DEVELOPMENT SPONSORED BY DOE

Thermal energy storage R&D is supported in two areas within the DOE: (1) the Office of Energy Storage and Distribution, and (2) the Solar Thermal Technology Division within the Office of Solar Heat Technologies. Both of these administrative areas are under the Asst. Secretary for Conservation and Renewable Energy. Therefore the main thrust of the work is toward commercialization of conservation and renewable energy technologies such as solar thermal, waste heat utilization, improved building space heating. These are, in general, directions which differ significantly from SDI requirements. Therefore, we would not expect to identify a large area of technology development supported by the DOE that applies directly to SDI.

C.1 Thermal Storage R&D Supported by the Solar Thermal Technology Division

The primary thrust of the work supported by this division is the development of commercial scale solar technology utilizing thermodynamic power cycles for generation of electricity. Through its principal contractor, the Sandia National Laboratory, this work has culminated in the construction of the Barstow Solar Thermal Facility which is currently in operation.

Solar thermal electric systems require diurnal thermal storage for full, 24-h operation. Sandia has selected nitrated salts as the storage medium for the Barstow facility; hence compatibility testing and material selection in this program relate to containment of nitrate salts. Since nitrate salts would not be chosen for SDI burst power applications due to their low specific latent heat values and relatively low temperature capability, it is unlikely that this program has developed heat storage technology that is adaptable to SDI.

C.2 Thermal Storage R&D Supported by the Office of Energy Storage and Distribution

The principal objectives of thermal storage R&D supported by the Office of Energy Storage and Distribution are: (1) the development of media for systems that provide both winter heating or summer cooling of building space, (2) improved systems for industrial waste heat utilization, (3) development of passive solar systems for space heating, (4) performance of research on new thermal storage media. These objectives are implemented through R&D projects monitored by ORNL (currently) in the areas of Industrial Storage and Building Heating and Cooling. Up until FY 1986, the Solar Energy Research Institute (SERI) was also a principal contractor in the area of thermal storage assessment and basic research.

C.2.1 ORNL-Sponsored work for the Office of Energy Storage and Distribution

The active research tasks sponsored through ORNL are listed in Table C.1, adapted from the 1985 Program Plan [Martin (1985)]. Tasks listed in the priority 1 category were funded; priority 2 tasks were not. Table C.1 also provides the FY 86 funding level for research activity. Though the objectives assigned to this DOE office are quite different from that required in SDI burst power systems, some potentially applicable research is noted by the starred tasks in Table C.1 and will be described briefly below.

Composite High-Temperature Storage Media

Research performed at the Institute of Gas Technology (IGT) has developed the concept of containing a PCM within the connected porosity of a non-melting solid matrix. To date, IGT has applied the concept to the containment of carbonate PCMs in oxide ceramics, a particular selection not especially pertinent to SDI. However, the concept has certain desirable features which may find application with other materials. Potentially useful features of this containment concept are (1) enhancement of effective thermal conductance of the storage medium by use of a metallic matrix, and (2) an inherent method of allowing for large phase change volume differences.

Table C.1. Thermal Storage Research Sponsored by the Office of Energy Storage and Distribution, DOE, through ORNL (FY 1986)

Program elements	Budget ($ in thousands)
Priority 1	
Passive solar model	50
Passive solar system criteria	0
Composite high-temperature media development (*)	180
Heat of mixing research (*)	60
Encapsulated metallic alloy (*)	70
Dual-temperature ammoniates	150
Clathrate system heat transfer optimization	75
Priority 2	
Clathrate research	75
Economic assessment	50
Slurry heat transfer (*)	100
Summary of code constraints on advanced storage system	25
Solid state transition PCM	75
Analysis of solar central receiver storage system requirements	50
Joint NASA/DOE space power TES research (*)	100
Active solar cooling storage	50
Laboratory model of dual temperature storage system	100
System studies - composite high temperature media application	200

*Researach which may complement SDI program needs.

Evaluation of the Heat of Mixing in Solutions for Thermal Storage

Though this work, performed by Polytechnic Institute of New York, is currently directed toward evaluation of the heat of mixing as an energy storage mechanism for only low temperature systems, the concept may also apply to higher temperature applications. Of itself, the heat of mixing probably does not represent a significant energy storage potential, but metal/salt slurry systems may prove advantageous for other reasons (chemical compatibility, improved thermal conductance), and heats of mixing may enhance heat storage capacities for these dual phase systems.

Encapsulated Alloy Storage Material

This research is directed toward developing ways to encapsulate metallic eutectic PCMs within high melting shells. As noted in Sect. 1.3.1.1, a few metals, such as Si (and perhaps only Si), have high latent heats and a series of eutectic alloys with a potentially useful range of melting points, up to 1685 K for pure Si. Therefore, Si-alloy PCMs may be of direct application to burst power systems, both for heat supply (front end) and cycle heat rejection service.

Work at Ohio State University has sought to develop microencapsulation techniques for the Si-Al eutectic (T_m = 850 K) in higher melting Si alloy material by various techniques. These have thus far not proved to be satisfactory. Future work is planned for the higher melting Si-Be system (T_m = 1363 K).

Slurry Heat Transfer

Although this is assigned a second priority, work was resumed in FY 86. The work is being performed at ANL. The object is to assess the use of a slurry of latent heat storage media in a heat transfer fluid for (a) enhancing the density of energy transport and (b) providing an enhanced heat transfer into an out of the slurry. The latent heat storage material must exhibit a solid/solid phase change or be appropriately encapsulated so as to not mix with its heat transfer fluid. The present research will utilize form-stable (by partial cross linking) polyethylene pellets with a phase change temperature of 130°C.

Joint NASA/DOE Space Power TES Research

This task is also rated as second priority; thus FY 86 funding is questionable.

The purpose of this proposed joint program is to make the DOE-developed thermal storage technology available to NASA.

C.2.2 SERI-Sponsored Work for the Office of Energy Storage and Distribution

The level of SERI sponsored research for the Office of Energy Storage and Distribution has ranged from a high of 1,500 K/y in FY 79 to a low of 400 K$/y in FY 85. SERI has phased out of this program as of FY 86. In FY 85, this program consisted of the following elements:

Advanced High-Temperature Molten Salt Containment

The objectives of this task in FY 84 were to (1) select a candidate heat storage salt, (2) evaluate potential container alloys, and (3) develop a containment vessel conceptual design. The work is directed toward diurnal heat storage technology for solar thermal electric systems.

The salt systems selected was the Li-K-Na carbonate eutectic with 666 K melting temperature. The compatibility of this salt was tested at 1173 K with the following container alloys: Hastelloy N, $Ni_3A\ell$, Haynes 550, Inconel 600, Cabot 214, Ni, Incoloy 800. In general, high oxidation was experienced in the results presented by Coyle et al. (1986).

Sand-Air Direct Contact Heat Exchanger

This work is directed toward developing a hot air supply for a Brayton power cycle with turbine inlet in the 900 to 1400 K temperature range.

Salt-to-Air Direct-Contact Heat Transfer

Direct contact heat exchangers were tested up to 1000 K with ultimate temperatures of 1400 K envisioned. A pump loop for this purpose has been fabricated and tested up to 1000 K.

C.3 Application of DOE Thermal Storage Program Elements to SDI Program Needs

As noted earlier in this appendix, the basic thrust of the DOE sponsored thermal storage work is toward commercialization and solar thermal, building space heating, and cooling and industrial waste heat utilization. As such, one would not anticipate a major degree of applicability to SDI burst power systems. Nevertheless, several tasks within the office of Energy Storage and Distribution either may apply directly to SDI requirements or involve processes that with different materials and different temperature levels may be applied in SDI systems. These have been identified in Sect. C.2 and are repeated here:

1. Composite high temperature media development,
2. Heat of mixing research,
3. Encapsulated metallic alloy PCM's,
4. Slurry heat transfer,
5. Joint NASA/DOE thermal storage research.

All of the above are supported in the Office of Energy Storage and Distribution. Item (5) is given as a priority -2 element, and as such may not be funded. The nature of application to SDI burst power systems development is outlined in Sect. C.2 for each item.

C.4 References for Appendix C

Coyle, R. T. et al., *Corrosion of Selected Alloys in Eutectic Lithium-Sodium-Potassium Carbonate at 900 C*, SERI/PR-255-2561, January 1986.

Martin, J. F., 1986, *Thermal Energy Storage Program Annual Operating Plan*, ORNL/TM-9745, November 1986.

Petri, R., et al., 1983, *New Thermal Energy Storage Concepts for Solar Thermal Applications*, SERI/STR-231-1860, April 1983.

Appendix D

FLYWHEEL TECHNOLOGY DEVELOPMENT SPONSORED BY NASA

D.1 Integrated Power/Attitude Control System (IPACS)

Administrative. In the early 1970s NASA became interested in the IPACS concept and work was funded through NASA Langley Research Center (LaRC) to explore the feasibility of the concept. The program produced a small scale-model of an IPACS module and was ended in 1978. The program was directed by:

Calude R. Keckler
NASA LaRC/MS161
Hampton, VA 23665
(804) 865-4591

Objective. The objective of the effort was to design, build and test an IPACS concept to demonstrate the applicability of the system to Earth-orbital vehicles.

Work description. In the Integrated Power and Attitude Control System (IPACS), energy storage is accomplished in the flywheel, which is simultaneously used for attitude control. By integrating these two functions into one, system mass savings of about 25% can be realized when compared to the conventional approach using batteries for energy storage and a control moment gyro for attitude control.

The laboratory hardware was designed to satisfy the requirements associated with an advanced solar observatory mission. To satisfy the requirements of this mission the IPACS module had to supply a power level of 3.4 kW and a pointing accuracy of 1 arcsecond. It was decided that the IPACS unit would be modular to provide sufficient system redundancy. Thus, each unit was required to provide a total energy storage capability of 5.4 MJ (1.5 kWh) and to deliver 2.5 kW of power to the spacecraft's subsystems. Wheel speed variation of 50% was used to extract 75% of the wheel's stored energy. At half speed each unit possessed a momentum capacity of about 1430 N•m and a torque output of 27 N-m (20 ft-lbs).

As shown in Fig. D1, the selected rotor shape was a constant stress disc in order to maximize the realizable shape factor. The rotor was 18 inches in diameter and fabricated from titanium. A brushless d.c. motor/generator was attached to each end of the shaft to accelerate and decelerate the wheel as required by spacecraft energy requirements. A detailed list of the laboratory unit's characteristics is given in Table D1. As shown the unit has a rotor operating speed range of 2:1 and a storage density of 106 kJ/kg (29.5 Wh/kg) for the rotor only. The energy density for the entire module is 68.8 kJ/kg (19.1 Wh/kg). The energy cycle was based on a typical orbit time-line, with 50 minutes of daylight for charging (spinning up the rotor), and 40 minutes of darkness during which energy is withdrawn from the wheel. For control purposes, the momentum capacity of the unit at half speed is 1430 N•m which is more than twice the 680 N•m required for the postulated vehicle control functions.

Schedule and status. The laboratory hardware was built and tested in 1976-1977. After the testing program was completed and the feasibility of the system demonstrated the program ended. At present, the only effort associated with the IPACS concept that is active at NASA LaRC involves an assessment of the concept for the space station.

Application to SDI needs. The IPACS concept is applicable to SDI needs and may result in further mass savings by eliminating the need for a separate attitude control system on the space platform. The specific systems of interest to NASA will be of only limited interest for SDI applications because the power and energy levels are relatively low. This means that the NASA systems can accept lower performance (specific power and energy density) from their systems than will be required for SDI systems.

D.2 Attitude Control and Energy Storage (ACES) System

Administrative. The integrated energy storage and attitude control concept was resurrected by NASA Goodard Space Flight Center (GSFC) in 1985. This time around it was named the Attitude Control and Energy Storage (ACES) concept and was based on advanced technology in all major

ORNL–PHOTO 6912–86

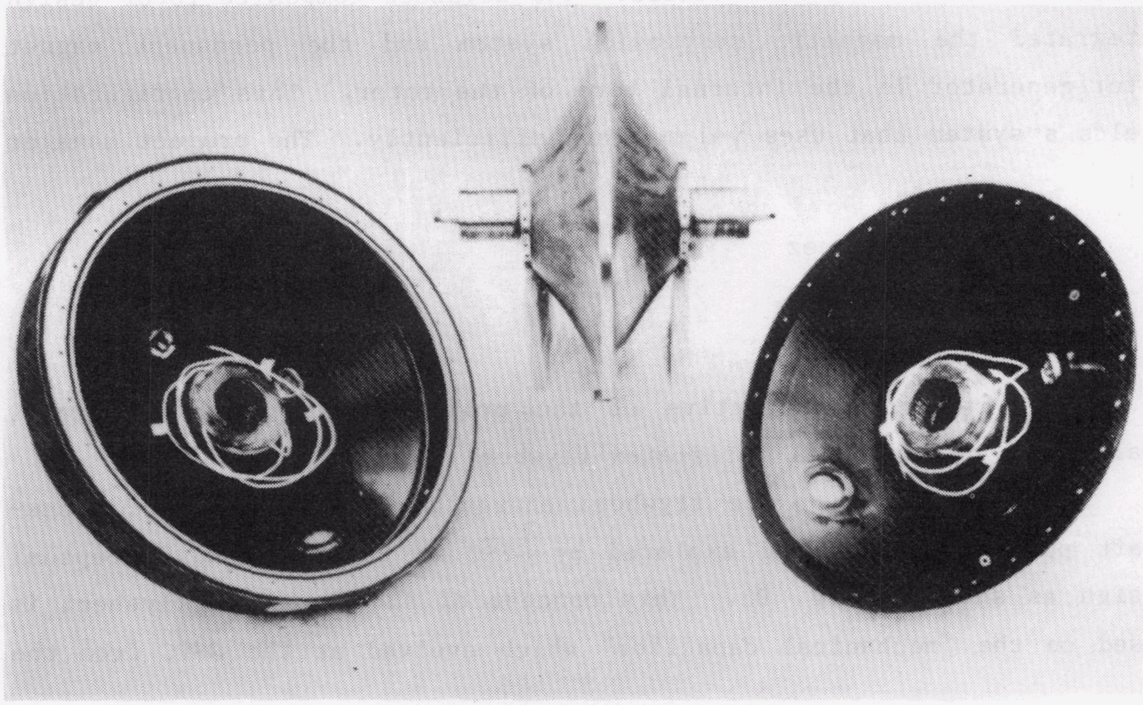


Fig. D.1. NASA LaRC flywheel rotor.

Table D.1. Characteristics of NASA LaRe flywheel module

Parameter	Value
Operating speed range, rpm	17,500-35,000
Operating momentum range, N•m	1430-2860
Energy capacity, MJ (kw-hr)	5.4 (1.5)
Deliverable power, kw	2.5
Rotor size, cm diam	45.4
Rotor weight, kg	50.8
Rotor energy density, kj/kg (w-h/kg)	106 (29.5)
Assembly weight, kg	78.5
Assembly energy density, kj/kg (w-h/kg)	69 (19.1)
Size of assembly, cm	57.7 x 53.1
Charge/discharge cycle duration, min	50/40
System efficiency (including electronics), %	52

subsystems of the flywheel module. The advanced composite rotor design integrated the magnetic suspension system and the permanent magnet motor/generator in the internal bore of the rotor. This configuration yields a system that uses volume very efficiently. The project manager is:

G. Ernest Rodriguez
NASA GSFC/Code 711
Greenbelt, MD 20771
(301) 286-6202

Objective. The objective of the project is to produce a small scale model of the total integrated flywheel concept.

Work description. The flywheel energy storage concept for spacecraft power systems being explored by GFSC is based on the conceptual design as shown in Fig. D2. This concept of an integrated flysheel is based on the "mechanical capacitor" which evolved at the GSFC from the

ORNL–DWG 86–5440 ETD

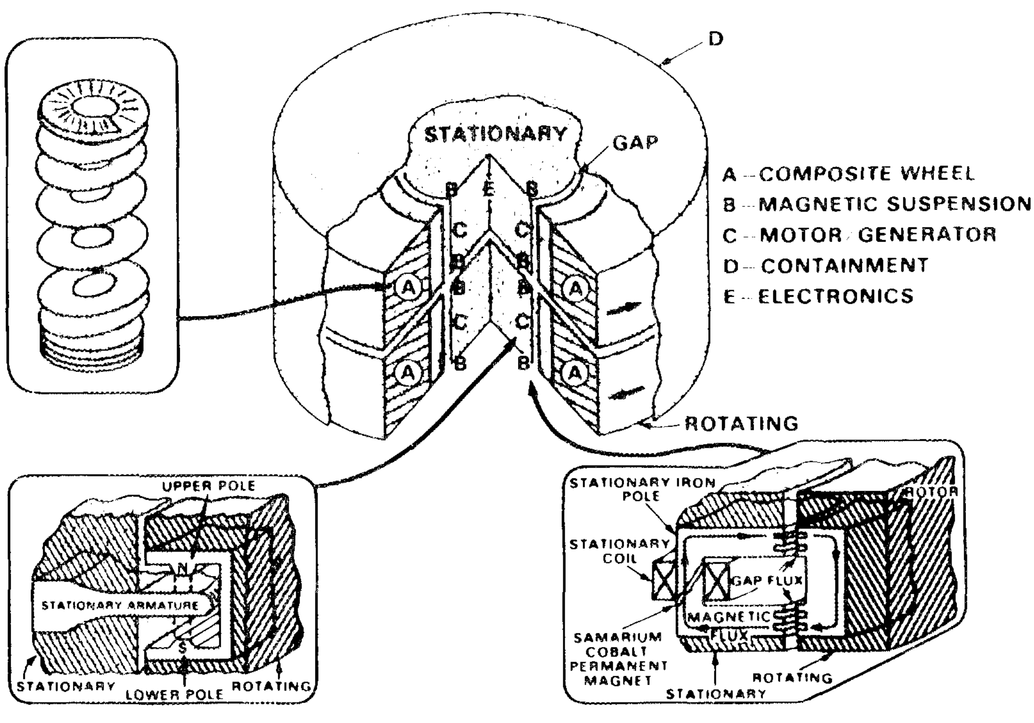


Fig. D.2. NASA GSFC conceptual flywheel design [Keckler et al., (1983)].

development of magnetic bearings and permanent magnet ironless-brushless DC motors. The mechanical capacitor is based on three key technologies: (1) a composite rotor with a low internal diameter (ID) to outer diameter (OD) ratio for achieving high energy density; (2) magnetic suspension close to the geometric center of the rotating mass to minimize loads normally encountered on the ends of a shaft, to provide a no-wear mechanism in a vacuum environment, and to minimize losses at high rotational speeds; (3) permanent magnet ironless-brushless DC motor/generator for high efficiency of conversion and low losses. The complete system also includes the necessary electronics for the motor/generator, containment, and counterrotating wheels for attitude control capability. As shown in Table D2, the energy storage system under development

Table D.2. Potential advantages of inertial energy storage in spacecraft power systems

Characteristic	Mechanism
Long lifetime.....30 years	Magnetic suspension of rotating mass - no wearout mechanism
	Design to 10^5 cycle fatigue stress
Simple state-of-charge (SOC) monitoring and control	Wheel speed determines SOC
Adaptable voltage level implementation	Easily accommodated by PM m/g design
High temperature rejection of waste heat	Waste heat concentrated in stationary mass - easily removable by conduction/radiation
$\pm 2\%$ voltage regulation	PWM of motor control electronics required for differential speed control (A/C compatibility)
Perform attitude control functions	Inherent high momentum bias in wheel
Minimize system power processing components	Shunt regulator ($\pm 2\%$ voltage regulation) is only power processing component required
Higher energy density than NiCd	16 whr/kg versus 5-7 w-hr/kg 18 kwhr/m^3 versus 7 kw-hr/m^3

has potential advantages of long lifetime (20 to 30 years), high temperature (50 C) waste heat rejection, simple charge detection and control (wheel speed), inherent high voltage (>200 V), higher energy density than baseline NiCd batteries and higher volumetric density than NiH_2.

Achieving the potential advantages of the inertial energy storage concept will depend on the successful design of an integrated flywheel system. Five technologies were identified as being critical to the successful development of the integrated system. In descending order of priority they are: (1) a thick rim composite rotor with an ID/OD ratio of less than 0.6, (2) magnetic suspension of the rotating mass close to its center of mass, (3) a permanent magnet motor/generator integrated in the rotating (permanent magnets) and stationary (ironless armature) mass (4) power electronics to interface between the spacecraft bus at 250 V DC and the motor/generator and (5) safe containment of the wheels in the event of wheel or system failure.

A program was begun in 1985 to demonstrate the feasibility of the integrated flywheel concept. The original intent was to design, build and test a 1.08 MJ (300 Wh) flywheel system with a power rating (discharge) of 500 W. The program, however, was based on restrained resources (funding limitations) and accomplishments have been modest. The design has been completed but the funding is not available to build the integrated flywheel. The design calls for the use of Celion 1200 graphite fibers in the flywheel. This results in an overall energy storage density for the system of 72 kJ/kg (20 Wh/kg). Some experimental work was performed on the magnetic suspension system using a smaller wheel) and the power electronics.

Schedule and status. Funding has been exhausted and the project is coming to a close. Since current NASA plans do not include flywheels for storage on space station, it is highly unlikely that a new research program will be initiated or the current effort extended.

Application to SDI needs. The integrated flywheel concept is interesting because of its attractive volumetric storage density. However, the concept is essentially fixed on the use of a motor/generator. This is acceptable because the charging and discharging power levels are of almost equal magnitude. In SDI applications the discharging power level can be several orders of magnitude greater than that during charging. Thus, it is highly likely that the generating function should be separated from the charging function. Also, the energy density levels need to be much higher than those embodied in the NASA design.

D.3 References for Appendix D

Evans, H. E. and Kirk, J. A., "Inertial Energy Storage Magnetically Levitated Ring-Rotor," IBID.

Keckler, C. R., Rodriguez, G. E., and Groom, N. J., editors, "Integrated Flywheel Technology 1983," *Proceedings of Workshop held at NASA Goddard Space Flight Center, Greenbelt, MD, August 2-3, 1983* (NASA Conference Publication 2290).

Keckler, C. R., Bechtel, R. T., and Groom, N. J., editors, "An Assessment of Integrated Flywheel System Technology," *Proceedings of Workshop held at NASA Marshall Space Flight Center, Huntsville, AL, February 7-9, 1984* (NASA Conference Publication 2346).

Keckler, C. R. and Groom, N. J., "An Overview of Integrated Flywheel Technology for Aerospace Applications," *Proceedings of 20th Intersociety Energy Conversion Engineering Conference, Miami Beach, FL, August 18-23, 1985.*

Loewenthal, S. H., Scibbe, H. W., Parker, R. J., and Zautsky, E. V., "Operating Characteristics of a 0.87 kW-hr Flywheel Energy Storage Module," IBID.

Van Tassel, K. E. and Sima, W. E., "Inertial Energy Storage for Advanced Space station Application," IBID.

Appendix E

FLYWHEEL TECHNOLOGY DEVELOPMENT SPONSORED BY DOD

E.1 Homopolar Generator Rotor Development

Administrative. In FY 1985 the Enrichment Technology Applications Center (ETAC) of Martin Marietta Energy Systems teamed with the University of Texas to develop a homopolar generator (HPG) for the Defense Advanced Research Projects Agency (DARPA). ETAC was to be responsible for the development of the inertial energy storage (flywheel) component of the machine. To allow for a fast track program DARPA provided $700,000 in advanced funding to ETAC to build a facility that had the capability of spin testing the rotor required for the HPG. Soon after this money was allocated the DARPA focus was changed. The HPG was deemphasized and compulsator technology became the primary emphasis. As a result the HPG program was halted. Since flywheels will be required for the compulsator, DARPA decided to continue the ETAC work and directed it to the demonstration of high energy density rotors. The program director is:

Mr. David U. O'Kain
Enrichment Technology Applications Center
Martin Marietta Energy Systems, Inc.
P.O. Box K
Oak Ridge, TN 37831
(615) 576-0262

Objective. The objective of the work is to build test facilities for high performance flywheels and to perform generic development design and prototype testing of advanced rotors.

Work description. A spin test chamber has been designed to accommodate rotors with diameters of up to 21.6 cm (55 in.). The unit is now being fabricated and will be operational in early 1987. The testing facility will have the capability of testing flywheels to a total stored energy of at least 50 MJ.

Development activities aimed at increasing flywheel storage density above those achieved in the MEST Program were initiated in October 1985. The focus of this effort is to design, fabricate, and spin test carbon/epoxy composite flywheel rims. The first series of tests were designated as Demo 1. The rims were fabricated using carbon fiber (Hercules IM6 and AS6) and epoxy (ERL 2258). The lower modulus material (IM6) was used for the outer portion. The fibers were wet wound and cured on a 0.61-m (24-inch) diameter mandrel to form a thick ring with an outside diameter of 0.69-m (27 inches); the ring was then cut into lengths to form test rims. The characteristics of the rims are given in Table E.1.

The rims were mounted on existing spin arbors and subjected to spin tests. Spin testing was performed in a vacuum test chamber (<0.02 mm Hg) using an air turbine drive system in a test facility located at the Oak Ridge Gaseous Diffusion Plant. The results of the test program are given in Table E.2.

Table E.1. Characteristics of test rims

Demo unit	Axial length mm (in.)	Radial thickness mm (in.)	Rim weight (kg)	Rim inertia (kg-m^2)
1A	101.6 (4.0)	38 (1.5)	12.5	1.34
1B	48.3 (1.9)	38 (1.5)	5.8	0.63
1C	48.3 (1.9)	38 (1.5)	5.8	0.63

Table E.2. Flywheel demonstration test results

1985 Date	Demo unit	Velocity m/s	Rim specific energy kJ/kg (Wh/kg)	Results
Oct. 17	1A	1055	495 (138)	Web failure, small crack. No rim damage.
Nov. 8	1B	1173	605 (168)	Stopped for inspection. No damage.
Nov. 12	1C	1221	663 (184)	Stopped for inspection. No damage.
Dec. 9	1C	1405	878 (244)	Intentional failure test.

The relatively low speed (1055 m/s) achieved with Demo 1A is attributed to web damage that occurred during installation of the web into the rim; a crack was discovered in the web after the unit was spun to 1055 m/s. The speed of Demo 1B was limited by dynamic instabilities associated with the spin arbor configuration; the axial length of the web resulted in an unfavorable ratio of moments of inertia. Units 1B and 1C were inspected carefully after the spin tests to 1173 m/s and 1221 m/s respectively; no evidence of damage was found.

The objectives of the intentional failure of Demo 1C on December 9, 1985 were as follows:

1. to determine the speed capability of the unit for use in guiding the design activities, and
2. to obtain information relative to the safety and containment requirements of high speed flywheel rims.

Demo 1C was accelerated until failure occurred. Peripheral speed at failure was 1405 m/s. At this speed the specific energy of the rim was 878 kJ/kg (244 Wh/kg). The kinetic energy of the unit at failure was 7.28 MJ (2.02 kWh). It is not known whether the failure initiated in the rim or in the web. The central hub suction of the web was intact after the failure, but the remainder of the web was broken into small pieces. The rim material was found to be broken into extremely small pieces similar to dust or soot. The high speed failure was valuable in terms of the knowledge gained concerning containment requirements. The failure was monitored to obtain data on crash loads. It was determined that breakup of the rotor into small pieces resulted in significant axial loads in addition to the expected radial loads. The 1405 m/s failure speed provided firm experimental support of the design of flywheels which operate at 1100 to 1200 m/s.

The results from the Demo 1 series are compared with the results from the MEST program in Fig. E.1. In the figure, ultimate values (those obtained at flywheel maximum speed) are represented by solid symbols. The open symbols represent values obtained in non-failure tests and are hence more representative of operational limits. Rim-only values are represented by triangles, while total flywheel (i.e., rim

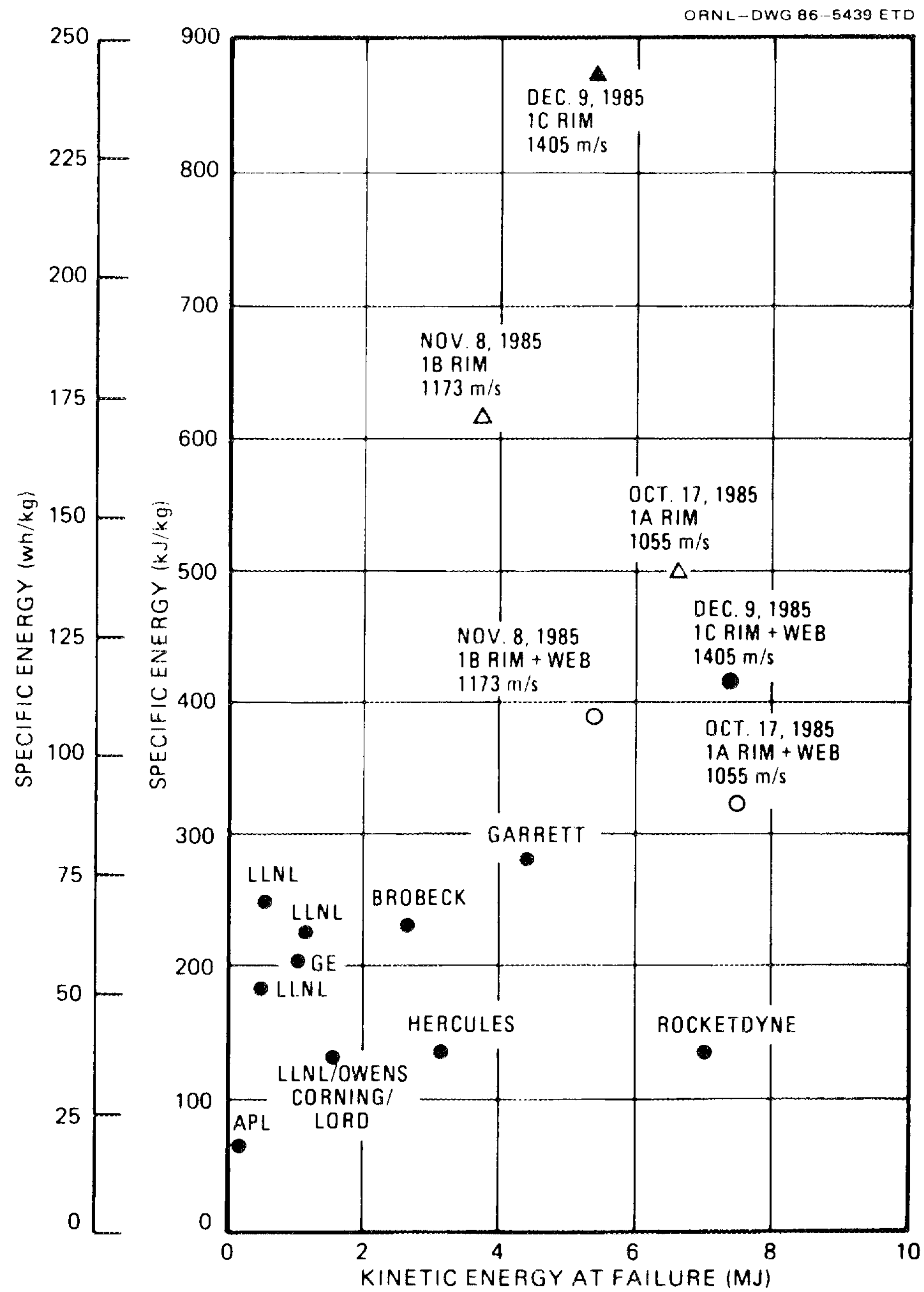


Fig. E.1. Comparison of rotor performances.

● total/ultimate, o total/operation

▲ rim only/ultimate, Δ rim only/operational

(Olszewski, 1986)

plus supporting web structure) values are represented by circles. As shown in the figure, the operational values demonstrated by the advanced rotors exceed, by one-third, the best ultimate value achieved in the MEST program.

Schedule and status. The program is currently unfunded pending DARPA's decision on the compulsator development program. If the program is funded and ETAC is chosen to develop the flywheels the development program will focus on rotors of lower performance. To match the compulsator needs, the flywheel will operate with a relatively low peripheral speed (on the order of 500 m/s). This will allow the use of S-glass rather than high strength carbon fibers.

Application to SDI needs. The rotor performance demonstrated in the program is on a level required for SDI applications. The high strength graphite fibers used in the rotor are those that will be required to meet SDI performance levels. Thus, the development activities are directly applicable to SDI program goals. The spin testing facility being constructed is of sufficient size (in items of total stored energy) to test prototype flywheels.

E.2 References for Appendix E

Olszewski, M. and O'Kain, A. V., "Advances in Flywheel Technology for Space Power Applications," *Proceeding of 21st Intersociety Energy Conversion Engineering Conference, San Diego, CA, August 25-29, 1986*.

Appendix F

FLYWHEEL TECHNOLOGY DEVELOPMENT SPONSORED BY DOE

F.1 Mechanical Energy Storage Technology Program (MEST)

Administrative. From FY 1977 to FY 1983, the DOE Office of Energy Storage sponsored a program to develop mechanical energy storage technology. Over that time period total funding for the program was on the order of $10.5 million. Program funding peaked in FY 1980 at a level of $3.8 million for the year. The program was initially managed by Lawrence Livermore Laboratory. However, in the later years (FY 1981 and beyond) the Oak Ridge National Laboratory was responsible for managing the program. During this period M. Olszewski was the program manager. The program focused primarily on flywheel technology although a small project was conducted in the area of elastomeric storage.

During the early years of the program ORNL was directly involved in designing, fabricating and spin testing flywheels. To facilitate technology transfer, the program philosophy changed and industrial firms were used as the primary supplier of innovative flywheels. Oak Ridge expertise was focused on development of spin testing capability acting as the independent test facility to verify performance characteristics. Subsequently the program management responsibilities were added to the ORNL role.

Objective. The objective of the program was to develop flywheel energy storage technology that could be used to improve energy efficiency in the transportation sector. Specifically, the program focused on the use of flywheels in automobiles and buses. The flywheel was to be used for accelerating the vehicle thus reducing the size of the engine. Braking energy was to be captured by the flywheel and this would affect an increase in fuel efficiency.

Work description. The program goal for flywheel performance was to achieve an energy density of 316 kJ/kg (88 Wh/kg) at the ultimate speed (the speed at which flywheel failure occurs). In order to accomplish this it was necessary to use composite materials (see Table F.1). Thus, composite flywheel technology was established in the DOE MEST Programs.

Table F.1. Characteristics of materials used in flywheels in DOE MEST program

Material	Ultimate tensile strength (σ) MPa	Density (ρ) g/cm^3	σ/ρ [kJ/kg (Wh/kg)]
Steels			
4340	1517	7.7	197 (54.7)
18 Ni (300)	2070	8.0	259 (71.8)
Composites			
E-glass/epoxy	1379	1.9	726 (201.6)
S-glass/epoxy	2069	1.9	1089 (302.5)
Kevlar[a]/epoxy	1930	1.4	1379 (382.9)
Graphite/epoxy	1586	1.5	1057 (293.7)
Other			
METGLASS[b]	2627	8.0	328 (91.1)

[a]Kevlar is a trademark of Du Pont.

[b]METGLASS is a registered trademark of the allied Corporation, Morristown, N.J.

Performance testing during the first phase of the MEST Program concentrated on ultimate speed evaluations. The purpose of this testing regime was to obtain energy density data at the maximum wheel speed and determine the failure mechanism that acted as the limiting factor for the design.

The results of these initial ultimate speed tests are presented in Table F.2. As shown, the wheels were generally of the rim or disk type with several hybrid disk/rim designs also included. A variety of materials were used including S-glass, Kevlar, graphite and Metglass. The highest ultimate energy achieved was 286 kJ/kg (79.5 Wh/kg) with a Kevlar rim.

In the next phase of the MEST Program, the field of candidate rotors was narrowed and the testing regime expanded to include cyclic fatigue tests. Results from these tests are given in Table F.3. The

Table F.2. Performance results for initial ultimate speed configuration tests

Manufacturer	Wheel type	Material[a]	Energy density at maximum speed (KJ/kg)	Energy stored (MJ)
ORNL	Overwrap	K49	178	2.02
Brobeck	Rim	SG/K49	229	2.55
Garrett/AiResearch	Rim	K49/K29/SG	286	4.43
Rocketdyne	Overwrap Rim	G	143	7.67
APL-Metglass	Rim	M	81	0.14
Hercules	Disk (contoured pierced)	G	135	3.06
AVCO	Disk (pierced)	SG	158	1.44
LLNL	Disk (tapered)	C	225	1.12
LLNL	Disk (flat)	SG	242	0.58
GE	Disk (solid/ ring)	SG/G	198	1.01
Owens/Lord	Disk	SMC	63	0.61
	Disk/ring	SMC/G	90	1.01
		SMC/G	100	1.30
		SMCG	132	1.44

[a]Material legend is: SG = S-glass; K49 = Kevlar 49; K29 = Kevlar 29;
G = Graphite;
M = Metglass; SMC = S-glass sheet molding compound

Table F.3. Performance results for fatigue and ultimate speed tests of advanced rotors tested in DOE MEST program

	Flywheel design			
	Disk	Disk/rim	Subcircular rim	Bidirectional weave
Material	SMC	SMC/G	K49	K49
Completed 10,000 Cycle Test	Yes	Yes	No[a]	[b]
Ultimate energy density, (kJ/kg)	175[c]	229	237	134
Total stored energy, (MJ)	1.86	2.32	2.24	1.50
Speed at failure, (rpm)	40,638	47,058	30,012	27,575

[a]Rotor failed at 2586 cycles.

[b]Rotor was not cycle tested.

[c]Rotor had previously completed cyclic test.

disk and disk/rim concepts completed the full 10,000 cycle tess. Subsequent ultimate speed tests of these rotors yielded energy densities of 172 and 229 kJ/kg (48.6 and 68.5 Wh/kg) for the disk and disk/rim designs, respectively. The disk/rim results were of particular interest because ultimate speed data were obtained for the design before and after cyclic fatigue testing. Test results for a new rotor showed an energy density of 198 kJ/kg (55 Wh/kg). After 10,000 cycles the design yielded a measured energy density of 229 kJ/kg (63.5 Wh/kg), the increase being ascribed to a "work hardening" effect in the rotor material.

Schedule and status. The MEST Program was phased out by the DOE in FY 1983 and the program is currently inactive.

Application to SDI needs. The establishment of composite flywheel technology was important since composite rotors will be required to meet SDI performance requirements. However, performance of the fibers used in the MEST Program is not sufficient to meet SDI needs. To meet the performance needs of SDI MMW applications the newest graphite fibers will be required. These fibers represent an eightfold increase in specific strength (compared to the fibers used in the MEST Program) and may require new designs or fabrication techniques to make fullest use of their properties. Thus, while the technology base established in the MEST Program can be used to as a starting point, the performance levels desired were much lower than those in the SDI program and new techniques will be required to realize the full potential of the new high-strength graphites now available.

F.2 Technology Transfer Activities

Administrative. The Enrichment Technology Application Center (ETAC) organization was formed at Martin Marietta Energy Systems in October 1985, and DOE provided FY 1986 funding to permit application of the technology developed over 25 years in the Enrichment Program to other areas. Flywheel development was one of the major activities undertaken by ETAC with \$3 to \$3.5 million (the total technology transfer budget was \$6 million) being budgeted for the activity. The program is directed by:

Mr. David U. O'Kain
Enrichment Technology Applications Center
Martin Marietta Energy Systems
P.O. Box K
Oak Ridge, TN 37831
(615) 576-0262

Objective. The objective of the program is to build upon existing expertise and enhance the capability to perform generic flywheel development projects. Primarily, this involves the procurement and installation of fabrication, assembly, and testing equipment for the development of high performance composite flywheels.

Work description. The activities undertaken in FY 1986 included development of flywheel design and analysis capability, design and procurement of a new flywheel winder and design and procurement of assembly tooling required to assemble flywheels. These facilities and analytical tools will allow ETAC to design fabricate and assemble flywheels. Since the facilities are geared to the use of high-strength advanced fibers they will be applicable to the development of flywheels with high energy storage densities. When coupled with the testing capabilities being developed in conjunction with a program being funded by DARPA (see Appendix E) ETAC will have capabilities in the development of high performance flywheels that are unique in the country.

Schedule and status. The technology transfer funding is for one year only. All activities will be completed during FY 1986.

Application to SDI needs. The capability in flywheels being developed by ETAC is specifically targeted to SDI needs. The design, fabrication and assembly capabilities being developed are focused on the new high strength fibers that will be required to produce composite flywheels capable of meeting SDI performance specifications.

F.3 References for Appendix F

Barlow, T. M., and Zygielbraum, P., editors, *Proceedings of 1980 Flywheel Technology Symposium, October 1980, Scottsdale, AZ* (CONF-801022).

Olszewski, M., "Flywheel Performance: Current State-of-the-Art," *Proceeding of 19th Intersociety Energy Conversion Engineering Conference, San Francisco, CA, August 19-24, 1984*, pp. 1150-1155.

Internal Distribution

1. D. E. Bartine
2. T. M. Besmann
3. R. H. Cooper
4. J. M. Corum
5. W. G. Craddick
6. J. R. Distefano
7. H. W. Hoffman
8. A. L. Lotts
9. D. G. Morris
10. J. Moyers
11. F. R. Mynatt
12. J. P. Nichols
13. D. V. O'Kain
14. M. Olszewski
15. H. Postma
16. C. E. Pugh
17. M. A. Schmidt
18. M. Siman-Tov
19. H. E. Trammell
20-22. R. P. Wichner
23. F. W. Wiffen
24. P. T. Williams
25. R. G. Wymer
26. ORNL Patent Office
27. Central Research Library
28. Document Reference Section
29-30. Laboratory Records Department
31. Laboratory Records (RC)

External Distribution

32. K. R. Absher, DOE - Richland Operations Office, P.O. Box 550, Richland, WA 99352
33. J. O. Barner, Pacific Northwest Laboratory, Battelle Boulevard, Richland, WA 99352
34. S. A. Bassett, W. J. Schafer Association, 1901 N. Fort Myer Drive, Arlington, VA 22209
35. J. Beam, AFWAL/POOS-3, Wright-Patterson AFB, OH, 4533-6563
36. C. R. Bell, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545
37. D. R. Bennett, Department of Energy, NE/521 Germantown, Washington, DC 20545
38. S. K. Bhattacharyya, Argonne National Laboratory, 9700 South Cass, Bldg. 207, Argonne, IL 60439
39. R. J. Bohl, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545
40. J. Deariem, EG&G, Inc., P.O. Box 1625 - WCB E2, Idaho Falls, ID 83415
41. P. J. Dirkmaat, DOE - Idaho Operations Office, 785 DOE Place, Idaho Falls, ID 83402
42. D. S. Dutt, Hanford Engineering Dev. Lab., P.O. Box 1970, Richland, WA 99352
43. D. C. Fee, Argonne National Laboratory, 9700 South Cass, Bldg. 207, Argonne, IL 60439
44. C. R. Fisher, GA Technologies, P.O. Box 81608, 10955 John J. Hopkins Drive, San Diego, CA 92138
45. R. D. Hahn, U.S. Department of Energy, DP-22.2 Germantown, Washington, D.C. 20545

46. J. K. Hartman, Department of Energy San Francisco Operations Office, 1333 Broadway Ave., Oakland, CA 94612
47. J. Henscheid, EG&G, Inc., P.O. Box 1625 - WCB E2, Idaho Falls, ID 83415
48. E. E. Hoffman, DOE-Oak Ridge Operations Office, P.O. Office Box E, Oak Ridge, TN 37831
49. R. L. Holton, DOE - Albuquerque Operations Office, P.O. Box 5400, Albuquerque, NM 87115
50. J. L. Hooper, DOE - Chicago Operations Office, 9800 S. Cass Avenue, Argonne, IL 60439
51. S. V. Jackson, Los Alamos National Laboratory, Battelle Boulevard, Richland, WA 99352
52. R. P. Jenkins, Lockheed Missile and Space Co., Research and Development, 3251 Hanover St., Palo Alto, CA 94304
53. B. M. Johnson, Pacific Northwest Laboratory, Battelle Boulevard, Richland, WA 99352
54. E. U. Khan, Department of Energy, NE/521 Germantown, Washington, D.C. 20545
55. W. J. Krotiuk, Pacific Northwest Laboratories, P.O. Box 999, Richland, WA 99352
56. W. E. Lambert, Department of Energy, San Francisco Operations Office, 1333 Broadway, Oakland, CA 94612
57. E. T. Mahefkey, AFWAL/POOS-3, Wright-Patterson AFB, OH 4533-6563
58. R. Marsh, AFWAL/POOS-3, Wright-Patterson AFB, OH 4533-6563
59. J. Martinell, EG&G, Inc., P.O. Box 1625 - WCB E2, Idaho Falls, ID 83415
60. M. A. Merrigan, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87544
61. J. F. Mondt, JPL, 4800 Oak Grove Dr., Pasadena, CA 91109
62. N. R. Ortiz, Sandia National Laboratory, P.O. Box 5800, Albuquerque, NM 87185
63. J. R. Powell, Brookhaven National Laboratory, Upton, NY 11873
64. L. Preston, United Technologies Corporation, Power Systems, P.O. Box 109, Windsor, CT 06074
65. R. E. Rice, EG&G Idaho, Inc., P.O. Box 1625 - WCB E2, Idaho Falls, ID 38415
66. R. J. Sovie, NASA Lewis Research Center, 21000 Brookpark Rd., Cleveland, OH 44135
67. M. Stanley, EG&G, Inc., P.O. Box 1625 - WCB E2, Idaho Falls, ID 83415
68. R. Struthers, EG&G, Inc., P.O. Box 1625 - WCB E2, Idaho Falls, ID 83415
69. F. V. Thome, Sandia National Laboratory, P.O. Box 5800, Alburquerque, NM 87185
70. R. L. Verga, SDI Office/SLKT, The Pentagon Building, Washington, D.C. 20301
71. E. J. Wahlquist, Department of Energy, NE/521 Germantown, Washington, D.C. 20545
72. C. E. Walter, Lawrence Livermore National Laboratory, P.O. Office Box 808, Livermore, CA 94550
73. D. Warmack, AFWAL/POOS-3, Wright-Patterson AFB, OH 4533-6563

74. J. Whitbeck, EG&G, Inc., P.O. Box 1625 - WCB E2, Idaho Falls, ID 83415
75. R. D. Widrig, Pacific Northwest Laboratory, P.O. Box 999, Richland, WA 99352
76. R. L. Wiley, SDI Office/SLKT, The Pentagon, 1717 H. St., N.W., Washington, D.C. 20301
77. Office of Assistant Manager for Energy Research and Development, Department of Energy, ORO, Oak Ridge, TN 37831

78-107. Technical Information Center, Department of Energy, Oak Ridge, TN 37831

☆U.S. GOVERNMENT PRINTING OFFICE: 1987-748-168/40120