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Megawatt Class Nuclear Space Power Systems (MCNSPS) Conceptual Design and Evaluation Report

Volume IV—Concepts Selection, Conceptual Designs Recommendations

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5.0 CONCEPTS SELECTION

5.1 SELECTION CRITERIA AND SCREENING FOR PREFERRED SYSTEMS

From Fig. 4.2.3 of Vol II, which showed the candidate combinations of five reactor types, five power conversion technologies, and four waste heat radiator concepts, some 70-80 nuclear space power system concepts are possible. Furthermore, each candidate system must be considered over a range of power levels, size envelopes, development status, reliability, and risk. The goal of the MCNSPS study is to narrow these possibilities by constraining the candidates to be launchable and to have the capability of providing continuous power of from 1 to 10 MWe for a period of 5 years or more. In order to bound the candidate systems further and permit convergence to a recommendation, the following additional boundary conditions were adopted:

1. Systems capable of 10 MWe for 5 years continuously and requiring greater than 5 equivalent shuttle boosts to achieve that capability in low earth orbit (LEO) will not be considered further.

2. Systems with non-deployable radiators which are not capable of at least 500 kWe output in one shuttle boost to LEO will not be considered further.

3. Systems which would effectively use relatively established radiator concepts, as listed below and which are capable of meeting the above 2 requirements will receive priority consideration.

   a. Direct fin conduction
   b. Direct heat pipe
   c. Pumped loop to finned tube or heat pipe

4. Systems and radiators capable of being boosted directly to operational orbits (greater than 940 Km and inclined from 28° to 90°) will be preferred.

5. Survivable systems capable of evasive maneuvering will be preferred.

6. Self deploying systems will be preferred.

7. Static high reliability concepts will be preferred.

The more promising concepts might benefit from advanced radiator performance potentially offered by pumped loop-rotating drum, pumped loop-liquid droplet, or pumped loop-electrostatic particle, etc., radiators. However, this study could not identify an advantage for such radiator concepts.

The initial screening of power conversion systems was conducted early in the study to select the most favorable candidates for more intensive investigation. In this screening minimizing the size and the weight of the radiator was a primary consideration. The electric power produced per unit area of radiator (P_e/A_R) represents a major criterion for comparing different megawatt class candidate systems.

Particular attention was given to those systems which have received a relatively high degree of development or study for space power in the past. These include metal-vapor Rankine, thermoelectric, thermionic, and Brayton cycle systems. The alkali metal-vapor Rankine cycle and thermionic systems have the highest heat rejection temperatures and therefore were immediately the most promising candidates for MCNSPS. However, the Brayton system has also been extensively studied in past efforts and was therefore considered in some detail. As detailed previously, the other systems considered and/or examined in the screening phase, which have received less attention in the past, included: Stirling cycles, advanced thermoelectrics, MHD, and a conventional steam cycle.

The requirement of achieving a degree of compactness that will allow shuttle or single big booster launch is considered critical. It is also considered to be critical to minimize the need for low altitude, low inclination "manned" orbit assembly and construction prior to transfer to higher altitude and higher inclination operating orbits.

Table 5.1.1 present an initial screening of candidate systems based upon limiting the radiator area to 250 m^2 for 500 kWe output, a system which must be launchable in a single shuttle. Note that the total surface area of a cylinder that could fit into the STS shuttle bay (4.4 diameter x 17 m long) is 250 m^2. By the screening criterion that a 500 KWe system must fit into a shuttle bay with a fixed non-deploying radiator, the following elimination was recommended.

- Thermo-electric conversion was eliminated as a likely candidate for significant growth in power output.

- Brayton gas turbines coupled to liquid metal cooled reactors were eliminated as potential candidates for significant growth in power output.

- Free Piston Stirling Engines constructed of currently developed materials and coupled to liquid metal cooled reactors were eliminated from further consideration.

- The Steam Rankine cycle was also eliminated, based upon excessive radiator area requirements.

No suitable reactor-MHD cycles meriting inclusion in the analysis were formulated, although we note that the gaseous fueled reactor might be coupled to MHD cycles in later studies.

5.2 EVALUATION AND SELECTION

Following the initial screening and the parametric analysis, the comparative design study information for preferred systems was evaluated for 10 MWe systems with fixed radiators. These results are summarized on Table 5.2.1. For the fixed radiator systems only the potassium and sodium Rankine cycles survive the screening requirements of launchability in 5 shuttles, i.e. <1250 m^2 of radiator. Clearly, a suitable means of stowing an expandable radiator during launch must be developed to meet program goals. Assuming this can be accomplished with the consequence of effectively increasing the

RADIATOR AREA REQUIRED AT 500 KWE (250M^2 LIMIT)

THERMO ELECTRIC		Reactor Out K	Radiator Area M^2	Reactor Power MWT	
SP-100 Fallback SiGe		1350	520	14	
SP-100 Baseline SiGe GAP		1350	390	12	
SP-100 Advanced LaSx		1350	345	9	
THERMIONICS	Emitter K				
SP-100 Fallback	1650	1050	165	7	*
SP-100 Baseline	1750	1100	140	6	
SP-100 Advanced	1850	100	98	5.5	
Potential	1960	1100	78	4	
BRAYTON	Turbine In				
Fallback LMCR	1100	1200	----	----	
Baseline LMCR	1250	1350	550	3.6	
Advanced GCR	1500	1500	210	2.5	*
Potential GCR	1800	1800	93	2.5	
STIRLING	Engine Hot				
Fallback LMCR	1000	1050	600	2.3	
Baseline LMCR	1100	1150	420	2.1	
Advanced LMCR	1400	1420	110	3.1	*
Potential LMCR	1500	1570	75	1.5	
RANKINE					
Steam	730	800	2,000	2.2	
Mercury	1030	1100	225	2.0	
Cesium	1200	1250	105	2.9	*
Potassium	1450	1520	63	3.0	
Sodium	1600	1650	40	2.7	

*Possible Systems Studied

TABLE 5.1.1

RADIATOR AREA REQUIRED AT 10MWE

		Reactor Out K	Radiator Area M^2	Reactor Power MWT
THERMO ELECTRICS				
SP-100 Fallback SiGe		1350	10,400	280
SP-100 Baseline SiGe Gap		1350	7800	240
SP-100 Advanced LaSx		1350	6900	180
THERMIONICS	Emitter(K)			
SP-100 Fallback	1650	1050	3300	135
Baseline	1750	1100	2800	125
Advanced	1850	1100	1950	110 *
Potential	1960	1100	1550	80
BRAYTON	Turbine in			
Fallback LMCR	1100	1200	----	----
Baseline LMCR	1250	1350	11,000	73
Advanced GCR	1500	1500	4200	49
Potential GCR	1800	1800	1850	49 *
STIRLING	engine hot			
Fallback LMCR	1000	1050	12,000	45
Baseline LMCR	1100	1150	8400	42
Advanced LMCR	1400	1420	2200	63
Potential LMCR	1500	1570	1500	30 *
RANKINE				
Steam	730	800	40,000	44
Mercury	1030	1100	4500	41
Cesium	1200	1250	2100	58
Potassium	1450	1520	1250	59 *
Sodium	1600	1650	800	54

*Potential, examined in more detail

TABLE 5.2.1

launchable area of radiator to 2000 m^2 (1/2 acre), then the candidate systems can be expanded to include the thermionic, Brayton, Stirling, and Rankine systems as indicated in Table 5.2.1. Note however, that gas conversion systems heated by LMCR's are still too large and hence are not given further consideration.

The Free Piston Stirling Engine (FPSE) Cycle (Section 4.5.4 of Vol. III) could be considered only if a ceramic fibre wound, low mass, ceramic cylinder can be fabricated. This cylinder must be compatible with liquid metal, have high thermal conductivity, and be capable of containing (several thousand psi) 10-30 MPa internal pressure at 1570 K without creep for 5 to 10 years. A second major requirement is that a long lived linear alternator must be developed with a specific mass of 1 Kg/KWe. Such a development will be long, costly and might not be possible. These caveats aside, a Stirling cycle system was evaluated on the basis of achieving either this postulated highly advanced ceramic cylinder engine and the metallic tantalum alloy-ceramic fibre wound composite engine postulated by Martini.

Table 5.2.2 summarizes the important characteristics and the masses of each of the systems which survived the preliminary screenings and were studied in depth. High pressure gas cooled reactors coupled to closed cycle, ceramic blade, brayton gas turbines, with moderate (80%) or no recuperation, were found to be reasonably compact, requiring only one shuttle for launching the power system and two for the associated radiator. The Brayton system based on a metallic turbine requires two shuttles for the power system and three for the associated radiator. Here again the relatively low temperature of the radiator resulted in the requirement for a pumped loop triform radiator, which increases the number of dedicated shuttle loads from 2 to 3, in order to deliver it to LEO. The results show that there is little hope of achieving an attractive system using metallic turbines operating at 1500K, but a ceramic turbine system capable of operating at 1800K and at high spin speed for 5 to 10 years without significant creep, could be attractive.

The relatively low temperatures of the Brayton system radiator require the use of pumped loop heat transport and distribution to relatively short alkali metal heat pipe radiating tubes. The use of mercury for large

SUMMARY SYSTEM MASS AND NUMBER OF SHUTTLE LOADS, 10 MWe SYSTEM

	GAS-COOLED REACTOR		LITHIUM-COOLED REACTOR				LITHIUM-COOLED REACTOR	
	Inert Gas Turbine 80% Recuperator		Stirling Engine		Potassium Turbine		In-Core Thermionic Conversion	
Temperatures (K)	Ceramic	METALLIC	Ceramic *	Ta-Alloy Composite	W-HfC	ASTAR 811-C	CVD-W	CVD-Re
Reactor Fuel Surface	2000+	1750	1600	1500	1630	1550	1900	1960
Reactor Outlet	1800	1500	1570	1420	1600	1520	1100	1100
Reactor Inlet	1322	1100	1470	1370	1500	1420	1000	1000
Turbine Inlet (T_h)	1800	1500	1500	1400	1550	1450	1900	1960
Compressor Inlet (T_c) (condenser)	667	556	775	922	1100	1040	1110	1110
Cooler Inlet	640	530	700	840	Direct Telescoping		Direct Telescoping	
Cooler Outlet	1010	840	800	940	Heat Pipes		Heat Pipes	
Average Radiator (T_R)	~820	~680	700	840	1000	940	1010	1010
Power								
Reactor Power (MWt)	49	49	29	63	58	59.5	99	80
Cycle Efficiency (%)	22	22	38	18.4	19.9	19	11.5	13.6
System Efficiency (%)	20.4	20	34.5	16	17.5	16.8	10.1	12.5
Radiator Area (m^2)	1850	4200	1500	2200	900	1250	1650	1550
Mass (kg)								
Reactor	9200	9200	3500	7600	6500	6600	15400	13000
Shield	3000	3000	1500	2800	2000	2100	5800	4400
Converter	5000	14400	22000	46000	7000	7000	0	0
Heat Transfer & Structure	13100	19300	6000	13000	15000	16600	9300	8000
Power Module Mass, STS**	30400(1)	45900(2)	33000(1)	69400(3)	30500(1)	32300(1)	30500(1)	25400(1)
Radiator Mass, STS**	38000(2)	72000(3)	22400(2)	32000(2)	15000(1)	20000(1)	25950(1)	24000(1)
PC & T Module	4300	4300	5000	5000	4300	4300	9000	9000

TABLE 5.2.2

* Highly Advanced
** Space Transport Systems (Shuttle)

thermal transport conductors was considered to be impractical due to the potential consequences of major mercury leaks, and due to the high pressures if the mercury heat pipes are heated significantly while under laser attack. Consequently, the most advanced closed cycle Brayton System will require substantial orbital assembly and welding if launched to LEO by shuttle. The large triform radiator with bellows folded heat pipes, is not very suitable structurally for transfer from the manned LEO low inclination assembly orbit to the higher altitude and inclination operating orbits. The large triform radiator is also difficult to package into large cargo boosters (at reasonable shield cone angle) for boost of ground assembled units directly to operational orbits.

The Brayton system mass optimization results are presented in more detail in Figure 5.2.1, as a function of the compressor inlet temperature. This figure shows that the minimum mass system is not strongly dependent upon the compressor inlet temperature in the 500-700K range, that 80% recuperation results in a lower mass system than either no recuperation or 95%, and again, that the lower turbine inlet temperature systems are significantly heavier and non-competitive.

Fig. 5.2.2 shows LMCR-FPSE system mass versus the engine cold side temperature. Due to the low radiator temperature of the Stirling engines, a pumped loop is required to distribute the engine waste heat to the half acre of radiating heat pipes. The best packaging arrangement of a practical lower temperature radiator was found to be the triform pumped loop, heat pipe radiator (Fig. 4.3.30, Vol. II). The volume packing fraction of that radiator would require 2 dedicated shuttle loads to lift the 10 MWe Stirling system radiator to LEO. A third shuttle load would be required for the power module. The FPSE system would require extensive orbital assembly and welding of liquid metal filled piping. Even if successfully developed, this system could not reasonably be launched to an operational orbit (i.e.>900km altitude and typically >70° inclination) as one ground assembled unit, with a foreseeable shuttle derived cargo booster.

The 10 MWe potassium Rankine-LMCR systems and the incore thermionic systems both require only 2 shuttles to lift to LEO. The system masses calculated

10 MWe SYSTEM WEIGHTS
BRAYTON CYCLE

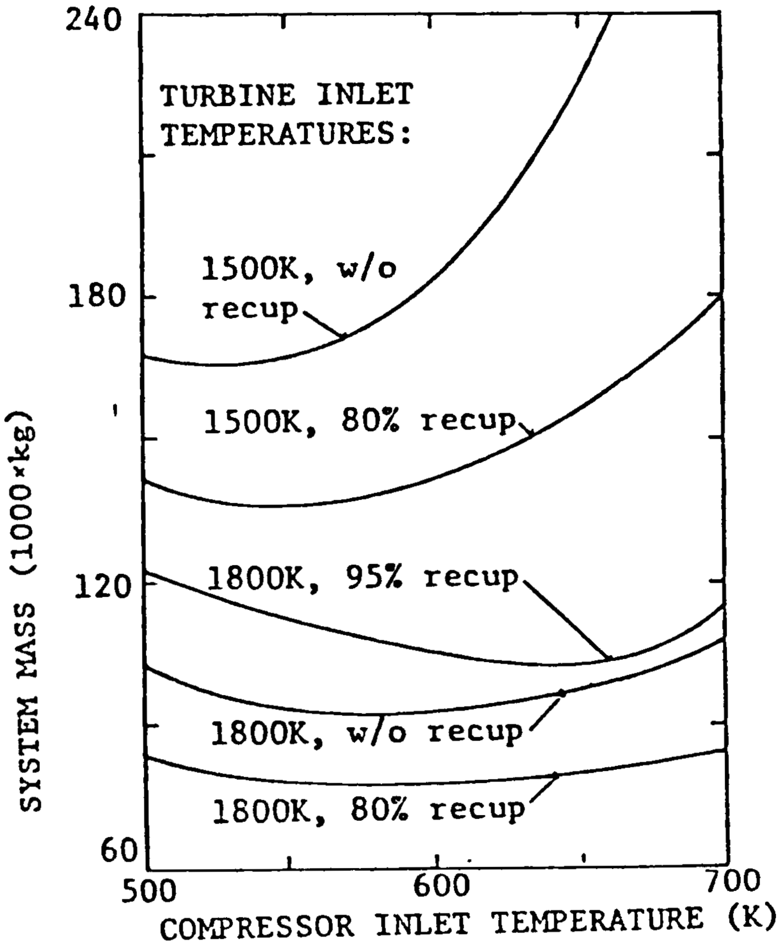

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FIG. 5.2.1

10 MWe SYSTEM WEIGHTS
STIRLING CYCLE

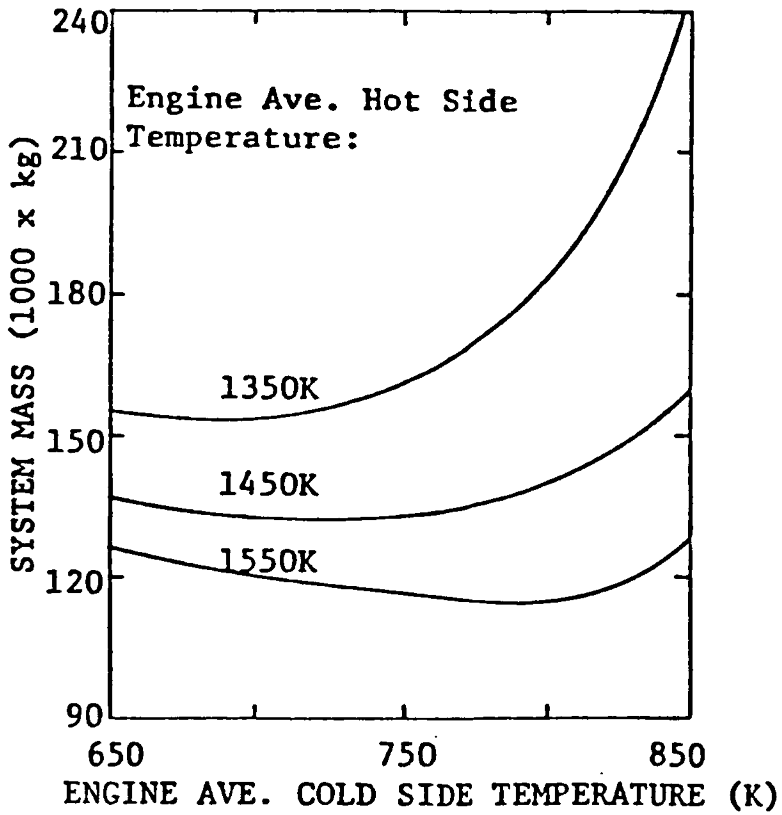

FIG. 5.2.2

as a function of the heat sink temperatures are shown in figures 5.2.3 and 5.2.4. The heat rejection temperature of either cycle is high enough to utilize the alkali metal heat pipe radiator effectively (with telescoping cylindrical sections). This type of radiator can be coupled to either power system in LEO without welding. Either system could be ground assembled with the SPI telescoping radiator and could be boosted directly to operational orbit with big cargo boosters. Furthermore, the telescoping radiator renders it very suitable for rendezvous, docking and inspection with the payload in LEO, and for subsequent orbital transfer of the integrated and inspected spacecraft to operating orbit.

Because the potassium Rankine-LMCR and the incore thermionic reactor power systems showed considerable advantages over the other concepts in terms of low system mass and number of shuttles required for launch, these two concepts were selected for further conceptual design and study (see Section 6, following).

Either system, with the telescoping radiator, has high inherent survivability to natural environment, to beam weapons, and to kinetic energy (KEW) attack. The incore thermionic system has a larger radiator, a slightly larger mass and a lower efficiency than the Rankine systems. However, it is a static system with no moving parts (except control drums). It fails very gradually and can provide warning of at least a year before significant failure degradation occurs. It is very amenable to orbital startup and restart after dormancy. Thermionic conversion is the only PCS technology studied that has actually demonstrated (out of core) the required 5 year lifetime at the required emitter temperature of 1960K used in this conceptual study.

The potassium Rankine system is about 10% to 15% lighter than the incore thermionic. The power conditioning and radiator development will be substantially easier than for the thermionic approach. Uniform temperature potassium condensation heat rejection integrates more easily with a heat pipe radiator than does the sensible heat coolant system used for incore thermionics. On the other hand, the Rankine system lithium primary loop circulation pump must operate some 300 to 400 K hotter than the thermionic

10 MWe SYSTEM WEIGHTS
K-RANKINE CYCLE

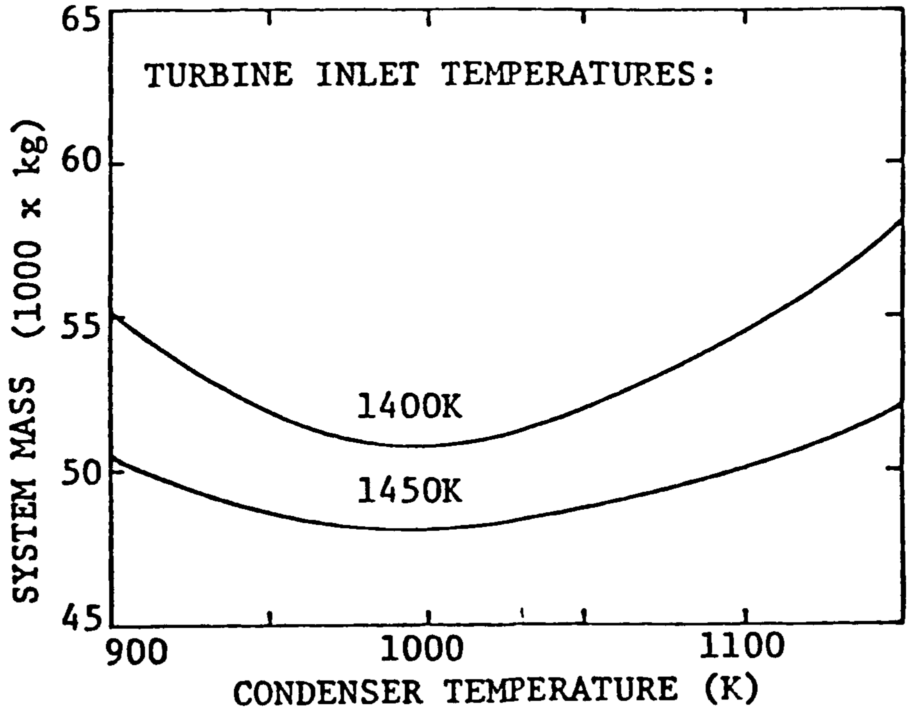

FIG. 5.2.3

10 MWe SYSTEM WEIGHTS
IN-CORE THERMIONICS

(POWER CONDITIONER WT.INCL.)

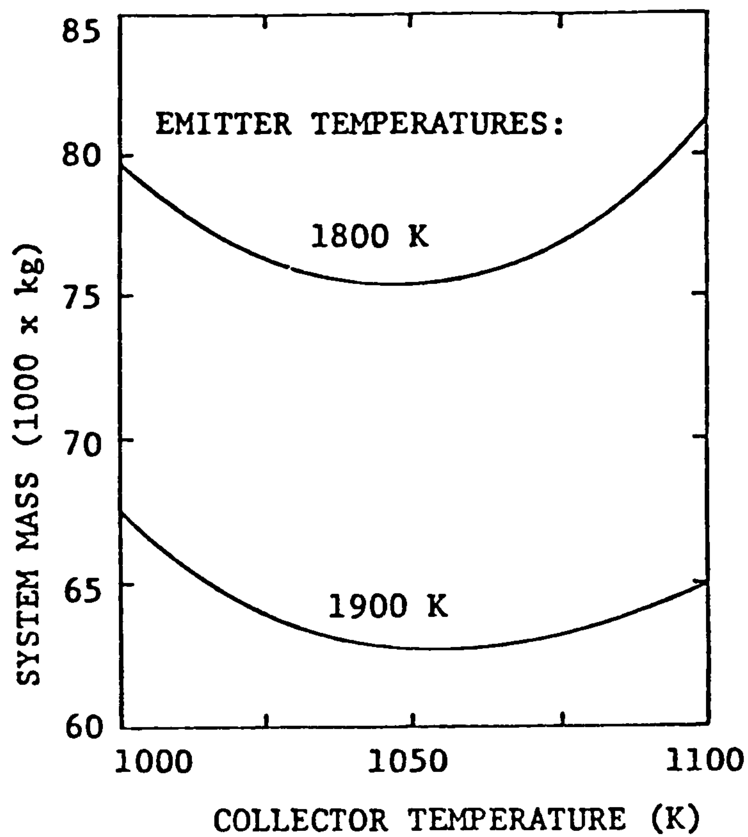

FIG. 5.2.4

system pump and well above the 1250 K Curie point of advanced magnetic materials. These substantially higher reactor and primary coolant loop temperatures will significantly impact reliability and development cost.

Zero-gravity boiling, condensing, startup, shutdown, restart, and bearing fluid scavenging also present development problems. Frozen coolant and other working fluids at launch and after long dormancy periods introduce problems and complexity during startup and shut down. These types of problems and potential solutions are described subsequently. Suffice to say that a great deal of expensive component, subsystem and system development and testing is required to demonstrate the potential and the verification for 5 to 10 year life. Critical problem areas anticipated are with alternator seals which are resistant to attack from alkali metal vapor, turbine blade creep, high temperature lithium corrosion and proof of fuel element endurance at 1600 K surface temperatures in lithium. As noted before, a boiling alkali metal reactor might reduce the peak fuel temperature some 50 to 75 K and relieve the lithium corrosion problems. However, this approach introduces major reactor containment, control and start up problems.

In Table 5.2.3 a qualitative assessment of concepts versus criteria is presented. Table 5.2.4 rates important system qualities for the 4 primary concepts and provides a quantitative overall comparison between the concepts.

If all criteria are weighted equally, the incore thermionic reactor system scores best (107), followed closely by the potassium Rankine system (95). The best Brayton and Stirling cycle systems rank substantially lower (80 each). If the compactness of launch and system mass are given weighting factors which are a factor of three and two, respectively, greater than the other criteria, the rankings remain unchanged (figures in parenthesis), except that the Brayton cycle system is slightly advantageous (96) over the Stirling (92). From this admittedly subjective rating, it is clear that the boiling potassium reactor with a potassium Rankine cycle power conversion system has an attractivness comparable to that of the incore thermionic

WHAT TECHNOLOGY BEST MEETS REQUIREMENTS -

	NEAR TERM 1995-2005	LONG TERM 2005-2015
MINIMUM MASS	KRS	ITR or SRS
MINIMUM SIZE	KRS	SRS
SURVIVABILITY	ITR	ITR
RELIABILITY	ITR	ITR
EASE OF DORMANCY & RESTART	ITR	ITR
GRADUALITY OF FAILURE	ITR	ITR
LOWEST FUEL SURFACE TEMPERATURE	KRS	KRS
LOWEST REACTOR STRUCTURE & SYSTEM TEMP	ITR	ITR
EASIEST REACTOR CONTROL	KRS	?
EASIEST SYSTEM CONTROL	ITR	ITR
EASIEST POWER CONDITIONING	KRS	KRS
GREATEST CRITICAL COMPONENT EXPERIENCE	ITR	Draw

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KRS = POTASSIUM RANKINE SYSTEM
SRS = SODIUM RANKINE SYSTEM
ITR = INCORE THERMIONIC REACTOR

TABLE 5.2.3

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A PRELIMINARY RANKING OF SYSTEMS

Best Rating	Rankine Cycle	Thermionic Cycle	Brayton Cycle	Stirling Cycle
Compactness of Launch (x 3 weighting)	10 (30)	9 (27)	6 (18)	4 (12)
Mass (x 2 weighting)	8 (16)	7 (14)	4 (8)	4 (8)
Size Deployed (maneuverability)	9	8	3	4
Survivability	7	9	3	4
Endurance	TBD	TBD	TBD	TBD
Reliability - Redundancy	4	9	6	7
Ease of Dormancy Cooling	6	8	3	6
Ease of Restart After Dormancy	4	8	9	7
Graduality of Failure	4	8	4	6
Lowest Fuel Surface Temperature	8	4	3	6
Lowest Reactor Coolant & Structure	6	9	3	6
Ease of Reactor Control	5	4	5	6
Ease of System Control	4	9	8	7
Ease of Power Conditioning	9	4	9	7
Greatest Critical Component Experience @ Temperature	4	7	6	1
Ease of Manufacture	7	4	8	5
TOTAL	95 (123)	107 (132)	80 (96)	80 (92)

TABLE 5.2.4

reactor system and consequently no clear cut decision for concentration of effort can be recommended at this time.

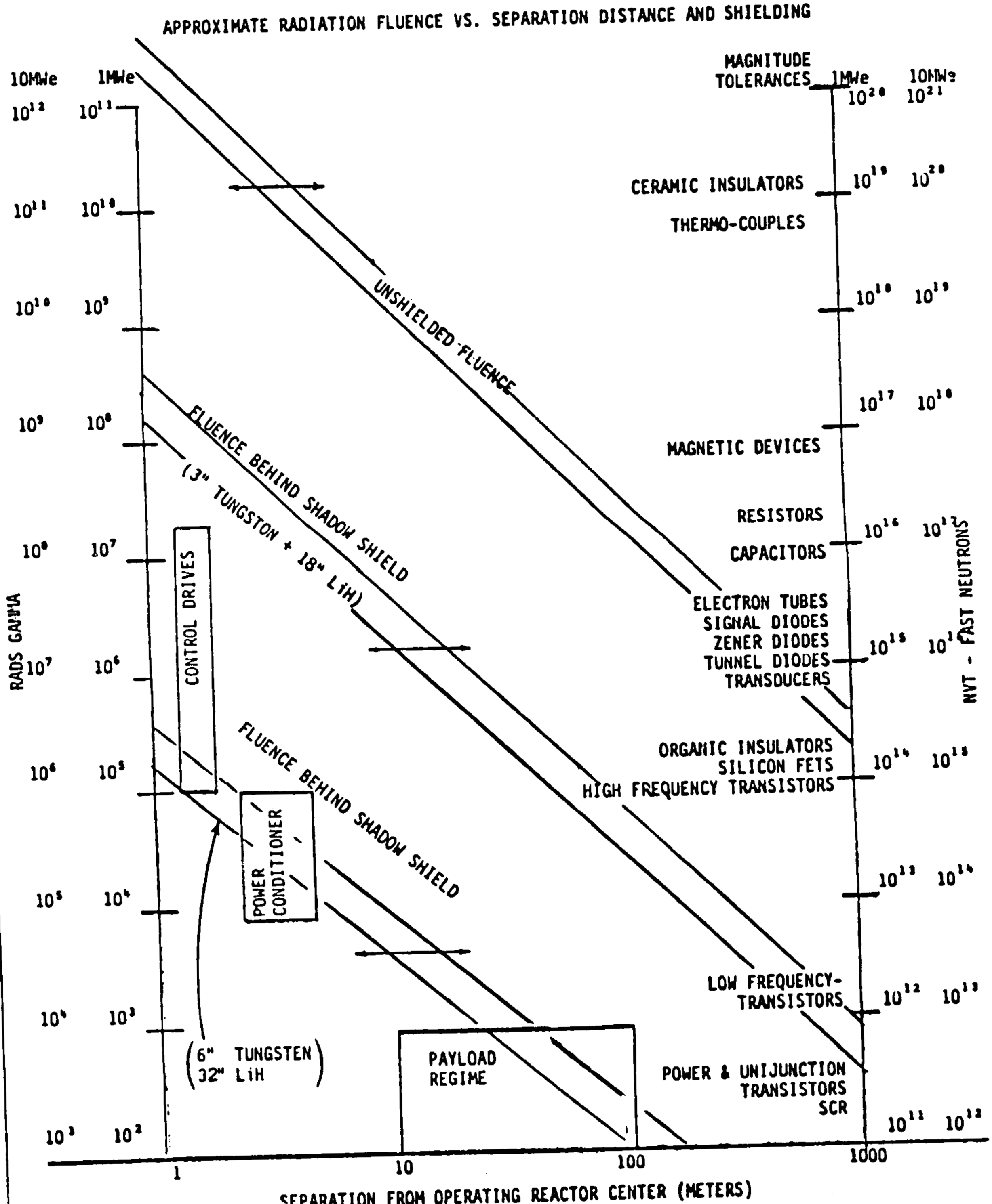
If the static thermionic system with series-parallel connected converters can achieve the required endurance and acceptable fabrication costs, it could prove to be the more desirable system for space power generation, in spite of having a mass slightly higher than that of the potassium Rankine system.

5.3 SYSTEM CONFIGURATION

Configuration influences radiator choice, and consequently conversion system and reactor concept choice. The criteria which strongly influence configuration are:

- Radiation shielding & payload radiation sensitivity
- Need for payload maintenance during spacecraft lifetime
- Minimum orbital construction
- Self deployment in orbit
- Maximum survivability
- Power transmission requirements
- Thermal isolation of the payload
- Minimum possible contamination of payload from coolant or radiator leakage.

Shielding and Radiation Protection are influenced by the radiation tolerance of payload components. Figures 6.2.7 and 6.2.8 (Section 6 of this Volume) provide an approximate range of radiation fluences tolerable by various payload components. Figure 5.3.1 provides an approximate magnitude comparison of these tolerances to the annual dosage that the components might receive from a 1 MWe and a 10 MWe reactor versus separation distance. For example, if the payload can only tolerate 10^{13} nvt fast neutrons and 5 X 10^{5} rads of gammas (SP-100 specification), then the neutron shield for 10 MWe at an equivalent of 5 years of full power operation might only require another 30 cm (~ 1 foot) more LiH shield thickness than the SP-100 shield, with the same 25 meter separation distance. However, at the probable 50 to



APPROXIMATE RADIATION FLUENCE VS. SEPARATION DISTANCE AND SHIELDING
10MWe
1MWe
MAGNITUDE TOLERANCES
RADS GAMMA
NVT - FAST NEUTRONS
UNSHIELDED FLUENCE
FLUENCE BEHIND SHADOW SHIELD
(3" TUNGSTEN + 18" LiH)
FLUENCE BEHIND SHADOW SHIELD
CONTROL DRIVES
POWER CONDITIONER
(6" TUNGSTEN 32" LiH)
PAYLOAD REGIME
CERAMIC INSULATORS
THERMO-COUPLES
MAGNETIC DEVICES
RESISTORS
CAPACITORS
ELECTRON TUBES
SIGNAL DIODES
ZENER DIODES
TUNNEL DIODES
TRANSDUCERS
ORGANIC INSULATORS
SILICON FETS
HIGH FREQUENCY TRANSISTORS
LOW FREQUENCY-TRANSISTORS
POWER & UNIJUNCTION TRANSISTORS
SCR
1
10
100
1000
SEPARATION FROM OPERATING REACTOR CENTER (METERS)

FIG. 5.3.1

100 meter separation distance, the neutron shield would only be some 10 to 20 cm thicker than the SP-100 shield if the Rankine system is used. The thermionic system requires thicker shielding at the reactor in order to protect the power conditioner. As a result, payload fluence, will be reduced substantially.

Payload Maintenance can be achieved during reactor shut down with the same shadow shielding, if the system has a long stretched geometry as shown on Fig. 2.1 of Volume I. For Li cooled systems, the reactor coolant activity will decay within several minutes after shutdown.

Figure 5.3.2 was derived from Origen II calculations performed by SPI to determine post operation shutdown decay of core radioactivity. If the system is shielded to the SP-100 payload fluence levels of 10^{13}nvt and $5X10^{5}$rad, then the shutdown maintenance dose at the payload can be estimated from this figure. Note that, if the system is started up in low orbit for system check out, operated at full power for 15 minutes (i.e. 10^{-2} days), and then shut down, an astronaut could approach the payload within the shadow shield cone angle after only 0.1 day (2.4 hrs.) following reactor shut down. His dose rate at the payload would be about 0.3 mr/min. At this dose, he could work on the payload for about 5 hours before receiving a typical Appollo mission dose rate of 100 mr/day.

Also note that if the reactor is operated for over 1000 days (-3 years) and is shut down and cooled for 30 days, than an astronaut could work on the payload for about 50 minutes (2mr/min) at the Apollo daily dose rate.

At Soviet maximum permissible emergency dose rates for cosmonauts, Table 5.3.1, maintenance periods of 8 hours per day for several months could be accommodated with less than 50R accumulated dose. More stringent U.S. military standards could be specified to limit the total emergency maintenance dose rate per astronaut. The accumulated dose rate would be about 1R per day at the SP-100 level of shadow shielding. A shadow shield for a manned mission with the sleeping quarters located 100 meters from the reactor (Fig. 2.2) might require about 40 to 50 cm of borated $ZrH_{1.85}$ and about 60cm of LiH. Such a shield would add less than 10% to the system

RADIATION DOSE vs OPERATION AND DECAY TIME

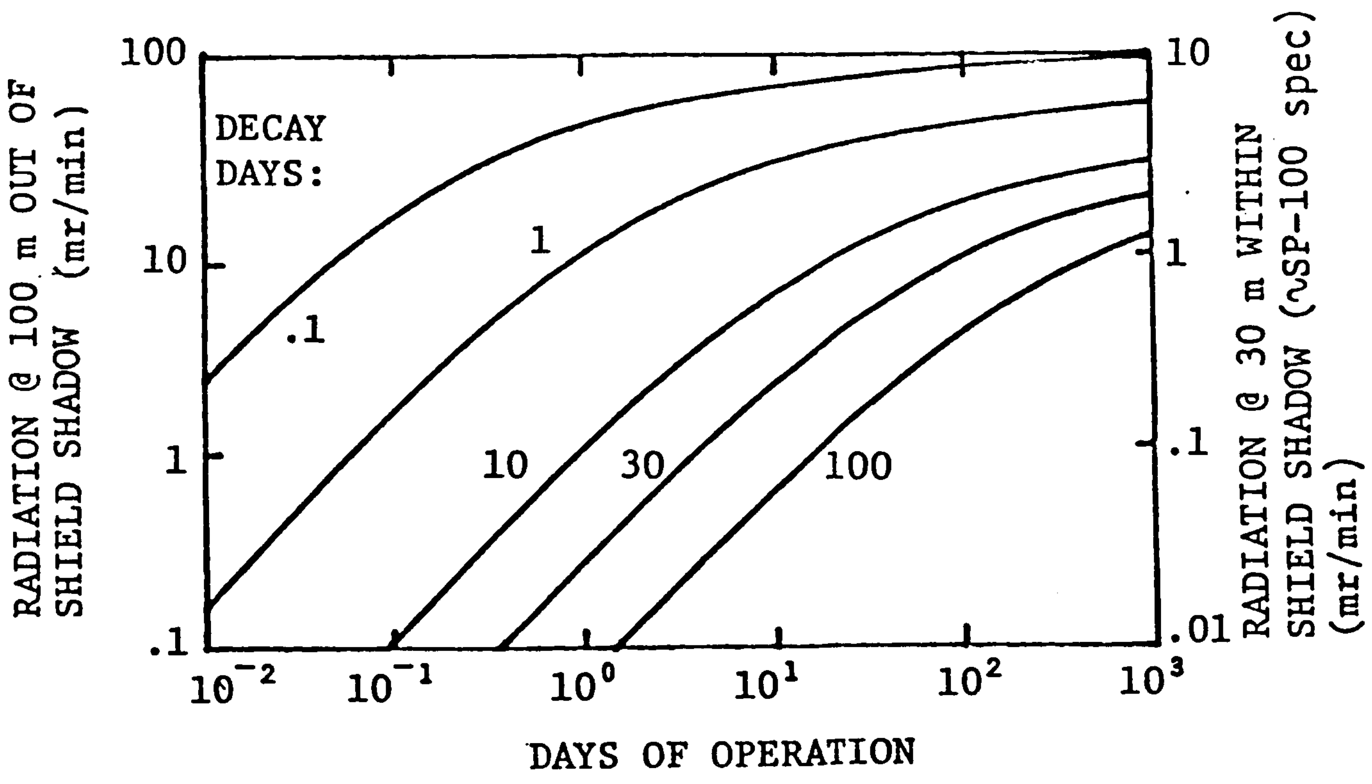


FIG. 5.3.2

PUBLISHED SOVIET MAX PERMISSIBLE DOSE LEVELS

T, MONTHS	MPD, REM
1	50
2	65
3	80
4	90
5	100
6	110
8	125
10	140
12	150

TABLE 5.3.1

masses reported herein. Special additional consideration must be given to the high energy bremmstrahlumg emitted by the decay of Li^8 in the primary coolant during operation.

Configurations were examined wherein the primary coolant, the power conversion and the hot radiator (1000K) were located on the end of the reactor opposite from the payload. The power conditioning, transmission lines, other special electrical gear, and the cold radiator (400K to 500K) were located between the reactor and the payload, as illustrated in Figure 5.3.3.

These configurations offer thermal control and electrical system advantages, but do introduce structural and shielding problems. Figure 5.3.4 provides the basis for the preliminary shielding effects analysis that was introduced into the SPI system design code used to study the Rankine and thermionic systems in more detail. The scatter shield shown was made up of LiH only. All primary coolant filled components were lined up on the center line behind the reactor and primary gamma shield.

The studies indicated that the scatter shield thickness required was nearly one half the primary LiH shield thickness. The studies also indicated that the "scattershield" diameter must be small enough and the thin "wings" of the primary shield large enough to intercept the back scatter from the scatter shield. In general, this arrangement did not lead to a minimum mass system, however it might be appropriate to certain applications or other system constraints.

5.4 SURVIVABILITY

Various natural and hostile threats will be encountered by any orbiting system that requires 10 MWe of power. Even a civil communications or surveillance unit of this nature will have significant strategic importance. At low altitude orbits, below 400 km, atomic oxygen reaction with hot refractory metals is a concern. Hot (1000K) niobium alloys exposed as radiators might quickly oxidize at atmospheric oxygen densities of 10^8 to

DEPLOYED 5MWe THERMIONIC POWER SUPPLY - SHUTTLE LAUNCHED

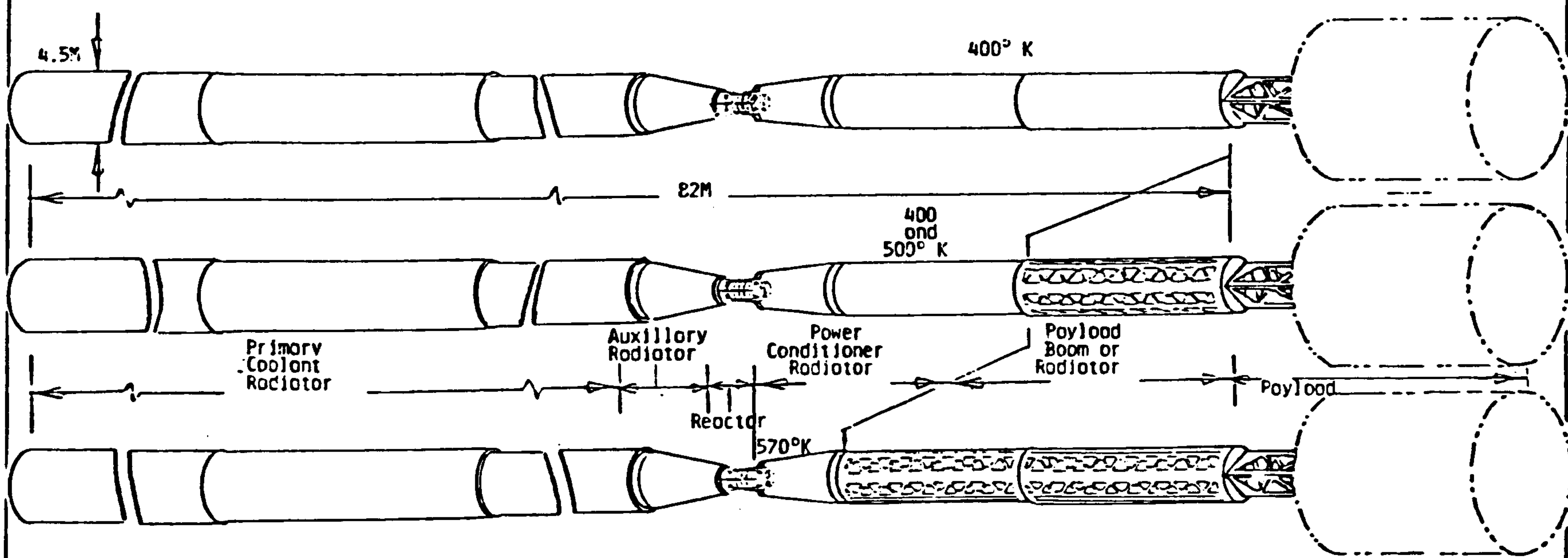
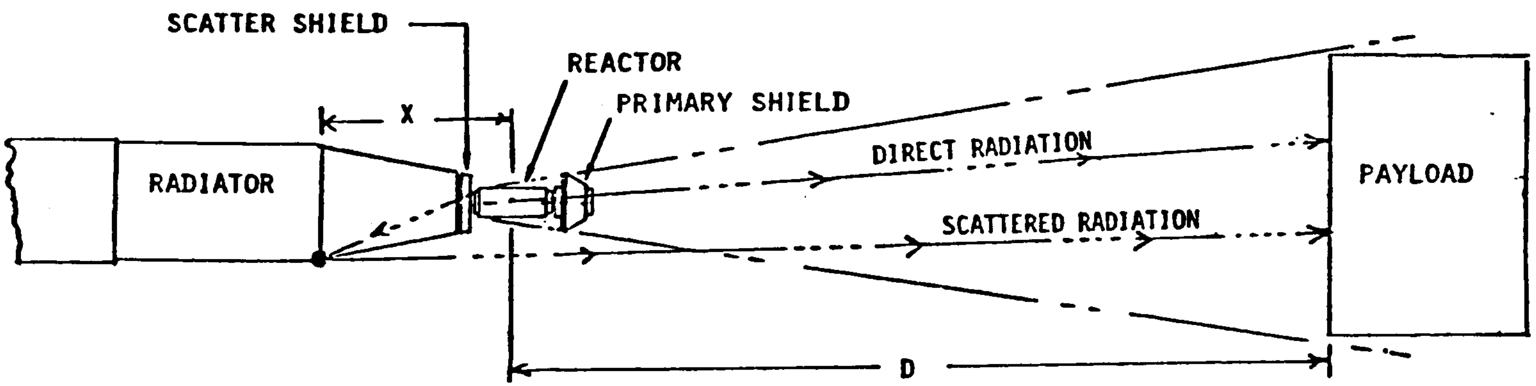


FIG. 5.3.3

SHIELDING ANALYSES



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- DIRECT RADIATION SHIELDING

$$\frac{P_R S_N T}{4\pi D^2} \text{EXP}\left(\frac{-T_N}{L_N} - 1\right) \leq 10^{13} \text{ NVT} \quad \text{(NEUTRONS)}$$

$$\frac{P_R S_\gamma T}{4\pi D^2} \text{EXP}\left(\frac{-T_\gamma}{L_\gamma}\right)\left(1 + \frac{T_\gamma}{L_\gamma}\right) \text{EXP}\left(\frac{-T_N}{34.2}\right) \leq 5\times10^5 \text{ RADS} \quad \text{(GAMMAS)}$$

- SCATTERED NEUTRON RADIATION

$$\int_{\text{all solid angles}} \frac{P_R S_N T}{4\pi (D+X)^2 4\pi D^2} \text{EXP}\left(\frac{-T_S}{L_N}\right)\left[1 - \text{EXP}^{(N_R \sigma_S T_R)}\right] \leq 10^{13} \text{ NVT} \quad \text{(SCATTERED NEUTRONS)}$$

$S_N = 10^{21}$ N/KW-YR	$L_N = 6.7$ CM (LIH)	P_R = REACTOR POWER (KWT)
$S_\gamma = 6.9\times10^{11}$ γ/KW-YR	$L_\gamma = 1.24$ CM (TUNGSTEN)	T = LIFETIME (5 YRS)

T_N = THICKNESS OF NEUTRON SHIELD
T_γ = THICKNESS OR GAMMA SHIELD
T_S = THICKNESS OF SCATTER SHIELD

FIG. 5.3.4

10^9 particles/cc. The migration of oxide through hot niobium might cause severe degradation.

The 10 MWe telescoping heat pipe radiators recommended by SPI would be made of armored heat pipes coated for high emissivity. Such systems may start up in 350 km orbits and power electric propulsion devices to accomplish orbital transfer to higher operating orbits [1]. Nuclear safety and operational requirements will tend to place operational orbits above 900 to 1000 km where atomic oxygen densities are less than 10^4 particles/cc. Transfer times would typically be only a few weeks. Multifoil insulation surrounding all primary and secondary piping will provide a shield against atomic oxygen reaction on critical hot external surfaces. With special care the atomic oxygen problem should be solvable.

Large spot, flood lasers from the ground can be a major threat to low altitude spacecraft. In section 4.3 it was shown that liquid droplet radiators could not sustain such an attack. A ground based laser that can track a target from -45° to +45° (from the vertical), can stay on target for over 200 seconds. It is also known that 10.5 μm CO_2 lasers and 3.8 μm DF lasers can effectively penetrate the atmosphere. The CO_2 laser effectiveness will peak on the high emissivity payload radiators operating near 273 K while DF lasers will be particularly effective against high emissivity power system radiators operating at 750 K. Normally the atmosphere is quite opaque to infrared wave lengths from 2.5 to 3.1 microns, (i.e. 1100 K to 900 K). The high temperature cycles utilizing refractory metal heat pipes operating at about 1000 K could utilize a surface coating that has a high emissivity near 1000 K and a lower emissivity at 750 K, (3.8 microns). This again reinforces the recommendation for pursuing the K-Rankine and the incore thermionic power systems utilizing 900 K to 1100 K radiators.

The natural gravity stabilization altitude recommended for spacecraft configurations using the telescoping heat pipe radiator minimizes the incident angle from ground based laser (GBL) attack. Spacecraft spin up, or the alternately spaced cylindrical heat pipe arrangement shown on figure 4.3.40 of Volume II, will further reduce the effectiveness of the GBL attack by about $1/\pi$. The reactor and primary loop will serve as a heat sink to flood laser attack, until excessive temperatures are achieved. The use of lithium primary coolant will permit a design in which the potassium or sodium heat pipes in the radiator will fail before the reactor vessel fails. This is another important consideration for selecting lithium as the primary coolant.

The low mass number micrometeorite berrylium armor on the radiator and a low mass number radiator emissivity coating, such as carbon-carbon, boron nitride, boron carbide, BeO, or possibly ZrB_2, will minimize the system generated EMP from nuclear weapon gamma release of surface electrons.

Very high intensity lasers emanating from space based attacking ASATS will by necessity usually have small spots. Depending upon the attack range, the spot might vary up to 2 meters or so in diameter. The long, large diameter molybdenum heat pipes specified herein can be designed to withstand anticipated spot heat fluxes over these diameters and for typical engagement durations. Upper limits are a function of design vehicle spin up, tube spacing, wick structure, tube diameter, length, material and assumed attack scenario.

Kinetic energy weapon or counter orbiting shrapnel attacks might best be met by means of a shield designed in a manner similar to a micrometeorite bumper-armor. The use of Be (λ>8000 cal/gm) and LiH (λ>4600 cal/gm) properly spaced could be designed to absorb counter orbiting shrapnel (~16 km/sec net velocity), for example as shown in figure 5.4.1 and 5.4.2.

Figure 5.4.3 shows that the accelerations (g's) and thrusts (lbs) to accomplish evasive maneuvers for a 30,000 kg cylindrical spacecraft in 5 to 10 seconds can vary from about 0.1g to 1g. Thus KEW threats might be avoided by maneuvering and/or shielding. The recommended telescoping radiator configuration could be designed to sustain such maneuvers when deployed. Figure 5.4.4 provides an estimate of the fuel mass expended for representative evasive maneuvers. Note that a 20 rpm spin requires very little fuel and only a small fraction of a g acceleration to the structure. To translate the spacecraft 100 meters within 10 seconds and restabilize can

SYSTEM SHIELDING FOR KINETIC ENERGY THREATS

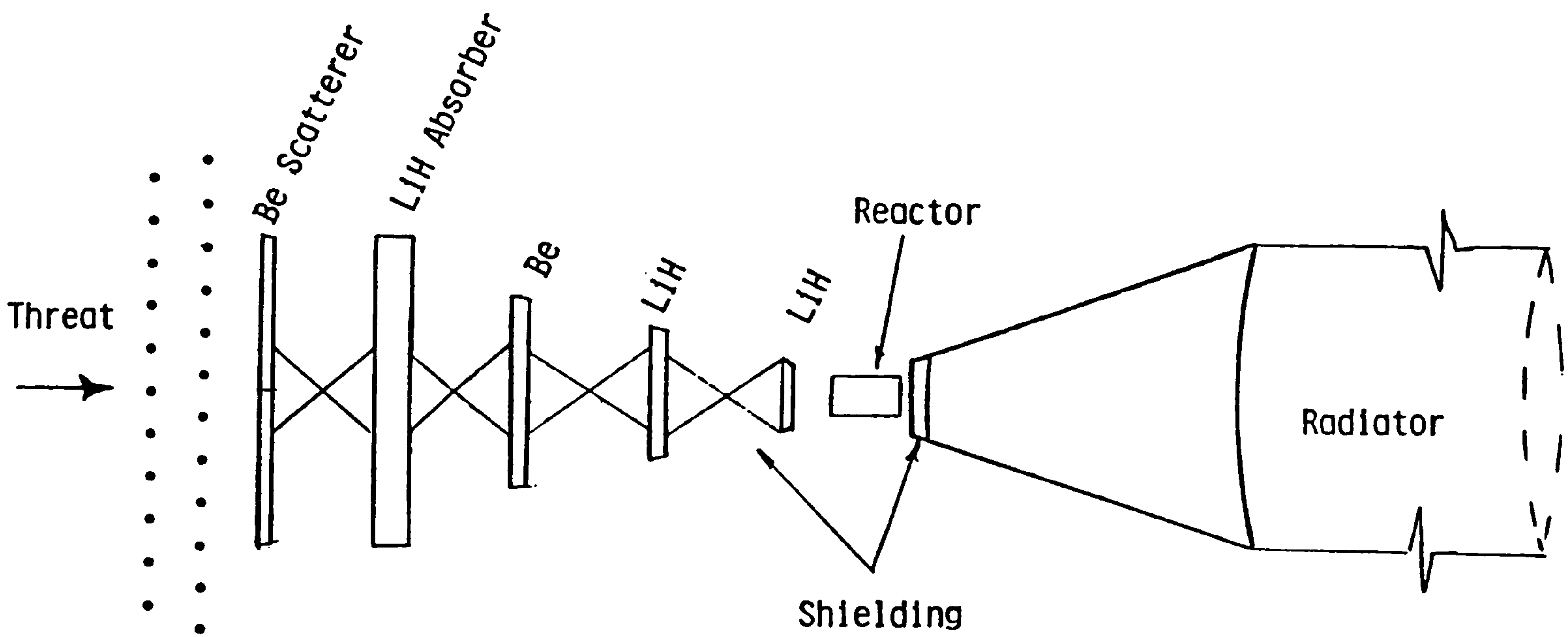

FIG. 5.4.1

TELESCOPING RADIATOR ENHANCES SYSTEM SURVIVABILITY

PROVIDES FOR MANEUVERABILITY AND SHIELDING

FOR KINETIC ENERGY WEAPON THREATS.

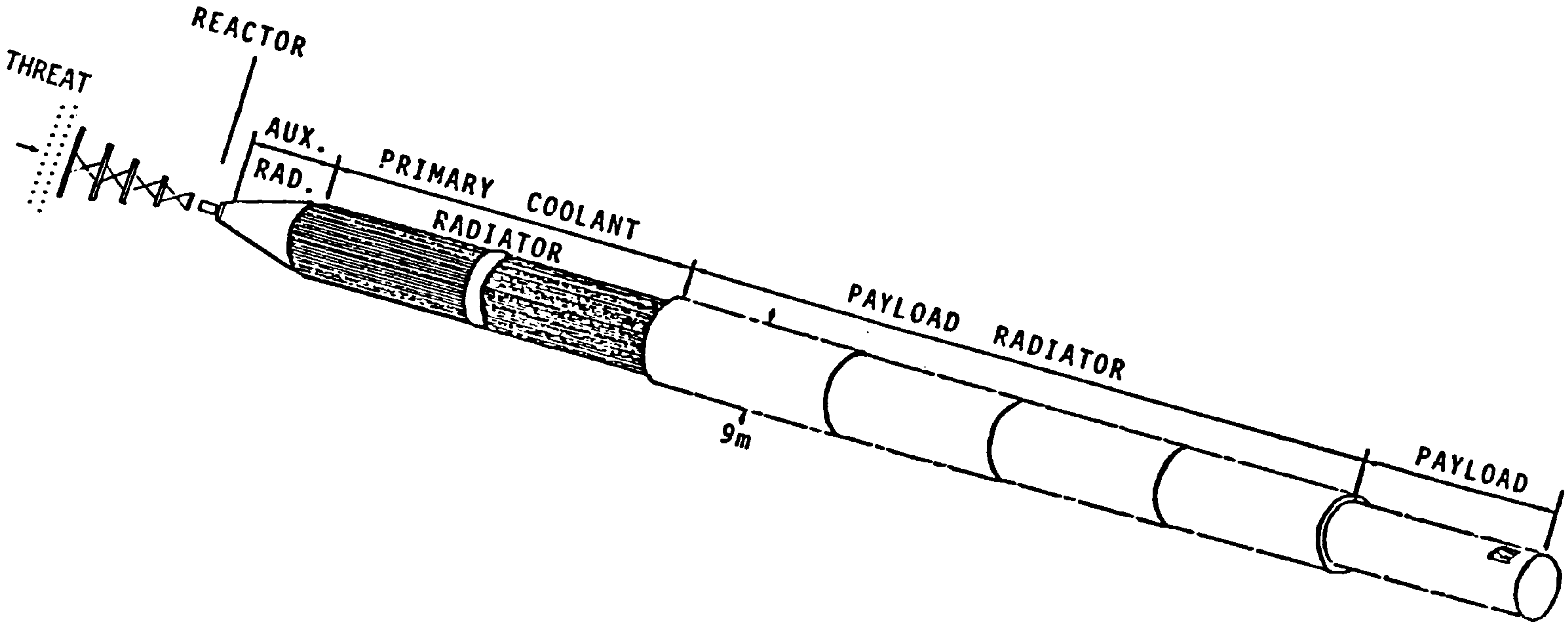

Fig. 5.4.2

THRUST REQUIRED TO PERFORM EVASIVE MANEUVERS

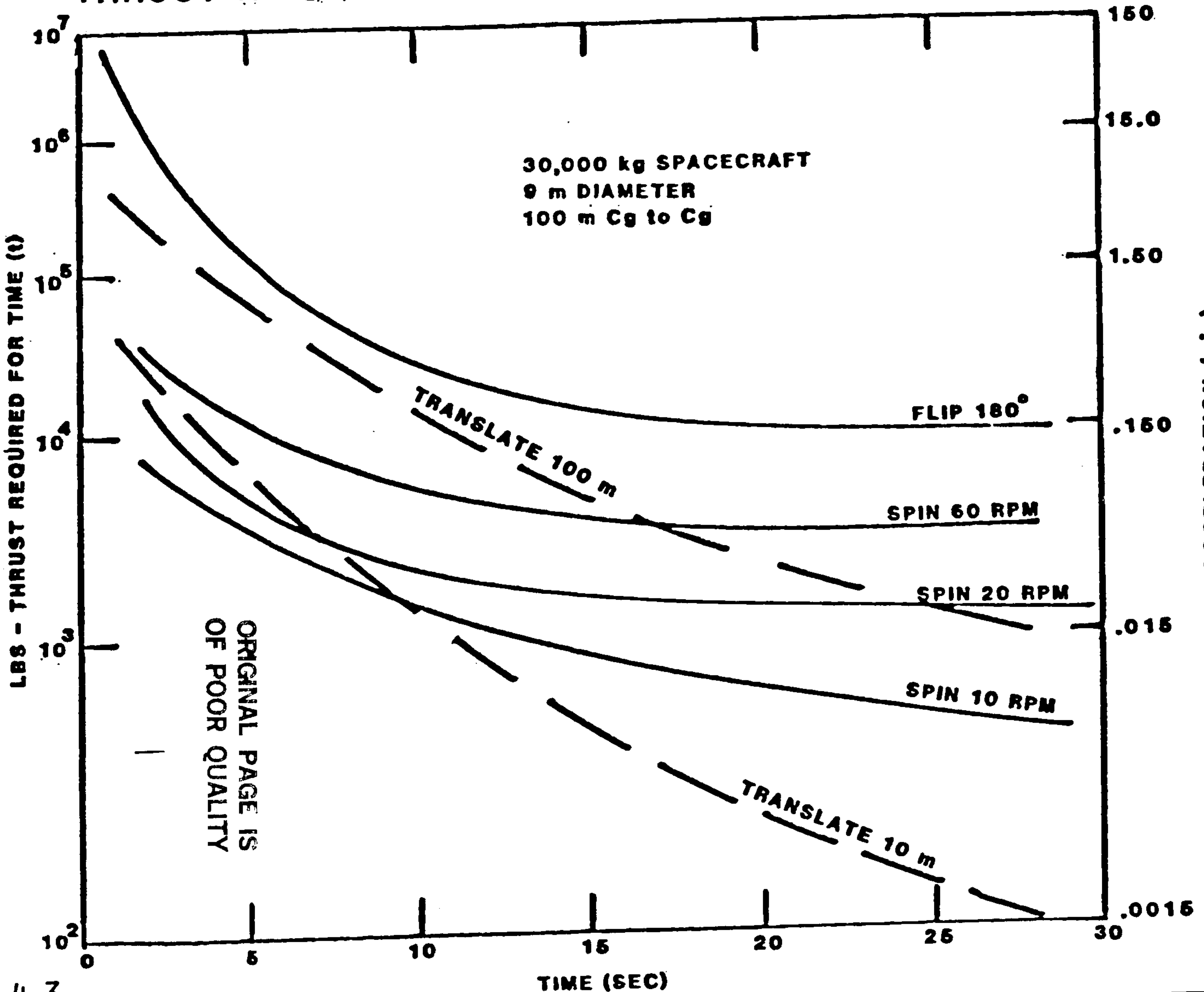

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FIG. 5.4.3

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TYPICAL EVASIVE MANUEVER REQUIREMENTS

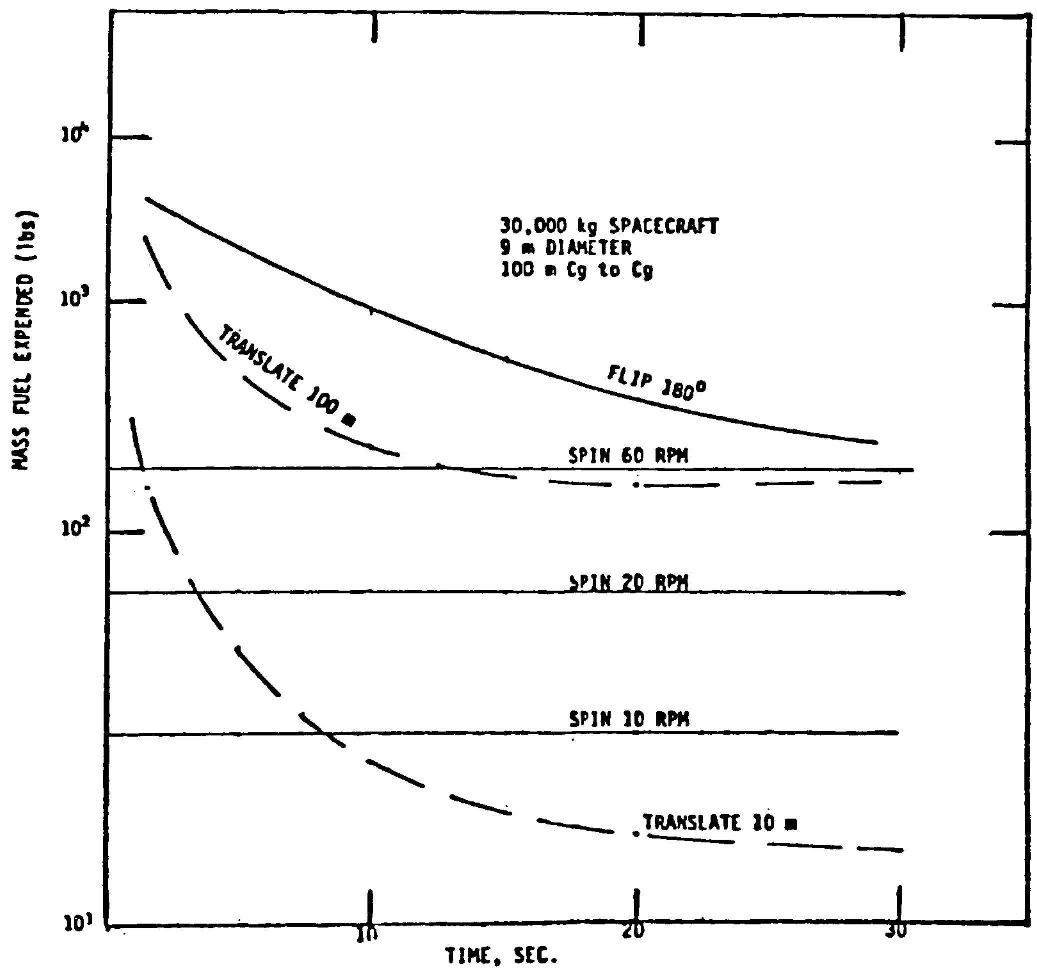

FIG. 5.4.4

require about 0.15g and some 200 lbs of fuel. A 180^0 end over end flip and recover in 10 seconds could require about 1/2 g and about 1000 lbs of fuel.

5.5 ORBITAL ASSEMBLY/START UP/SHUTDOWN/DORMANCY/RESTART/RELIABILITY

5.5.1 Orbital Assembly Considerations

From Table 5.2.2, the gas cooled reactor with a metallic Brayton cycle turbine and the lithium cooled reactor coupled with the tantalum-alloy composite Stirling cycle both required multiple shuttle launches for the power module. All Brayton and Stirling cycle systems required two or more shuttles for the radiator. The potassium Rankine and thermionic concepts each require one shuttle for the power module and one for the radiator. Hence, all concepts will require some assembly in orbit, the Brayton and Stirling more so than the Rankine and thermionic.

Considerations specific to certain of the concepts include: The gas cooled reactor, Brayton turbine power system with a metallic turbine requires that the high pressure gas loop be welded and inspected in orbit. The working fluid gas must be carried in separate high pressure cylinders and subsequently charged into the system. Additional welding and inspection will be necessary because the use of the preferred triform heat pipe radiator requires a series of parallel NaK heat distribution lines to be connected from the gas - NaK heat exchangers to the heat pipe radiator panels. This requirement is unique with the gas radiator distribution piping because of the need for thick micrometeorite protection since one leak from a gas line could lead to system failure. (While lithium would be over 20 times as efficient in pumping power and of lower mass, it would represent a nearly impossible frozen startup problem after every extended shut down.) The higher temperature ceramic turbine Brayton system offers the potential of being shipped to orbit with the gas lines welded, loaded and intact. For both Brayton cycle systems the multiple shuttle loads of liquid metal radiator elements will require assembly, welding and checkout of the radiator piping and structure in orbit.

The LMCR-FPSE system also represents a major construction project in orbit. The lithium primary coolant loop will consist of at least 3 shuttle loads when using ceramic fibre reinforced refractory metal alloys for the Stirling engine cylinders. If the all-ceramic cylinder can be developed, then this reactor-lithium-engine module might be ground assembled and launched intact. However, the heat rejection system for this approach is nearly comparable to the Brayton cycle, due to the relatively low temperature of operation. Thus, the orbital assembly requirements for the Stirling system will be approximately comparable to those for the Brayton cycle or worse.

The potassium Rankine system using tantalum alloy boilers and turbines is marginal as to whether or not it can be engineered to fit the power module system mass into one shuttle. The mass limiting component is the turbo-alternator. The telescoping radiator is easily lifted by a single shuttle to LEO for rendezvous and assembly. Hence, no welding or fluid charging would be required, since the connection between the power module and the radiator is effected by slip fit and self welding during initial system heat up.

The incore thermionic system easily fits into two separate shuttles with weld free orbital assembly. The power conditioner would probably be launched with the payload and does not require any welding.

5.5.2 Startup, Shutdown, Dormancy and Restart

The factors important to the initial startup of the system, as well as those associated with subsequent shutdowns, periods of dormancy, and restart have been examined. These factors are summarized briefly as follows:

1. Of the systems considered, the gas cooled reactor, Brayton PCS is the most easily started up. However, cooling of the reactor core during shut down dormancy after extended operation would require continuous operation of the main compressor. A separate compressor would be required to remove gas from the main system to a high pressure storage tank. Thus, the main compressor could be driven efficiently by the main turbine. Major power variations for extended time periods would also require the use of the

auxiliary compressor and storage system. The reactor could never actually be shut down and allowed to become dormant. Restart requires admitting the stored high pressure gas back into the system.

2. The LUNR-FPSE, LUNR-KRS, and the incore thermionic systems all use lithium cooled reactors. The lithium would be frozen during launch and deployment and quickly thawed with reactor startup heat. However, the extensive lithium piping network required for the LUNR-FPSE system would make "hot artery" heat pipe tracing throughout the loop very difficult, if not impossible. Reactor post operation shut down heat would be removed to the power conversion components by the "hot artery" heat pipes installed in the primary coolant loops. The FPSE systems would require some engines to operate during shut down in order to transfer the heat to the radiator NaK loops. Restart after primary loop freezing in the cylinder heads is questionable.

The potassium Rankine system (KRS) boiler is somewhat complex and is equipped with a shutdown K-vapor turbine bypass line to the direct condenser and with an EM pump to return the liquid to the boiler. While shutdown cooling is assured, startup-shut down and restart of this system is complex, as described in the Rankine cycle design Section 6.1.

The incore thermionic lithium loop is also thawed at startup with reactor heat. Shutdown heat is removed by "hot arteries" directly to the heat pipe radiator. Restart reliability is assured by repeat of the original start up sequence after long dormancy periods. The system can be shut down completely.

5.5.3 Reliability

The GCR-Brayton system receives a high reliability rating, if the 1800 K ceramic turbines and 2000 K fuel cladding can survive, and if the auxiliary compressors are reliable. Shut down cooling and the large radiators are a major concern. The major loss of capacity which occurs when one component fails is another concern, although gas system components promise good reliability at lower temperatures. The oxygen-mass transport in inert gas systems spanning a large temperature range is another concern.

The incore thermionic reactor system theoretically could be very reliable due to the extensive paralleling of thermionic fuel element (TFE) circuits, power conditioner elements and radiator heat pipes. A major concern is the absolute reliability of the TFE elements and the large number of primary core vessel penetrations for electrical lead outs. The penetrations are of concern since failure of seals could result in a coolant leak.

Major concerns of the LUNR-FPSE and LUNR-KRS are the very high temperature lithium pumps, the hot reflector control drums and bearings, and the power converters. Corrosion and mass transport in the coolant loops, bearing passage cold trapping and plugging, and high temperature, high stress creep of the turbines and cylinders are major concerns. Shutdown and startup of these systems must be assured under all conditions.

REFERENCES TO SECTION 5

(1) J.R. Wetch, C.J. Nelin, E.J. Britt and G. Klein, "Reactor Power Systems Deployment and Startup", First Symposium on Space Nuclear Power Systems, Albuquerque, N.M., Jan 11-13, 1984.

6.0 CONCEPTUAL DESIGNS

6.1 RANKINE TURBO ELECTRIC SYSTEMS

6.1.1 Introduction

The cycle schematic of the basic saturated Rankine cycle is shown in Fig. 6.1.1. Vapor generated in the boiler is separated from residual liquid, expanded through a turbine, condensed in a radiator, and recirculated to the boiler. The ORNL MPRE approach, Fig 6.1.2 integrates the boiler, the reactor heat source, and the vapor separator into a single component, with the separated saturated liquid recirculated to the reactor inlet by jet pumps, similar to the boiling water reactor. The majority of the vapor is expanded through the turbine, condensed in the radiator, and recirculated back to the reactor/boiler. A fraction of the vapor is expanded through a turbine driven recirculation pump, which pressurizes the liquid prior to heat addition and recombination with the saturated liquid from the boiler. Depending on the moisture content capability of the turbine, liquid extraction points on the turbine can be provided.

The evaluation of the Rankine system for this study was performed on a cycle configuration conceptualized by SPI to comply with the performance, size, and weight requirements. Previous studies by ORNL have been based on a uranium nitride fueled, boiling potassium cooled reactor (BKR) for the heat source, a technology under development in the 1960's as the Medium Power Reactor Experiment and presently receiving further attention. The technological problems of developing this concept have been discussed previously, briefly in this report as well as by ORNL (2). To reiterate, the major concerns specific to the differences between the direct boiling reactor Rankine cycle approach and indirect approaches, are: the understanding and control of zero g boiling in the core; neutronic control; the use of uranium nitride as a fuel; the need for a thick wall pressure vessel which dictates that the reflector control elements must be contained within the vessel or hot wells and operate hot.

CONVENTIONAL RANKINE LOOP

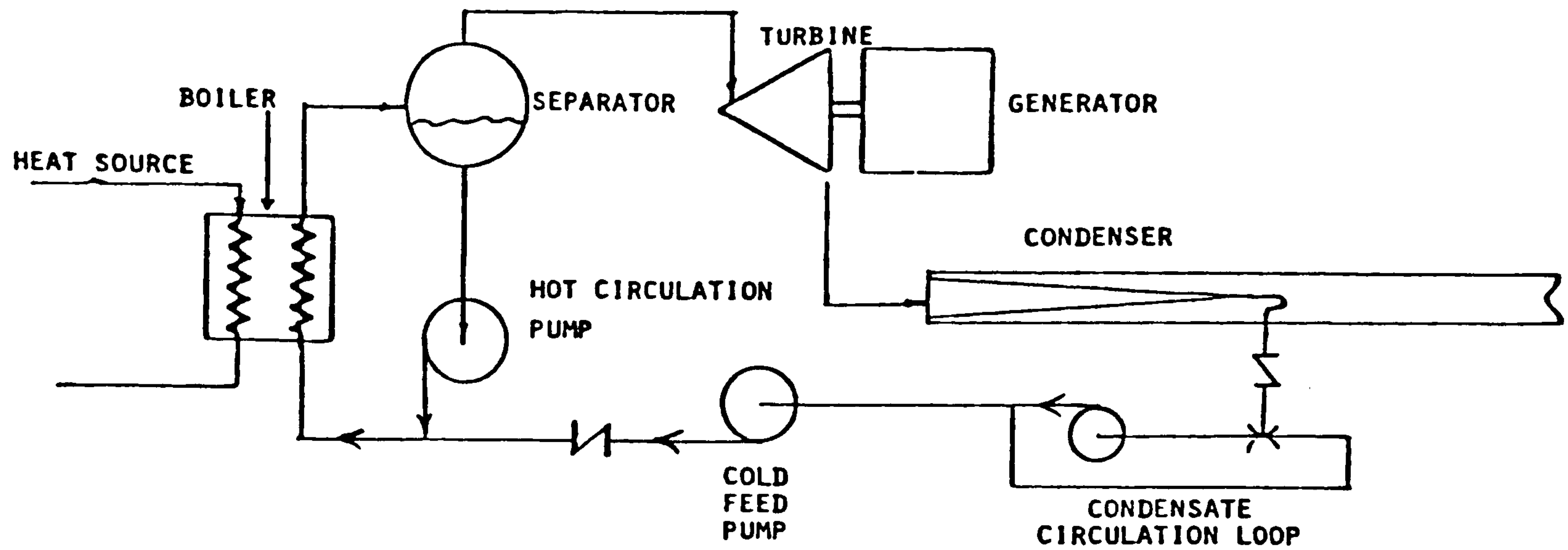

FIG. 6.1.1

SINGLE-LOOP MPRE SYSTEM WITH JET PUMPS TO RECIRCULATE LIQUID
THROUGH THE BOILER AND THE DIRECT-CONDENSING RADIATOR

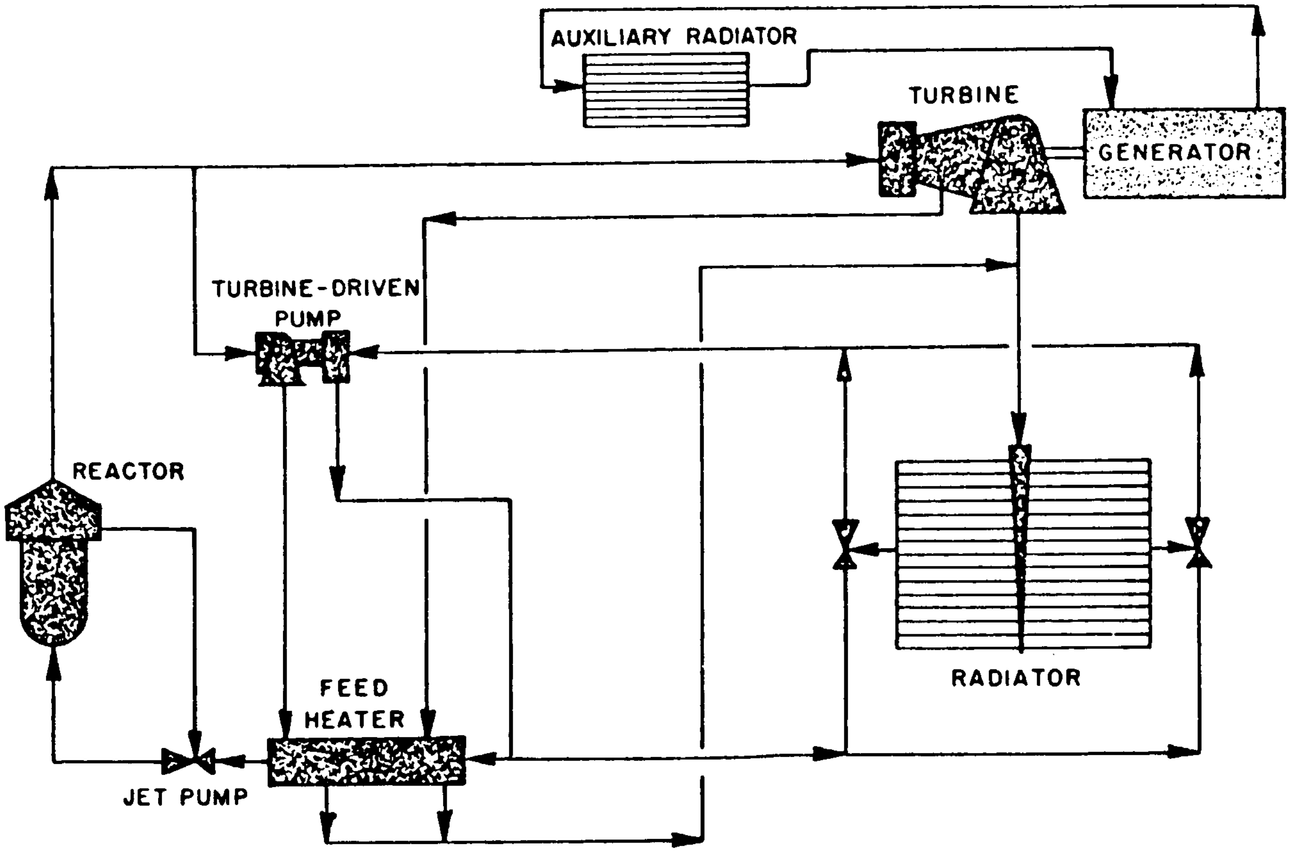

FIG. 6.1.2

The indirect concept attempts to bypass at least some of these problem areas by removing the boiling process from the reactor to an external liquid metal boiler, so that the reactor coolant loop is single phase and low pressure. The reactor coolant can now be any low vapor pressure liquid metal which is compatible with the fuel and with the neutronic and structural requirements at the desired operating temperature. Because the primary loop is low pressure, the core vessel can be thin walled, and the reflector control drums can be located external to the vessel, outside the coolant environment, and need not operate in a hot liquid metal environment.

This study has considered both uranium dioxide fuel together with lithium or potassium coolant and uranium nitride with lithium. The choice between these two options, while important to the reactor design and technology development requirements, are observed to have only a second order effect on the system size, mass or performance, the key indices of interest in this study. Consequently, for the comparisons, a reactor concept consisting of uranium nitride fuel and lithium cooling has been selected as representative.

Another consideration, relative to the choice of a two loop system versus direct boiling in the reactor core, is the possibility of enhancing the system reliability through multiple power conversion subsystems. In these studies the 10 MWe system is assumed to consist of four independent secondary loop subsystems. That is, a failure or loss of working fluid of any one system does not result in complete electrical power loss. Prudent design will allow the loss of one secondary loop to be compensated by a 1/3 increase in output from the other three loops, unless a 25% power loss is an acceptable design criterion. The 5 MWe system is assumed to consist of two (instead of four) of the same loops so that only one subsystem design is required to evaluate both power levels. The possibility of providing a comparable redundancy within the Boiling Potassium Reactor concept may be possible, but the control and high temperature valving problems appear severe.

Algorithms for component masses have been formulated to reflect a conservative (ie heavy) estimate for the system mass, an assumption which will undoubtably prove true for the near-term concepts. The radiator has also been conservatively configured to provide micrometeorite protection for up to ten years. Comparable assumptions have been used for the components of the thermionic system, so that the comparative evaluation is performed on a consistent basis within this Section, and neither concept is unfairly penalized by these assumptions.

6.1.2 Postulated Rankine Cycle Description

Fig. 6.1.3 shows the essential features of the power conversion (one of four for the 10 MWe system, one of two for the 5 MWe system) loop Rankine cycle evaluated for this study. In this approach, saturated liquid from the separator is cooled in an economizer prior to recombining with the condensate from the radiator. The cold coolant is pressurized and reheated in the economizer as shown, eliminating the need for the high temperature recirculation pump of the basic cycle.

Comparing this cycle with the MPRE cycle of Fig. 6.1.2, the major difference is seen to be that the pressurized feed of the MPRE cycle is pre-heated by the combination of the fraction of vapor used to drive the turbo-pump and the moisture extracted from the turbine, while in the SPI loop this heating is accomplished by the saturated liquid from the separator. Also, in effect, the jet pump of the BKR system is replaced by an EM pump in the reactor primary loop. Not shown in the SPI cycle, are possible options for superheating, moisture extraction from the turbine, reheat, and a turbine driven feed pump, some of which are also possible with the BKR. All of these options could be examined, but their consequence to the overall system size, mass, or performance, within the comparison accuracy intentions and limitations of this study, is not expected to change any conclusions made by their absence.

SPI PROPOSED RANKINE CYCLE

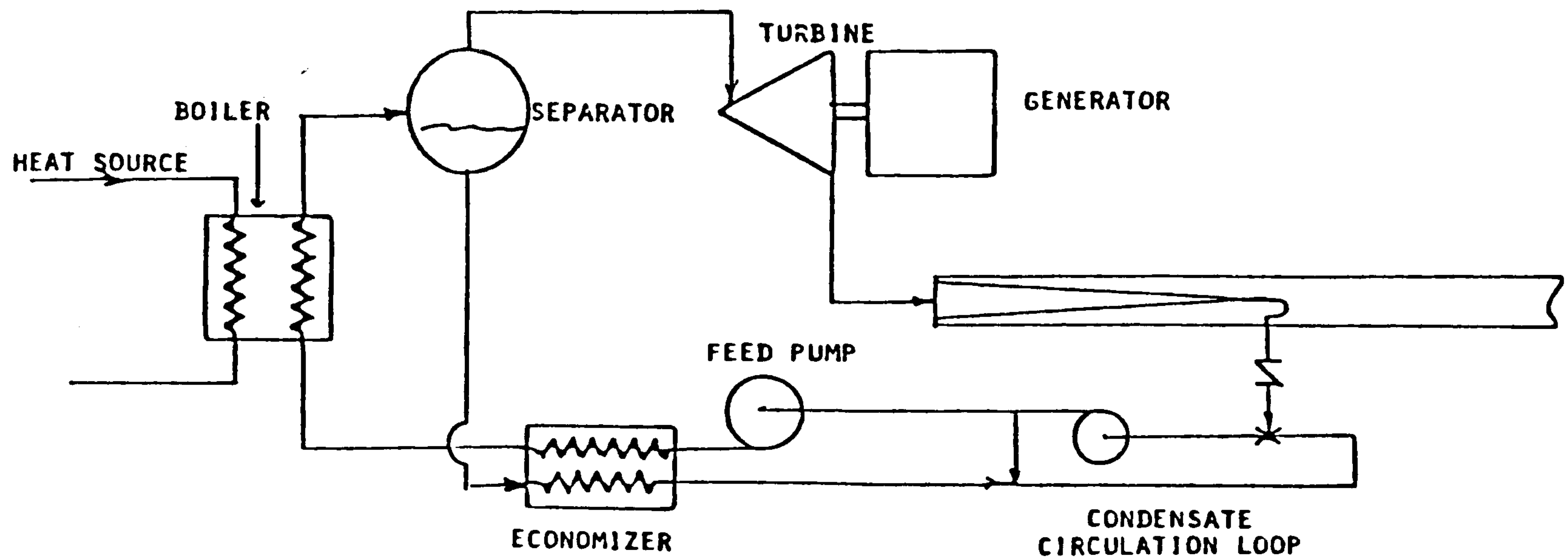

FIG. 6.1.3

6.1.3 Major System Components

Turbo-Alternator

In-depth potassium vapor turbo-alternator design studies of the 1960's were done at power levels of 300 kWe, 400 kWe and 1 MWe. Fig. 6.1.4 shows a 300 kWe 5-stage turbine designed by ORNL during this period. These studies served as the basis for extrapolation to the 1.5 MWe and 3 MWe turbo-alternators used in this study.

The most important factor limiting the peak temperature of a thermodynamic cycle is the creep strength of the structural material. For the Rankine cycle, the peak cycle temperature is often limited by stresses in the turbine rotor. Since these stresses are induced by centrifugal forces, which are proportional to material density, the controlling parameter is allowable creep stress divided by density. This parameter is presented in Fig. 6.1.5 as a function of temperature for several candidate materials. The minimum value for reasonable turbine design is also indicated. The creep rate of ASTAR 811-C is considered suitable for turbine inlet temperatures up to 1450 K. Erosion tests at 12% and 14% moisture showed no signs of degrading erosion.

Fig. 6.1.6 was used in this study to extrapolate potassium turbo-alternator size and specific mass. The bases for Fig. 6.1.6 were designs by General Electric, Pratt and Whitney, AiResearch, ORNL and Westinghouse in the 300 kW to 500 kW range. The specific weights of the turbines, alternators and generators were found to vary with power by the inverse 1/4 power law.

Boiler/Separator

The boiler/separator and the condenser become key components in assessing the feasibility of the proposed Rankine cycle. The boiler/separator must stably vaporize a large percentage of the liquid metal throughput to avoid large recirculation pump and friction losses. The condenser has to accommodate varying quantities of mixtures of vapor and saturated liquid in a zero-g environment.

FIVE STAGE POTASSIUM TURBINE DESIGNED BY ORNL FOR 300 KW (U)

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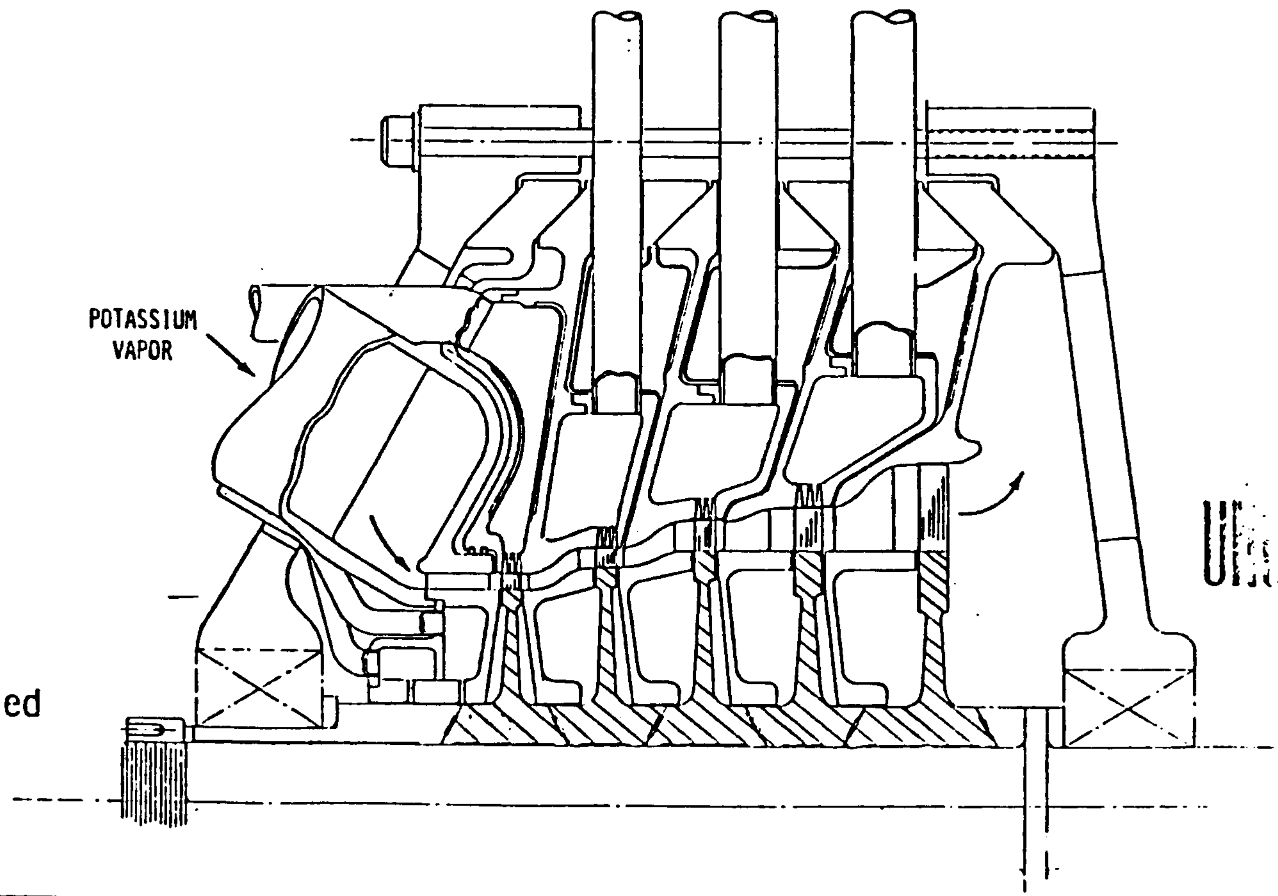

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FIG. 6.1.4

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WEIGHT SPECIFIC CREEP STRENGTH

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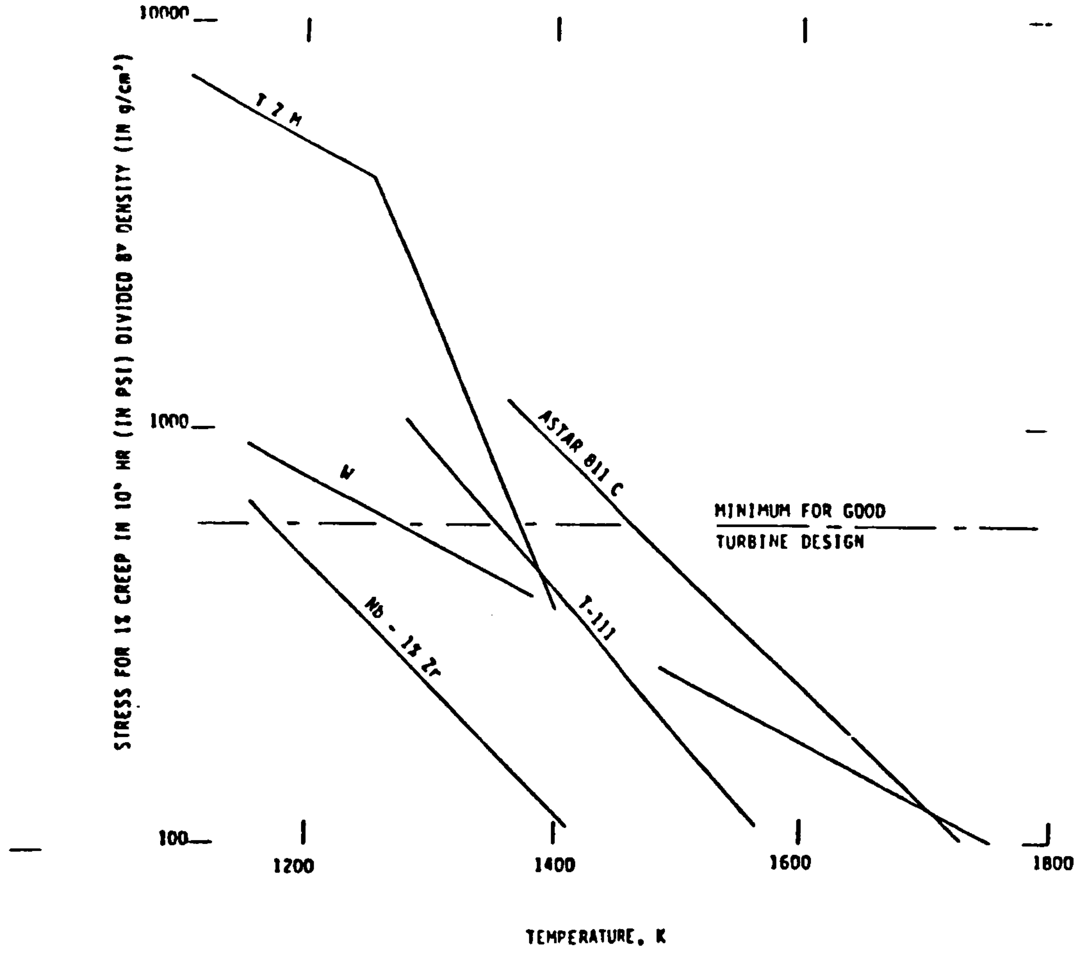

Effects of temperature on the ratio of the creep strength to the density of refractory alloys that might be used for turbine wheels.

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EXTRAPOLATION OF POTASSIUM TURBINE ALTERNATOR SIZE AND SPECIFIC MASS W/POWER OUTPUT*

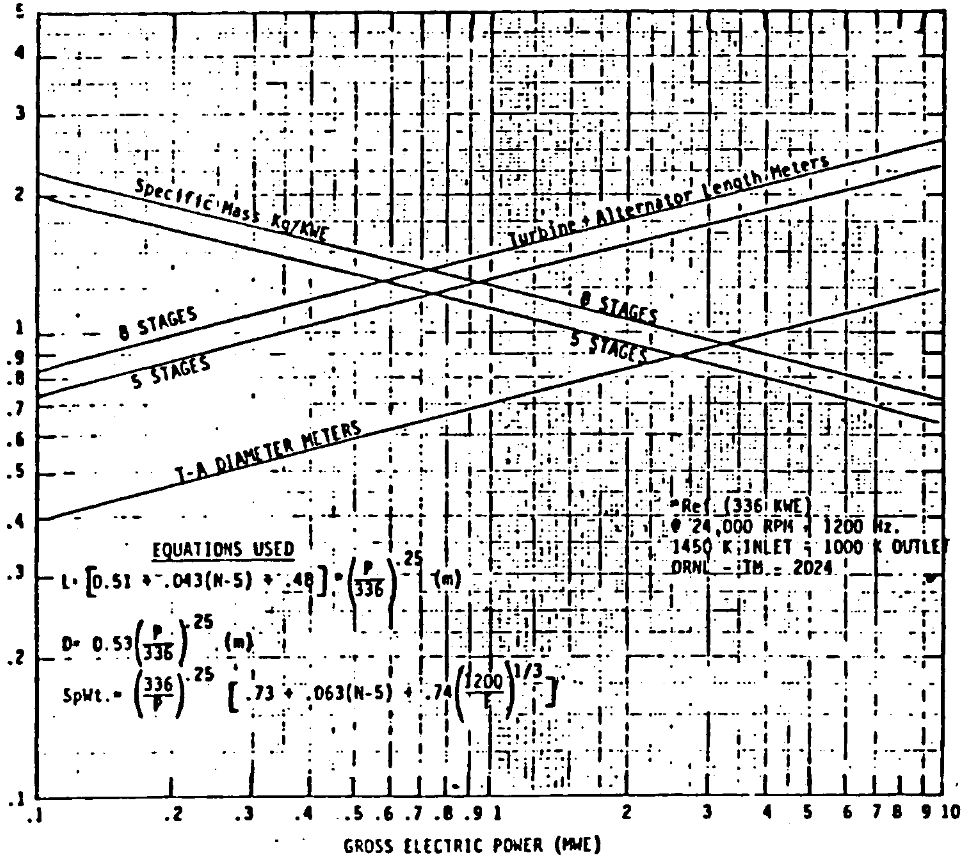

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FIG. 6.1.6

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In the SNAP 2 program in 1959, the most effective once through boiler-superheater, for mercury, was found to be achieved with a twisted ribbon in a straight tube. This type of pressure tube boiler provides high power density at very low circulation ratios for a liquid like K that reliably wets the tube walls. The boiler is independent of gravity because the twisted ribbon imparts 10's of g's of tangential acceleration to liquid droplets as they pass toward the outlet. When the individual tube inlets are properly orificed, vapor can be nearly dried by boiling alone, with stable operation across the boiler.

Preliminary optimization of this type of boiler for the MCNSPS requirements provides a design with 2 cm diameter tubes less than 1 meter long. The shell diameter is 43 cm. The ASTAR 811-C boiler tubes of this design are stressed to less than 1% creep in 5 years at the lithium inlet temperature. The nominal boiler/separator mass is 328 kg per unit, or a total of 1312 kg for four units. The lithium inlet temperature is 1550 K. All systems are designed to a minimum of 20 K ΔHt at the feed heater-boiler pinch point.

Condenser

The condensers of the ORNL MPRE design were too heavy to make a 30,000 kg system mass limit. The more recently proposed ORNL 5 MWe (2) direct condensing radiator (as understood) could lead to a single point failure if penetrated by debris/micrometeoroids. That design does not have sufficient armor to guarantee against this likelihood.

An SPI innovated condenser design has been used in this study for purposes of the PCS analyses. This condenser is used in conjunction with the telescope radiator concept described in Section 4.3, Volume II. A separate zero-gravity conical condenser is incorporated within each large heat pipe of the first telescope radiator section. These individual heat pipes will transport 500 to 1000 kWt. Heat flows radially outward, through the conical condenser walls, and evaporates potassium from the telescope heat pipe wick on the outer surface of the conical wall.

Primary vapor is condensed and carried out of the conical condenser by two means. As vapor condenses, it leaves behind an incremental lesser amount of vapor yet to be condensed. The conical shape of the condenser yields a decreasing vapor cross-sectional flow area as vapor flows into the condenser. These two facts produce a fairly constant vapor flow velocity through the condenser. The flow of this vapor along the conical condenser walls imparts a shear force on the condensed potassium deposited on these walls and pulls it in the direction of vapor flow. Also, the capillary forces of the condensed potassium tend to "pump" the fluid to the small diameter end of the condenser. These two forces, acting on the potassium, will provide a stable and reliable supply of condensate to the boiler feed pump.

Computer Analyses

Good system design is the result of a number of design optimizations. A computerized parametric analysis of the potassium Rankine system was made using an internally-produced systems code. Table 6.1.1 shows the flowchart of the potassium Rankine algorithm which has been incorporated into a computerized system code. Table 6.1.2 lists the input parameters which can be varied and a typical Rankine system code output is shown in Table 6.1.3.

This systems code was used to optimize the system mass of a 10MWe and a 5MWe Rankine nuclear space power system. The optimized system code output for each of these power levels appears in Tables 6.1.4 and 6.1.5.

FLOWCHART OF POTASSIUM RANKINE SYSTEM ALGORITHM

POTASSIUM RANKINE SYSTEM SOLUTION ALGORITHM

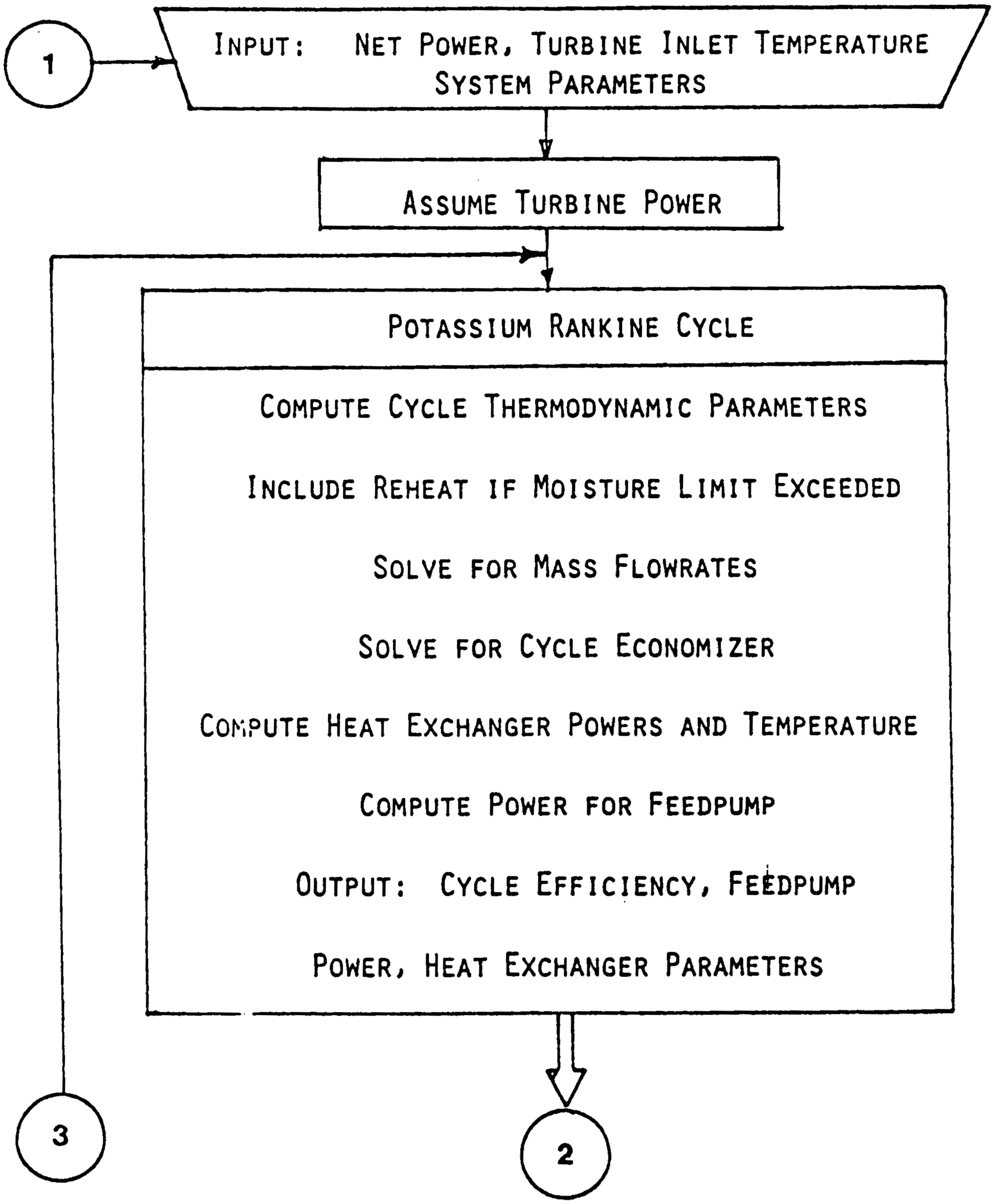

Table 6.1.1

FLOWCHART OF POTASSIUM RANKINE SYSTEM ALGORITHM

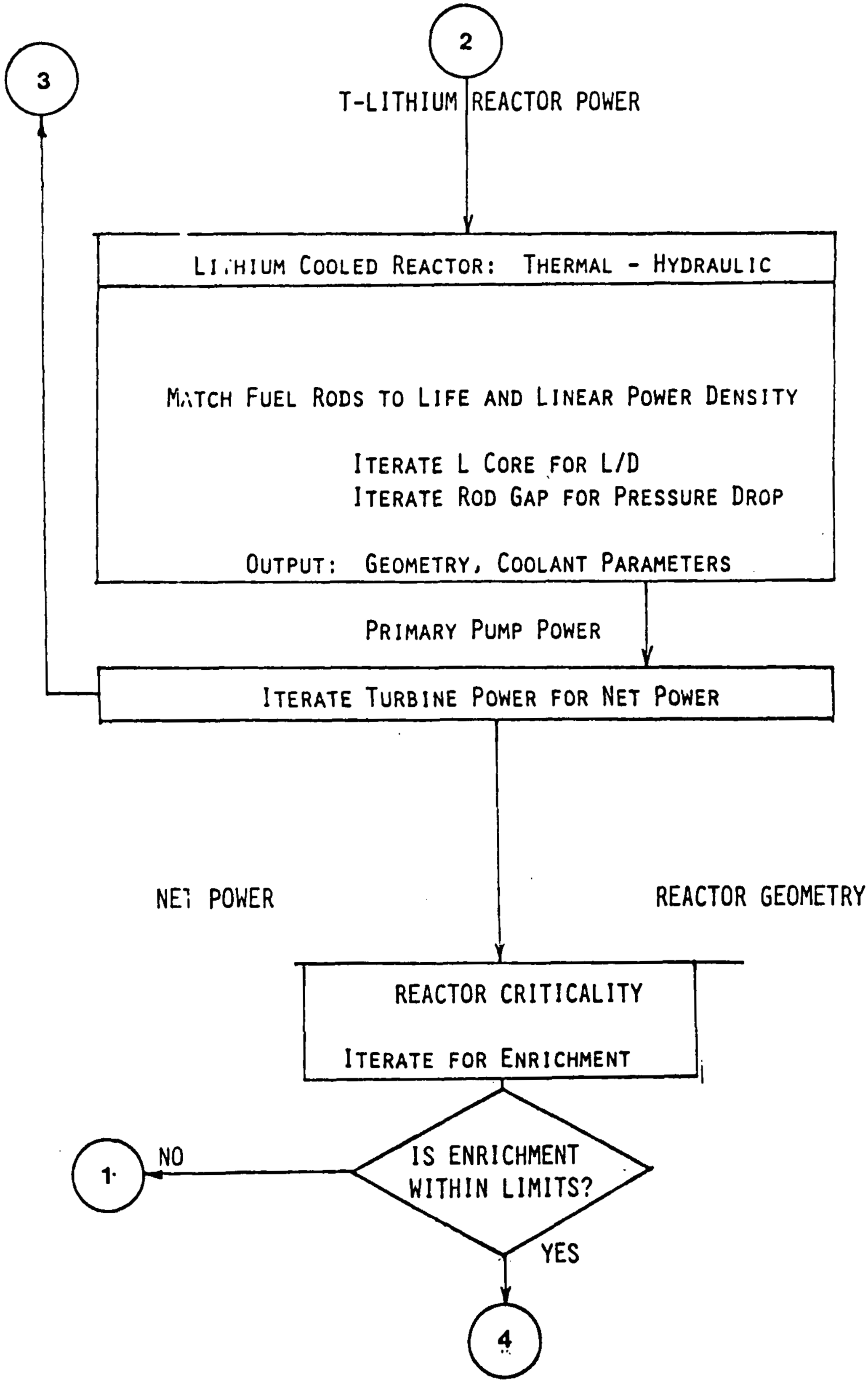

Table 6.1.1 (cont'd)

FLOWCHART OF POTASSIUM RANKINE SYSTEM ALGORITHM

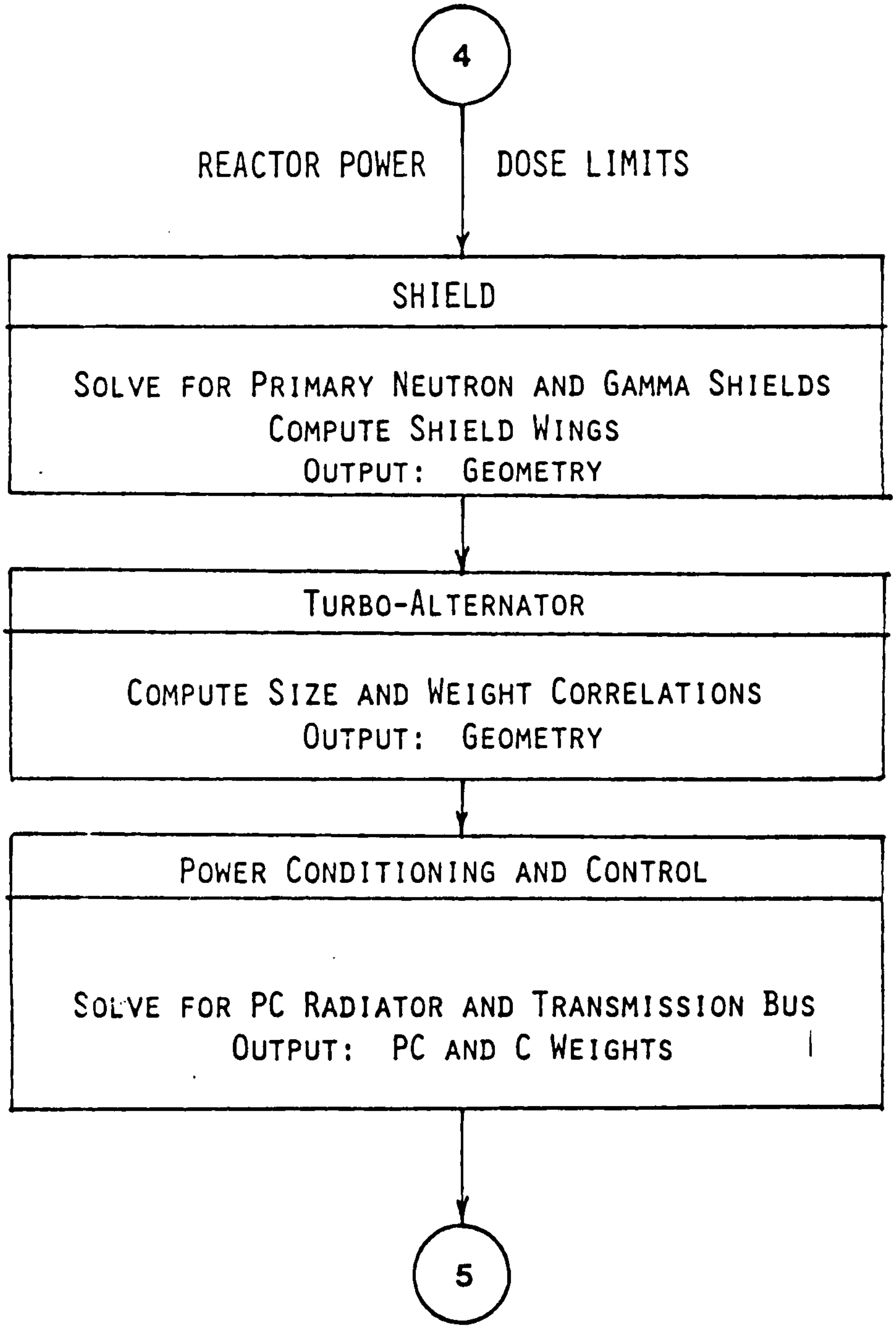

Table 6.1.1 (cont'd)

FLOWCHART OF POTASSIUM RANKINE SYSTEM ALGORITHM

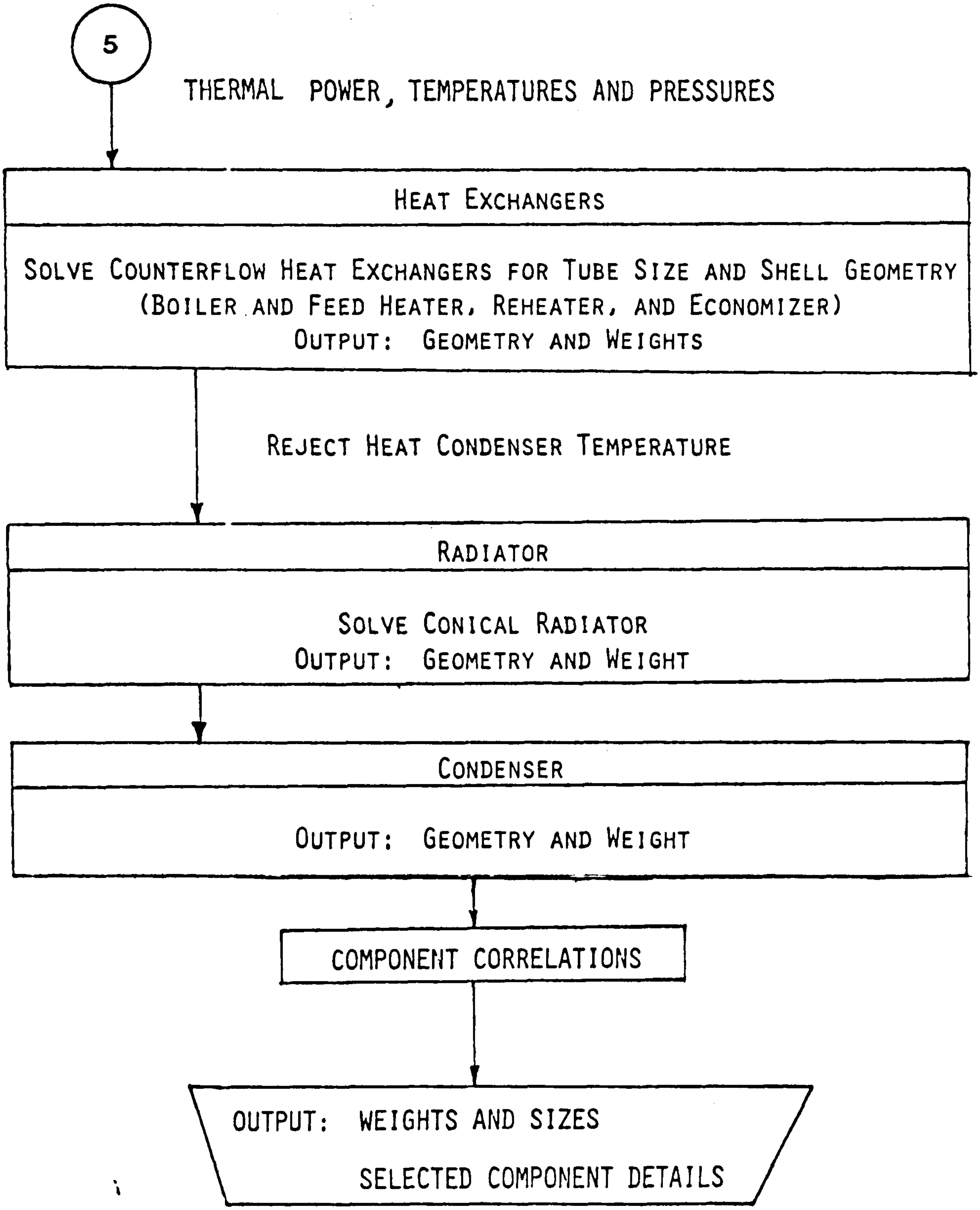

Table 6.1.1 (cont'd)

INPUT PARAMETERS FOR POTASSIUM RANKINE CYCLE CASE

page 1

VALUES of SYSTEM PARAMETERS ARE:

NET ELECIRICAL POWER = 10 MW
REACTOR LIFE in Years 5 Years
PAYLOAD DIAMETER = 10 m
PAYLOAD SEPARATION = 100 m
NEUTRON DOSE FACTOR (Ref: 1E+13 neutrons/sqcm) = 1
GAMMA DOSE FACTOR (Ref: 5E+5 Rad-Si) = 1
NUMBER of PRIMARY PUMPS = 1
NUMBER of TURBO-GENERATOR SETS = 4

VALUES of REACTOR PARAMETERS ARE:

FUEL IS URANIUM OXIDE.
REFLECTORS ARE BERYLLIUM OXIDE.

URANIUM BURN UP = 6 atom %
MAXIMUM U235 ENRICHMENT = .93
K-effective PARAMETER = 1.12
AXIAL REFLECTOR THICKNESS = 12 cm
RADIAL REFLECTOR THICKNESS = 11 cm
CORE LENIGH/DIAMETER RATIO = 1.8
REACTOR PRESSURE DROP = 30 psi

TABLE 6.1.2

INPUT PARAMETERS FOR POTASSIUM RANKINE CYCLE CASE

page 2

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VALUES of TURBINE PARAMETERS ARE:

TURBINE INLET TEMPERATURE = 1450 K
POTASSIUM MOISTURE CONTENT = 9 %
REHEAT MODE IS : ON
NUMBER of TURBINE STAGES = 7
PRESSURE RATIO per STAGE = 1.5
TURBINE REFERENCE EFFICIENCY (5 STAGES/300kW) = 76 %

VALUES of HEAT EXCHANGER PARAMETERS ARE:

LM CIRCULATION RATIO = 2
REACTOR COOLANT DELTA-T = 100 K
BOILER TUBE DIAMETER = 2 cm
ECOND TUBE DIAMETER = .7 cm

VALUES of GENERATOR PARAMETERS ARE:

GENERATOR EFFICIENCY = 95 %
GENERATOR FREQUENCY = 1200 Hz
BUS VOLTAGE = 500 volt
BUS POWER LOSS = 4 %
SPECIFIC WEIGHT of POWER CONDITIONING = .05 kg/kWe

VALUES of RADIATOR PARAMETERS ARE:

RADIATOR EMISIVITY = .85
SPECIFIC WEIGHT of RADIATOR = 16 kg/sqm
MAX RADIATOR DIAMETER = 8.4 m

TABLE 6.1.2 (cont'd)

11/14/84

TYPICAL OUTPUT OF POTASSIUM RANKINE PARAMETRIC SYSTEMS MODEL (U)

page 1


```
********************************************************
*           POTASSIUM RANKINE SYSTEM                   *
*           FILE: KR_107  CASE NUMBER: 1               *
********************************************************

NET ELEC. POWER =                  10 MW                   ** INPUT
REACTOR LIFE =                     5 years                 ** INPUT
PAYLOAD DIAMETER =     10          m                       ** INPUT
PAYLOAD SEPARATION =   100         m  .                    ** INPUT

****   CYCLE PARAMETERS             ****
INLET TEMP =           1460        K                       ** INPUT
SUPERHEAT del-T =      10          K at REHEAT QUALITY = 92.4 %
TURBINE EFFIC =        81          % with 7 STAGES
FH&BOILER POWER =      11.5 MW     & REHEAT POWER =  1.68 MW
INLET PRESSURE =       219         psi  with EXIT PRESSURE =  12.8 psi
REHEAT PRESSURE =      64.8        psi
CONDENSER TEMP =       1020        K at EXIT QUALITY = 97 %
K FLOW each set =      5.3         kg/sec
LM  CIRCULATION RATIO =  2                                 ** INPUT
GENERATOR OUTPUT =     10.7        MW
CYCLE EFFIC =          21.3        % versus SYSTEM EFFIC = 18.9 %
```


TABLE 6.1.3

TYPICAL OUTPUT OF POTASSIUM RANKINE

PARAMETRIC SYSTEMS MODEL (U) UNCLASSIFIED

page 2


```
*****************************************
*             WEIGHT SUMMARY            *
REACTOR WEIGHT =         5760      kg
SHIELDS WEIGHT =         2560      kg
REAC PUMP WEIGHT =       1330      kg for 1 pumps
HEATERS WEIGHT =         1750      kg
TURBOGENS WEIGHT =       10500     kg for 4 sets
FEED PUMPS WEIGHT =      785       kg
CONDENSER WEIGHT =       906       kg
PLUMBING WEIGHT =        1240      kg
STRUCTURE/MISC W =       2590      kg
PC&C+Rad WEIGHT =        1080      kg
HiV T_BUS WEIGHT =       4350      kg
RADIATOR WEIGHT =        16000     kg
                  -----------------
TOTAL WEIGHT =           48900     kg
*****************************************

****  REACTOR PARAMETERS            ****
REACTOR POWER =          52.8      MW
URANIUM BURN UP =        6         atom %  and K-effective =  1.12   ** INPUTS
REACTOR LENGTH =         1.72      m with REFLECTOR Thickness =  12 cm
REACTOR DIAMETER =       .949      m with REFLECTOR Thickness =  11 cm
CORE LENGTH =            1.15      m
CORE DIAMETER =          .639      m
FUEL FRACTION =          60        % with U235 ENRICHMENT =  .338
NUMBER of FUEL RODS = 1543 with DIAMETER = 14.1 mm
FUEL ROD GAP =  1.3 mm  with THAW TUBE DIAMETER =  3.68 mm
COOLANT FLOW RATE =  133 kg/sec with PRESSURE DROP = 29 psi
COOLANT OUTLET TEMP =  1550 K  & INLET TEMP =  1450 K
```


TABLE 6.1.3 (cont'd)

TYPICAL OUTPUT OF POTASSIUM RANKINE

PARAMETRIC SYSTEMS MODEL (U)

UNCLASSIFIED

page 3

```
****   SHIELDING PARAMETERS        ****
SHADOW SHIELD DIAMETER =        .83      m
SCATTER SHIELD DIAMETER =       3        m
NEUTRON SHIELD WEIGHT =         271      kg
GAMMA SHIELD WEIGHT =           295      kg
SCATTER SHIELD WEIGHT =         2000     kg

****   RADIATOR PARAMETERS         ****
RADIATOR AREA =        1001     sqm
RADIATOR LENGTH =      38.5     m
START DIAMETER =       8.1      m    / END DIAMETER = 8.4 m
GENERATOR RADIATOR AREA =  91.2 sqm at T = 600 K.

****   HEAT EXCHANGERS             ****
WEIGHT of BOILERS & FEED HEATERS =  1320 kg
WEIGHT of REHEATERS =           349 kg
WEIGHT of ECONOMIZERS =         85 kg
BOILER SHELL DIAMETER =   .43 m with 343 TUBES of LENGTH =   .67 m
BOILER TUBE DIAMETER =  2 cm   ** INPUT  with GAP =   .2 cm
ECONO SHELL DIAMETER =  .12 m with 122 TUBES of LENGTH =  .71 m
ECONO TUBE DIAMETER =  .7 cm   ** INPUT  with GAP =   .32 cm
CONDENSER CONE LENGTH =         2.07     m
****   COMPONENT SIZES             ****
TURBO-GEN LENGTH =    1.8       m
TURBO-GEN DIAMETER = .9         m
*******************************************************
```

UNCLASSIFIED

TABLE 6.1.3 (cont'd)

10MWe RANKINE SYSTEM CODE OUTPUT

```
*****************************************************
*           POTASSIUM RANKINE SYSTEM                 *
*           FILE: KR_J02  CASE NUMBER: 2
*****************************************************

NET ELEC. POWER =               10 MW                        ** INPUT
REACTOR LIFE =                  5 years                      ** INPUT
PAYLOAD DIAMETER =    10.       m                            ** INPUT
PAYLOAD SEPARATION = 100        m                            ** INPUT

****   CYCLE PARAMETERS          ****
INLET TEMP =          1460      K                            ** INPUT
SUPERHEAT del-T =     10        K at REHEAT QUALITY = 92.4 %
TURBINE EFFIC =       81        % with 7 STAGES
FH&BOILER POWER =     11.4 MW   & REHEAT POWER = 1.67 MW
INLET PRESSURE =      219       psi  with EXIT PRESSURE =  12.8 psi
REHEAT PRESSURE =     64.8      psi
CONDENSER TEMP =      1020      K at EXIT QUALITY = 97 %
K FLOW each set =     5.2       kg/sec
LM  CIRCULATION RATIO =  2                                   ** INPUT
GENERATOR OUTPUT =    10.7      MW
CYCLE EFFIC =         21.4      % versus SYSTEM EFFIC = 19.1 %

************************************
*           WEIGHT SUMMARY          *
REACTOR WEIGHT =      5725      kg
SHIELD WEIGHT =       2552      kg
REAC PUMP WEIGHT =    1317      kg for 1 pumps
HEATERS WEIGHT =      1737      kg
TURBOGEN WEIGHT =     10470     kg for 4 sets
FEED PUMP WEIGHT =    392.3     kg
CONDENSER WEIGHT =    897.6     kg
RADIATOR WEIGHT =     16010     kg
                  ----------------
TOTAL WEIGHT =        48280     kg
************************************

****  REACTOR PARAMETERS          ****
REACTOR POWER =       52.4      MW
URANIUM BURN UP =     6         atom %  and K-effective =  1.12   ** INPUTS
REACTOR LENGTH =      1.72      m with REFLECTOR Thickness =  12 cm
REACTOR DIAMETER =    .948      m with REFLECTOR Thickness =  11 cm
CORE LENGTH =         1.15      m
CORE DIAMETER =       .638      m
FUEL FRACTION =       60        % with U235 ENRICHMENT =  .339
NUMBER of FUEL RODS = 1535 with DIAMETER = 14.1 mm
FUEL ROD GAP =  1.3 mm  with THAW TUBE DIAMETER =  3.68 mm
COOLANT FLOW RATE =  132 kg/sec with PRESSURE DROP = 28 psi
COOLANT OUTLET TEMP =  1550 K  & INLET TEMP =  1450 K

****   SHIELDING PARAMETERS       ****
```

Table 6.1.4

10MWe RANKINE SYSTEM CODE OUTPUT

```
****   SHIELDING PARAMETERS        ****



SHADOW SHIELD DIAMETER =       .63      m
SCATTER SHIELD DIAMETER =      3        m
NEUTRON SHIELD WEIGHT =        269      kg
GAMMA SHIELD WEIGHT =          293      kg
SCATTER SHIELD WEIGHT =        1990     kg

****   RADIATOR PARAMETERS         ****
RADIATOR AREA =       1001     sqm
RADIATOR LENGTH =     38.5     m
START DIAMETER =      8.1      m    / END DIAMETER = 8.4 m
GENERATOR RADIATOR AREA =  91.2 sqm at T = 600 K.

****   HEAT EXCHANGERS             ****
WEIGHT of BOILERS & FEED HEATERS =  1310 kg
WEIGHT of REHEATERS =           346 kg
WEIGHT of ECONOMIZERS =         84.4 kg
BOILER SHELL DIAMETER =  .43 m  & TUBE LENGTH =  .67 m
BOILER TUBE DIAMETER =  2 cm  ** INPUT  with GAP =  .2 cm
ECONO SHELL DIAMETER =  .12 m  & TUBE LENGTH =  .71 m
ECONO TUBE DIAMETER =  .7 cm  ** INPUT  with GAP =  .32 cm
CONDENSER CONE LENGTH =         2.06     m
****   COMPONENT SIZES             ****
TURBO-GEN LENGTH =   1.8      m
TURBO-GEN DIAMERER = .9       m
*******************************************************
```

Table 6.1.4
(cont'd)

5MWe RANKINE SYSTEM CODE OUTPUT

```
***************************************************************
*            POTASSIUM RANKINE SYSTEM                         *
*            FILE: KR_J05  CASE NUMBER: 4
***************************************************************

NET ELEC. POWER =       5          MW
PAYLOAD DIAMETER =      10         m
PAYLOAD SEPARATION = 50            m
****   CYCLE PARAMETERS             ****
INLET TEMP =            1450       K
SUPERHEAT del-T =       60         K
TURBINE EFFIC =         80         %
TURBINE STAGES =        6
INLET PRESSURE =        165        psi
EXIT PRESSURE =         14.5       psi
CONDENSER TEMP =        1030       K at EXIT QUALITY = 87.5 %
K FLOW each set =       6.6        kg/sec
GENERATOR OUTPUT =      5.31       MW
CYCLE EFFIC =           19         % versus SYSTEM EFFIC = 17.3 %
****************************************
TOTAL WEIGHT =          26480      kg
REACTOR WEIGHT =        3562       kg
SHIELD WEIGHT =         1114       kg
REAC PUMP WEIGHT =      467.8      kg for 1 pumps
BOILER WEIGHT =         1015       kg
TURBOGEN WEIGHT =       4990       kg for 2 sets
FEED PUMP WEIGHT =      762.8      kg
CONDENSER WEIGHT =      2750       kg
RADIATOR WEIGHT =       7924       kg

****************************************
****   REACTOR PARAMETERS              ****
REACTOR POWER =         28.9       MW at OUTLET TEMP = 1500 K
URANIUM BURN UP =       6          atom %  and K-effective =  1.1
REACTOR LENGTH =        1.34       m with REFLECTOR Thickness =  10 cm
REACTOR DIAMETER =      .877       m with REFLECTOR Thickness =  12 cm
CORE LENGTH =           .835       m
CORE DIAMETER =         .554       m
FUEL FRACTION =         60         % with U235 ENRICHMENT =  .372
NUMBER of FUEL RODS = 1123 with DIAMETER = 14.4 mm
COOLANT FLOW RATE =  69.2 kg/sec with PRESSURE DROP = 11 psi
****   SHIELDING PARAMETERS            ****
SHADOW SHIELD DIAMETER =        .89        m
SCATTER SHIELD DIAMETER =       1.5        m
NEUTRON SHIELD WEIGHT =         309        kg
GAMMA SHIELD WEIGHT =           265        kg
SCATTER SHIELD WEIGHT =         540        kg
****   RADIATOR PARAMETERS             ****
RADIATOR AREA =         535.5      sqm
RADIATOR LENGTH =       39         m
START DIAMETER =        4.2        m    / END DIAMETER = 4.5 m
****   COMPONENT SIZES                 ****
TURBO-GEN LENGTH =      1.8        m
TURBO-GEN DIAMERER = .9            m
BOILER SHELL DIAMETER = .57        m
BOILER OUTER DIAMETER = 2.1        m
CONDENSER LENGTH =      1.2        m
CONDENSER DIAMETER = .4            m
***************************************************************
```

Table 6.1.5

6.2 THERMIONIC SYSTEM

6.2.1 Introduction

The following ground rules were used in the design of the thermionic power conversion system. The 10 MWe thermionic MCNSPS design uses thermionic performance corresponding to superior but actually achieved, laboratory thermionic converters. A bare emitter work function of 5.1 eV, probably the upper limit for oriented tungsten surfaces, is assumed. The 1900 K emitter temperature assumed is 200 K hotter than current SP-100 design, but only a modest extension of the 1850 K temperatures run in previous in-core TFE one year testing programs. The LC-9 out of reactor test was run for 5 years at 1970 K without significant performance degradation. This test used a rhenium emitter instead of tungsten. Higher performance and/or longer duration may be achieved with oxygenated converters, surface coatings, or other base emitter materials, such as alloys of rhenium.

In the UO_2 fueled in-pile tests which have been conducted, device lifetime was projected to be up to three years, being limited by emitter deformation. The emitters proposed in this study, also UO_2 fueled, are less than half as large (d=1cm) as those of the previous tests. This allows the fractional distortion ($\Delta d/d$) of the smaller emitters to be twice that of the larger devices before short circuiting would occur. The large size of the 10 MWe reactor allows for the U^{235} enrichment to be decreased to below 50%. An alternate course is to use fully enriched fuel and replace some UO_2 with THO_2. Life 4 code fuel swelling calculations indicate that an unenriched rind of UO_2 or THO_2 surrounding a fully enriched core of $^{235}UO_2$ will serve to provide a "hard" buffer between the soft fuel core and the emitter, thereby constraining the fuel swelling. This behavior has been demonstrated by Chubb et.al. Taking into account some expected saturation in fuel swelling and the subsequent development of higher creep strength fuel rind and emitter materials, projecting a five year life for these small diameter emitters appears to be a reasonable goal.

The sheath insulators are required to operate at 20 to 50 volts and at temperatures about 50° below the SP-100 design. Y_2O_3 and YAG sheath materials hold the most promise of meeting long term design requirements. Y_2O_3 shows particularly stable resistance to neutron damage (recent examination by LANL of the K-5 capsule previously irradiated at EBR-II. However, the possible electrolysis in Y_2O_3 at higher voltages may require the use of yttria-alumina garnet (YAG). The satisfactory fabrication of YAG sheath insulators is yet to be completed. Sheath insulator and power conditioner development are critical to the success of the incore thermionic system at high power output. An alternative approach is to accept a low voltage output from a TFE and transform this output to a higher voltage outside of the reactor with suitable power conditioners.

6.2.2 Thermionic Reactor

Figure 6.2.1 shows an end view of a 10MWe thermionic reactor. TFE's are electrically joined together in clusters of seven. Each seven-cluster lead penetrates the ends of the reactor vessel. A conceptual design of the cluster lead is shown in Fig. 6.2.2. This figure shows details of the power lead which penetrates the reactor end plenum for a 7 rod TFE cluster. The electric lead is insulated from the liquid metal coolant by a tri-layer sheath insulator and has doubly redundant seals where the penetration is made through the vessel head. The electric lead is drilled to provide a fission gas vent port that communicates with each of the TFE's in the cluster. An identical lead configuration for the cluster is also present at the opposite end of the reactor. Differential expansion is taken up in the reactor center plane where TFE's are grounded.

The cells within one TFE are connected in series. If a single cell shorts against the collector only the incremental voltage contribution from that single cell is lost. The remaining cells continue to operate stably and the TFE voltage decreases ~.5 volts. Since the 7 TFE's in the TFE cluster are connected in parallel, a small decrease in voltage in one cell has only a very small effect on the cluster output.

Referring back to Figure 6.2.1, four large bus lines, located at 90° with respect to each other, are attached to the TFE cluster leads at each end of

10 MWe THERMIONIC REACTOR END VIEW (U)

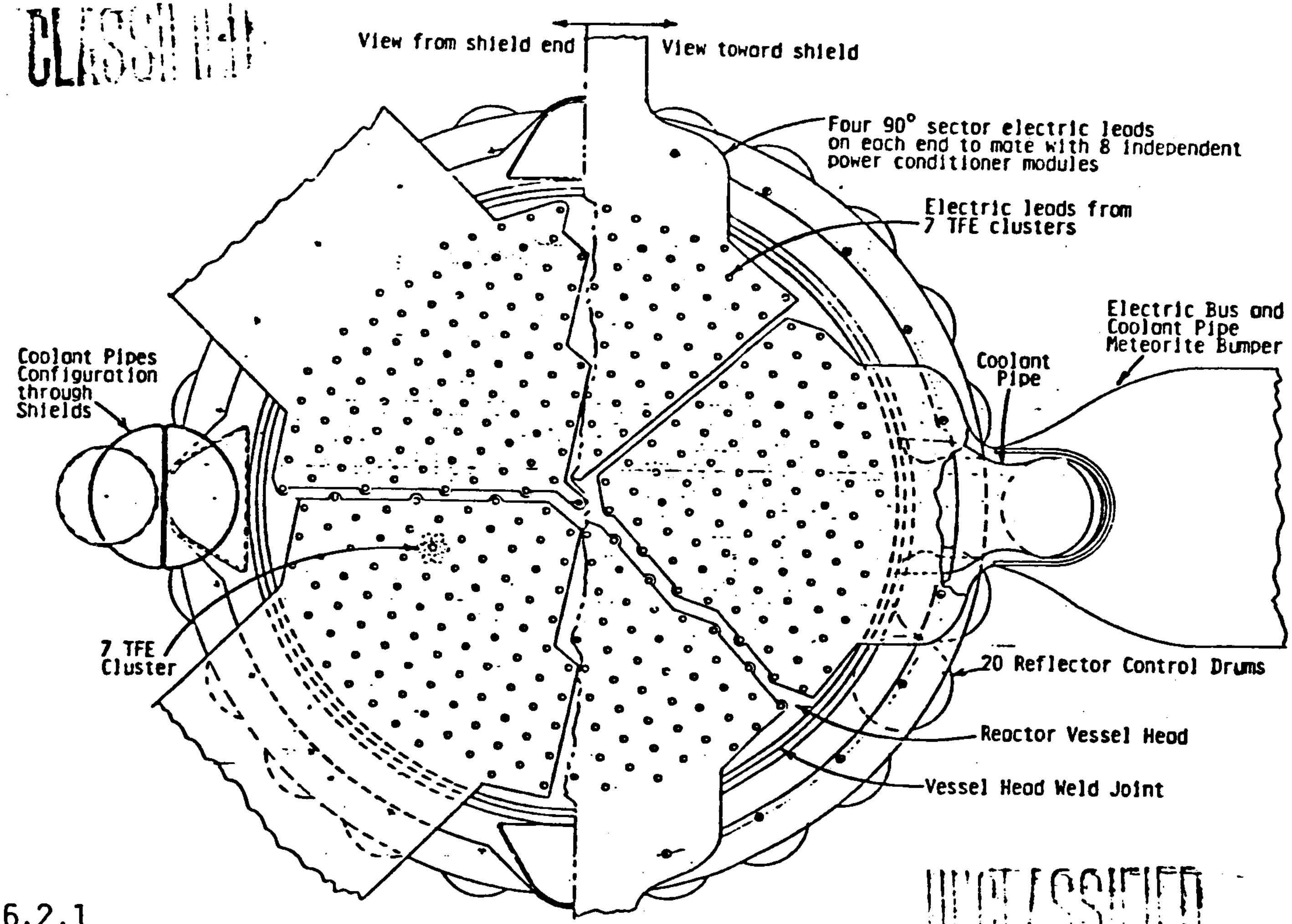

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FIG. 6.2.1

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TFE CLUSTER LEAD CONFIGURATION (U)

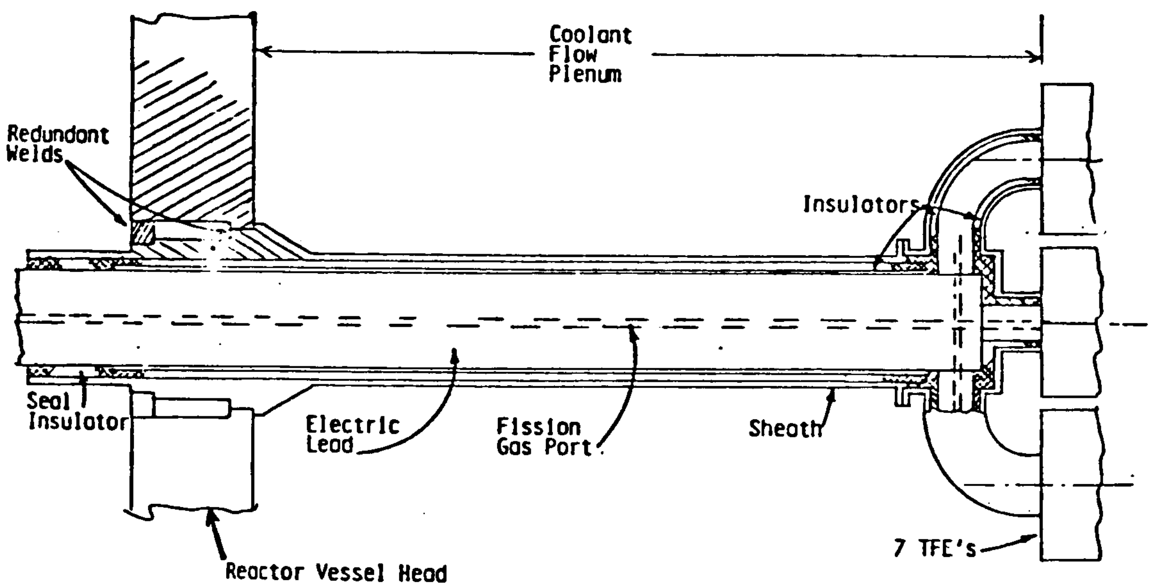

FIG. 6.2.2

unclassified

the reactor. The bus bars leaving the top end of the reactor are rotated 45° with respect to the corresponding group at the other end.

Each TFE can consist of as many as 60 cells and has a ground connection at midlength. Power from half of the cells is directed out each end through the TFE cluster lead. Figure 6.2.3 shows the detail of the central grid plate which locates and grounds the TFE's in the MCNSPS design. Two TFE's enter the coreplate, slipping together concentrically. The right hand portion of this figure shows one of the small thaw pin heat pipes used to melt frozen coolant during dormant startups. Grounding the TFE at the central grid plate allows approximately 19 volts to be delivered at each end of the reactor. This is the approximate voltage limit that current state-of-the-art sheath insulators can withstand without breakdown over their five year operational lifetime.

Figure 6.2.4 shows a side view of a 10MWe thermionic reactor. As shown here and in Figure 6.2.1, the electric bus forms the micrometeoroid protection armor for the reactor coolant pipes. One TFE cluster is also shown in a cutaway. A core aspect ratio (L/D) of 1.5 has been used in the base design. This yields a design with substantially more lateral leakage surface for neutrons than end leakage. This increased radial neutron leakage makes the reflector control drums relatively effective in reactivity worth. Nonetheless, because of uncertainties in core size and loading, it is not possible at this time to determine if reflector control drums offer sufficient reactivity swing. Control rods will likely be required to compliment the drums.

Although the TFE assemblies are fairly complex, it is a repetitious assembly of identical modules and should lend itself readily to volume production techniques.

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TFE CORE MID-PLANE CONFIGURATION (U)

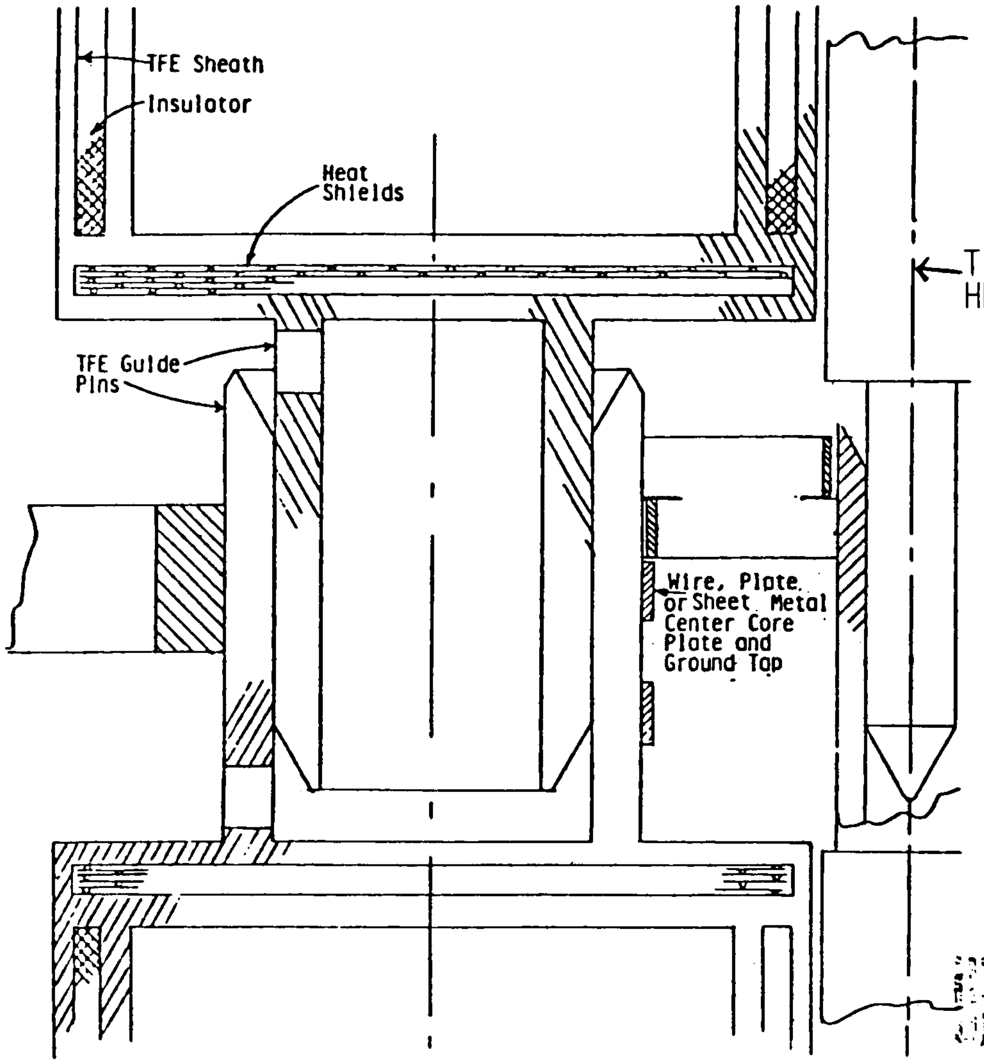

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FIG. 6.2.3

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10 MWe THERMIONIC REACTOR (U)

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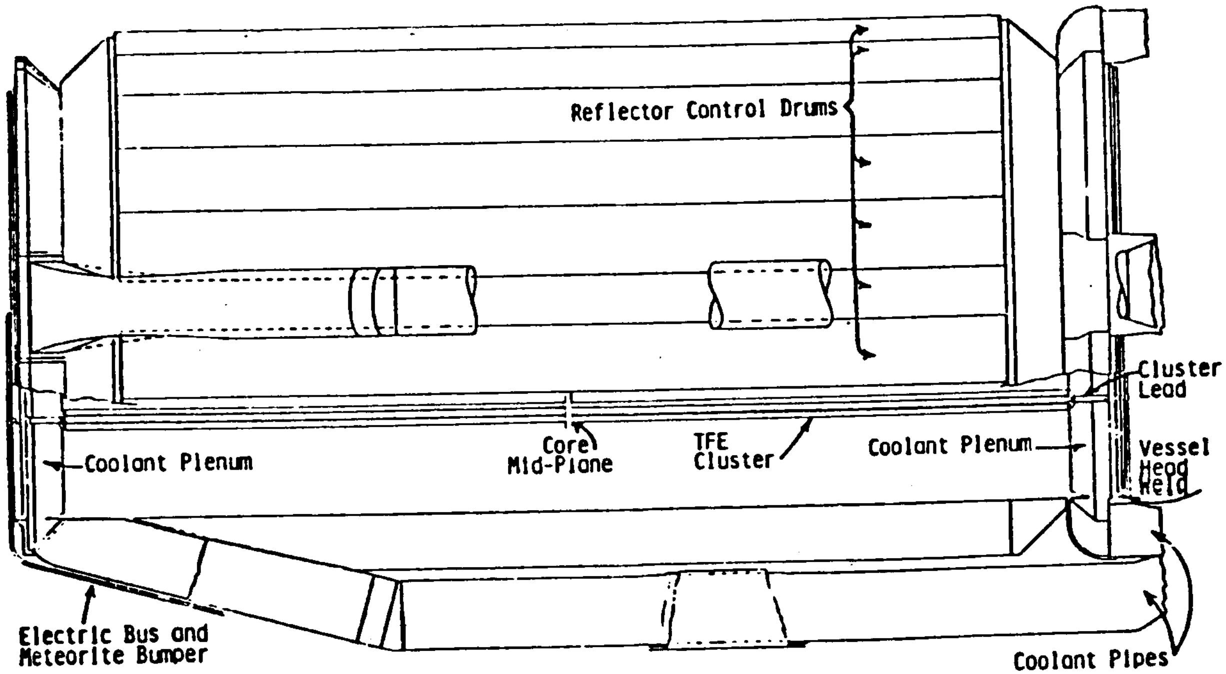

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FIG. 6.2.4

unclassified

6.2.3 Power Conditioning

General Considerations

Thermionic convertors in a space nuclear power system are inherently low voltage devices which produce high-current DC power. The generating voltage of a reactor system can be selected by adjusting the number of cells which are connected in series. However, in order to retain parallel groupings of cells for redundancy and to minimize the chances of electrical breakdown or electrolytic degradation of ceramic insulators, the voltage of an in-core thermionic system should be designed to be as low as possible. An extensive data base exists, which shows that output voltages of 10-30 volts are acceptable in long life (>1 year) systems. While higher voltages may prove feasible, their use is as yet undemonstrated.

Compact power conditioning can be is usually accomplished by a series resonant or a transformer-coupled inverter system with solid state switching. It is necessary to switch high currents, on the order of 6000 amperes for a 100 kilowatt system, in the power conditioner. The use of conventional power-conditioning designs at such low voltages results in low efficiency (due to the forward voltage drop which is imposed by the use of bipolar transistor technology).

The low efficiency of conventional power conditioner designs, combined with the low operating temperature of past solid state systems, would result in the need for massive power-conditioning waste heat radiators. This penalty has been high enough to drive previous system designs to specify the technically challenging development of high voltage ($\pm$50 V) reactor components, in particular the previously discussed sheath insulators. Thus, a need exists for an innovative and efficient low-voltage, high-current power-conditioning system.

In this study, power conditioning is assumed to be provided by a low voltage power conditioning unit (PCU) of the type under development by SPI. This compact PCU can be designed with power MOSFETs to provide a 10:1 to 20:1 DC voltage step-up. The power MOSFET, which is making in-roads in electronic power applications, is uniquely suited for the task of power conditioning a thermionic reactor. Because of the importances of the PCU to the viability of the ITR and of the MOSFET to achieving a very low mass, efficient, compact PCU, a detailed discussion of the characteristics of MOSFETs is warranted.

The MOSFET is an array of field effect transistors with parallel-connected source electrodes densely located on a single silicon chip (~1/4" die). It can handle high-current switching at high frequencies. Typical source densities of present MOSFET devices are over $10^5 cm^{-2}$ of area on the chip and new devices are under development which will have twice the source density of present devices.

MOSFET's have several distinct characteristics which make them superior to bipolar transistors at low voltages. Being a field-effect transistor, the power MOSFET has no junction voltage-drop, only a resistive component or IR voltage loss during conduction. By contrast, a bipolar transistor, which is composed of P-N junctions, always has at least a 1/2 volt or more that is made up of both the junction voltage and the resistive component. If a large number of MOSFETs are paralleled, the resistive voltage drop can be reduced to an arbitrarily low value. This means that high efficiencies can potentially be obtained with large currents in a MOSFET switch by paralleling devices.

A breakdown of the component masses for several candidate low power PCU designs is presented in Fig. 6.2.6 for a 10 kWe buck regulator [4]. The 100 kHz MOSFET unit shown in the right side of this figure has a specific mass of slightly over 0.5 kg per kilowatt. The greatest savings in component mass is in the small filter components associated with the high-frequency MOSFET design. The SPI 18V/180V conditioner mass is 0.33 kg/kWe at 400 K and 94% efficiency. Higher voltage input in similar future systems should achieve 0.1 to 0.2 kg/kWe.

The MOSFET-based power conditioner bench tests have achieved 94% to 95% efficiency at 425 K. Some of the losses are generated in the transformers, which have the potential for operation at 570 K, (i.e. the waste heat would

12 MWe SOLID STATE POWER CONDITIONER (U)

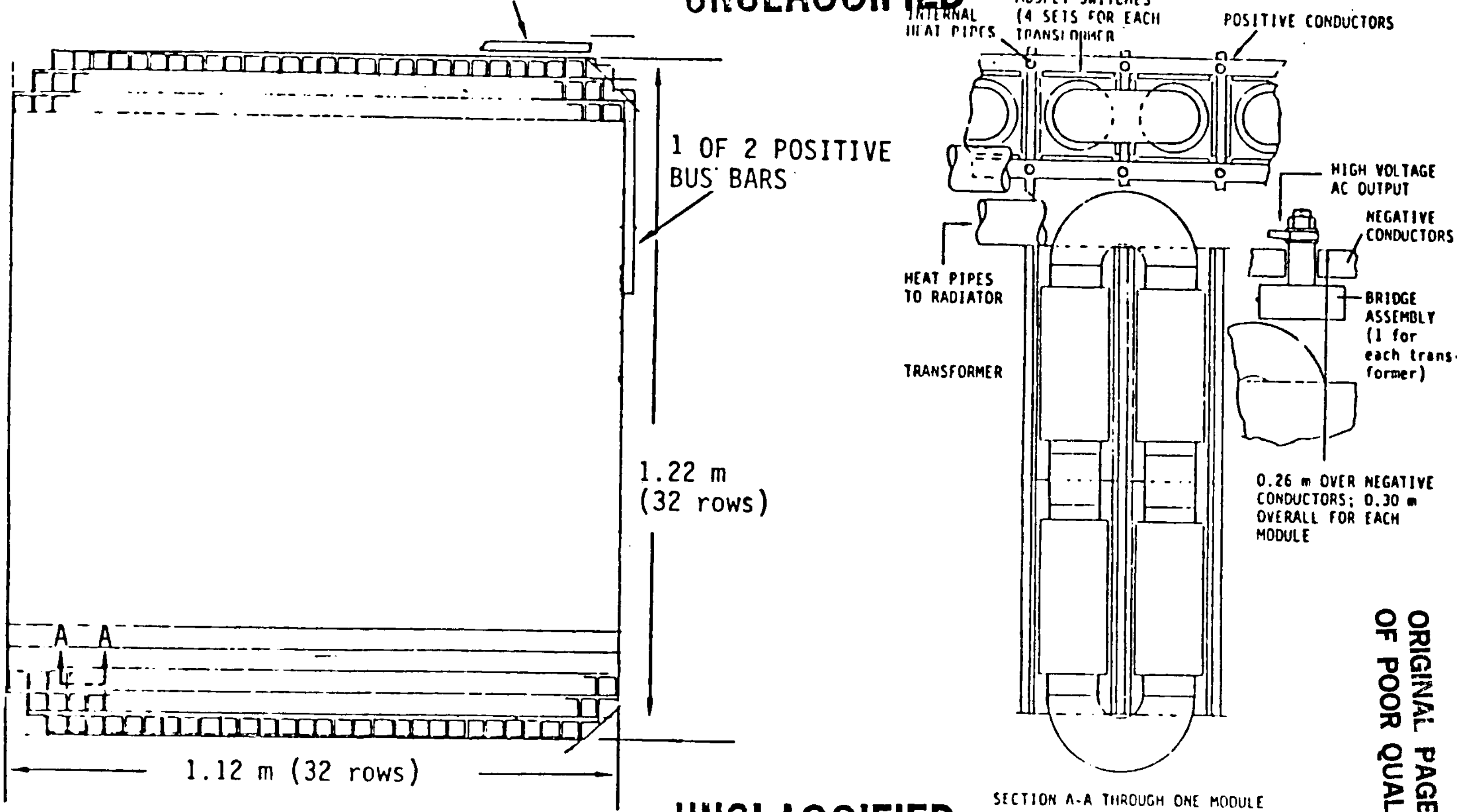


FIG. 6.2.5

Weight Breakdown/Solar Array Buck Regulator

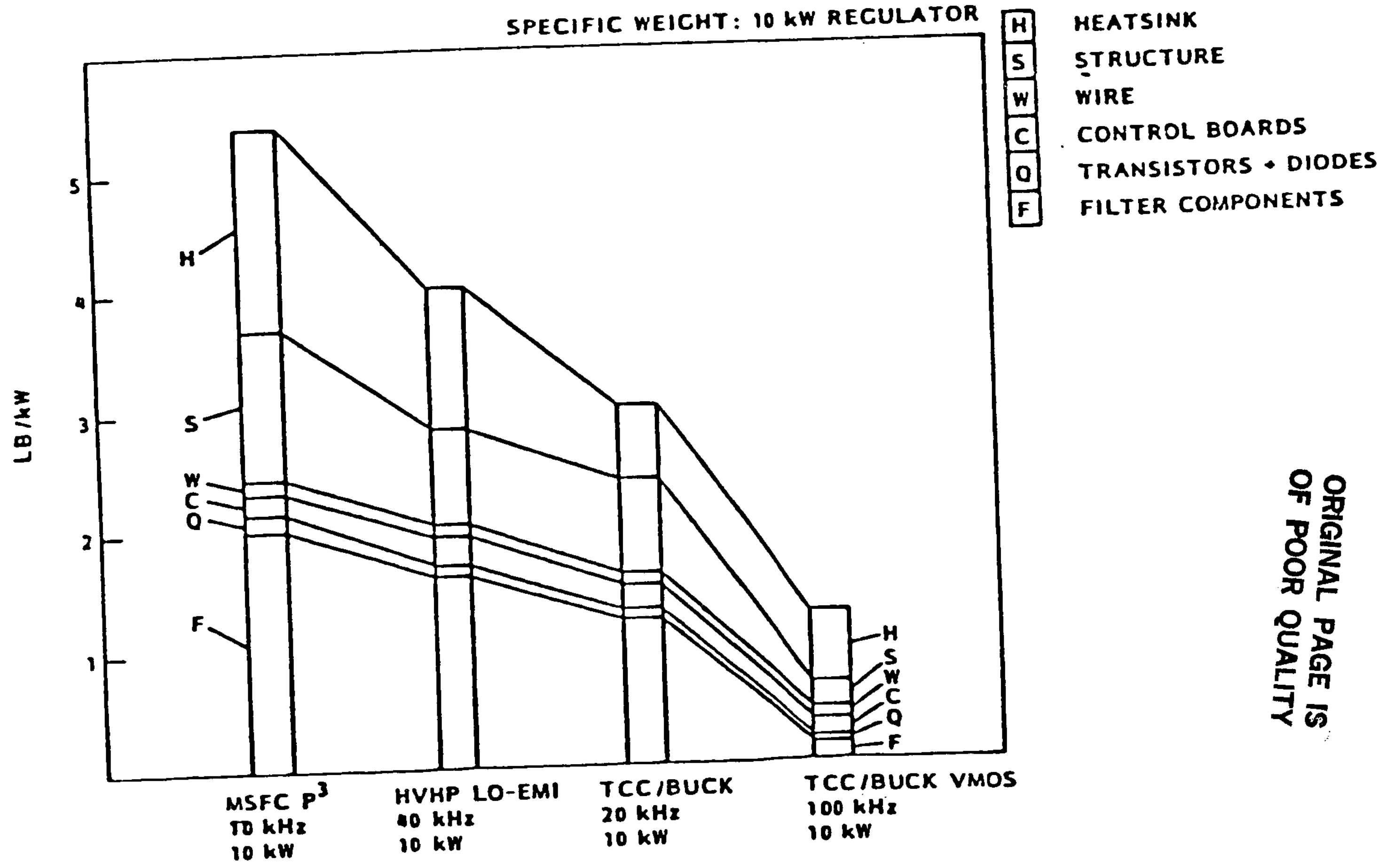


FIG. 6.2.6

be radiated at this temperature). Most of the remainder of the heat losses are generated in the semiconductor switches, which would presently be radiated at a lower temperature of 420 K. Each of these losses is transported out of the power conditioner package by a pumped NaK loop. Higher temperature operation of these solid state switches leads to reduced efficiency, but also seems to reduce sensitivity to radiation damage.

The placement of the power conditioning system is governed by a trade-off between isolation from radiation sources and bus bar lengths from the reactor. In addition, the location of the power conditioner must permit a view factor to space for the PCU radiator, which is at a temperature lower than the primary radiator. A thermal radiation barrier would isolate the power conditioner from the primary radiator. Heat dissipation from the power conditioning unit would be accomplished by using a separate NaK cooling system to a separate low temperature (400 K to 500 K) radiator.

Additional gamma ray and neutron shielding would be placed immediately above the power conditioning unit to protect the semiconductor switches. If possible, radiation-hard components, such as transformers, bus bars, etc., should help to provide shielding for the semiconductors.

Radiation effects on different semiconductor types [5] are shown in Figs. 6.2.7 and 6.2.8. In general, bipolar semiconductors are less sensitive to gamma radiation and FET devices are less sensitive to neutrons. Siliconix, Inc., Motorola, and International Rectifier are developing power MOSFET's for hardened equipment. Radiation resistance of present-day power MOSFET's is typified by the published characteristics of International Rectifier's HEXFETs, shown in Figs. 6.2.9 and 6.2.10. The main effect of gamma radiation is to introduce charges into the gate oxide which produce a shift in the gate-to-source threshold voltage $V_{GS(th)}$. The value of $V_{GS(th)}$ for N-channel HEXFETs becomes smaller with increasing gamma dose, while the $V_{GS(th)}$ of P-channel HEXFET's increases with the dose. The change in threshold voltage is essentially independent of the dose rate and depends only on the total dose.

EFFECTS OF GAMMA RADIATION ON SEMICONDUCTORS

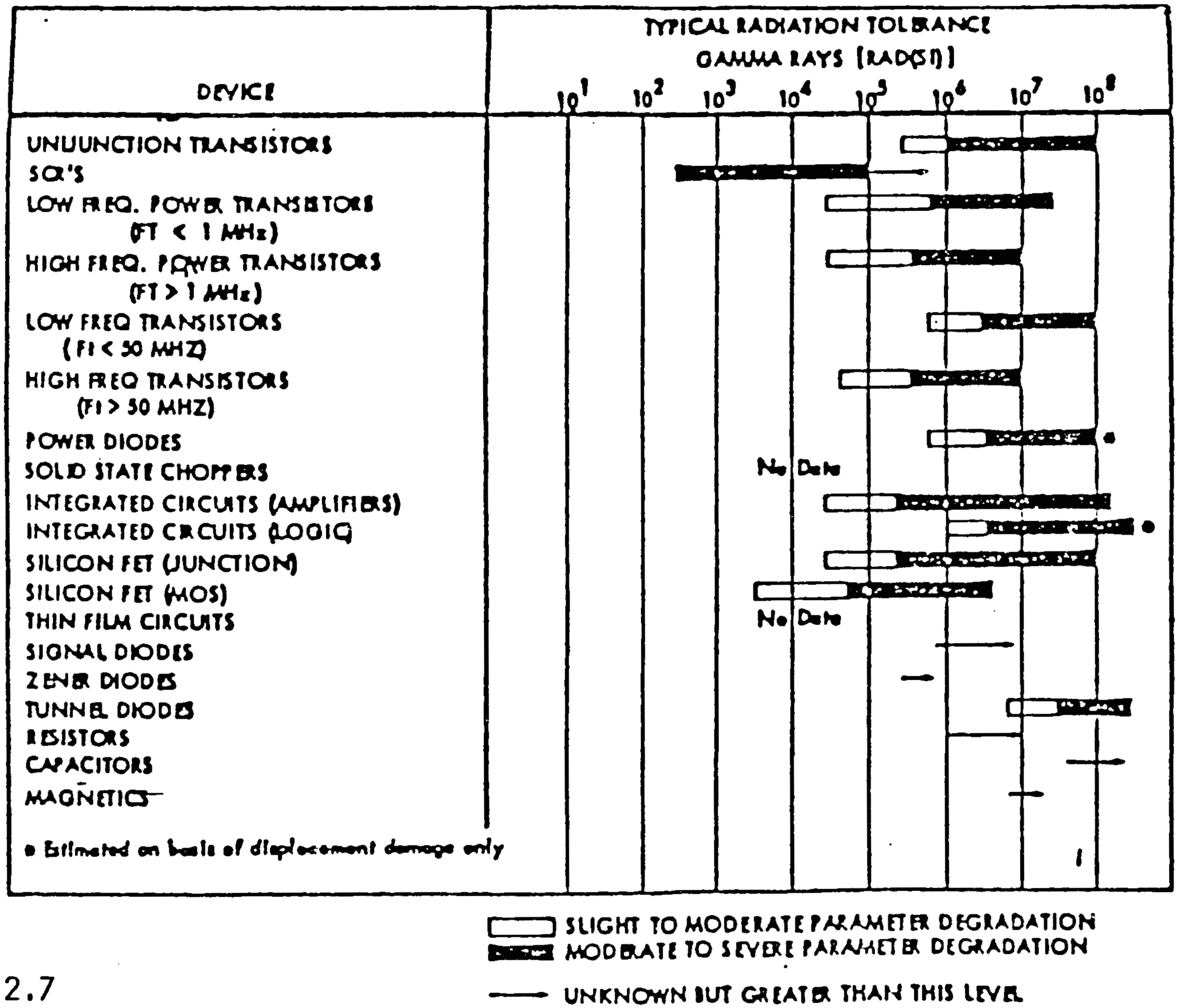


FIG. 6.2.7

EFFECTS ON NEUTRON RADIATION ON SEMICONDUCTORS

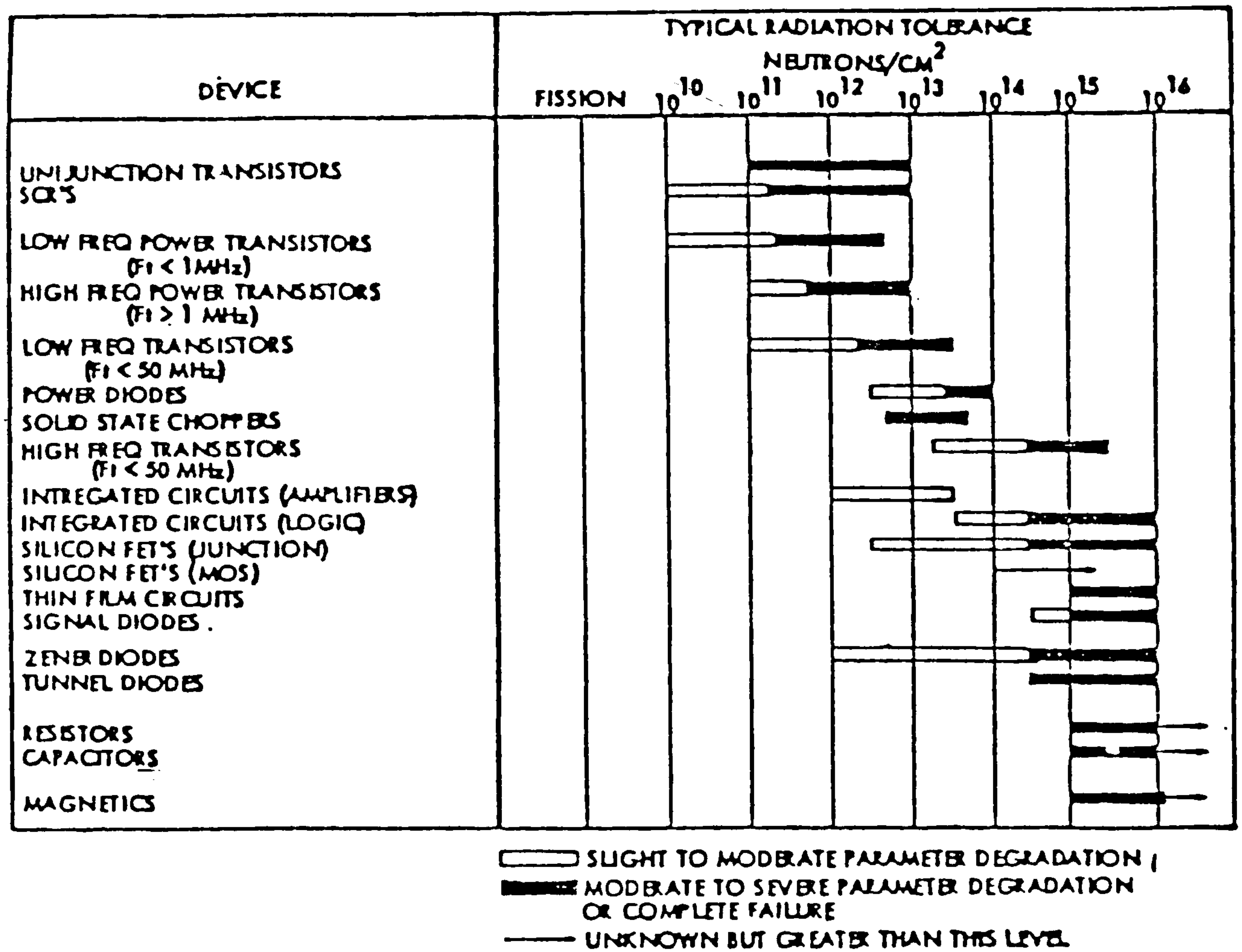
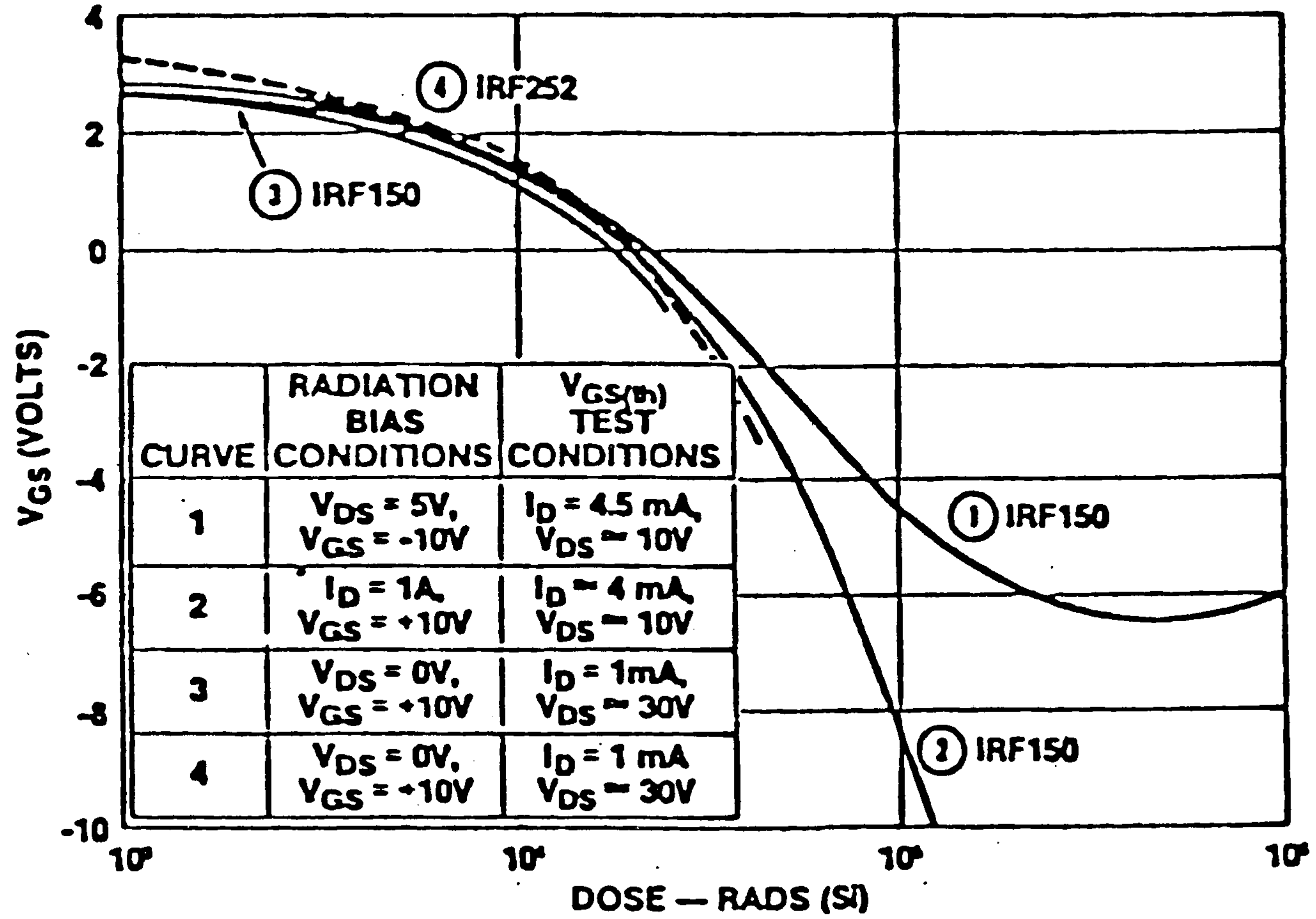


FIG. 6.2.8

Variation of Hexfet Gate Threshold Voltage vs Gamma Dose



CURVE	RADIATION BIAS CONDITIONS	$V_{GS(th)}$ TEST CONDITIONS
1	V_{DS} = 5V, V_{GS} = -10V	I_D = 4.5 mA, V_{DS} ≃ 10V
2	I_D = 1A, V_{GS} = +10V	I_D ≃ 4 mA, V_{DS} ≃ 10V
3	V_{DS} = 0V, V_{GS} = +10V	I_D = 1mA, V_{DS} ≃ 30V
4	V_{DS} = 0V, V_{GS} = +10V	I_D = 1 mA, V_{DS} ≃ 30V

FIG. 6.2.9

VARIATION OF HEXFET ON-RESISTANCE vs NEUTRON FLUENCE LEVEL

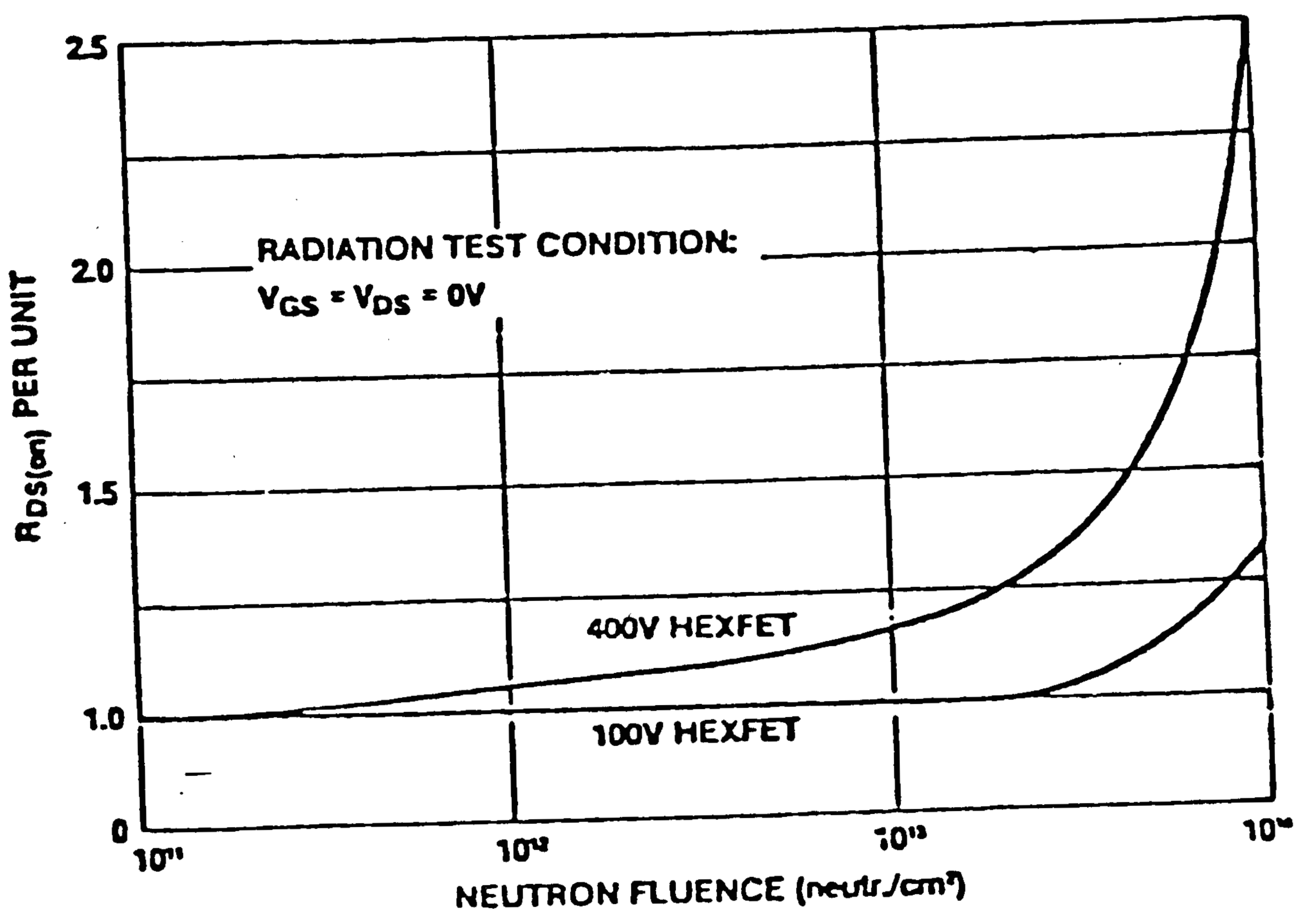


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FIG. 6.2.10

The gate-drive circuitry for switching applications can be designed to nullify the radiation-induced threshold voltage shifts by over-riding them with appropriate biasing levels. Fig. 6.2.9 shows a typical variation of gate-to-source threshold voltage for 4 HEXFET devices under various biasing conditions.[6] For bias-off tests ($V_{GH(th)}$ = -10V, curve no. 1), the threshold voltage of 1 IRF 150 decreases to a value of approximately -6V at 2 x 10^5 Rad Si then stays practically constant at this value with further increase in radiation. An applied voltage to the gate of -10V would ensure that the device would remain fully "off" even up to 1 megarad of gamma dose.

The effect of neutron radiation is to produce an increase in HEXFET on-resistance. Fig. 6.2.10 shows typical measured relationships between the on-resistance and neutron fluence of 2 power MOSFET's rated at 100 V and 400 V, respectively.[5]. The on-resistance of the 100 V unit hardly increases even with a fluence of up to 2 x 10^{13} nvt, while about a 30% increase is observed at 2 x 10^{14} nvt. By allowing for an increase of the on-resistance in the design, predictable and reliable operation of the MOSFET power conditioner in a neutron radiation environment can readily be achieved to beyond 10^{14} nvt.

MCNSPS Design Specific Considerations

Low voltage power delivered by a 10 MWe reactor must be stepped up to a transmission level of about 500 volts DC by the power conditioning system. To accomplish this, the DC unit must perform multiple functions:

1) Current division from the high-current bus to parallel sub-units;
2) Current interruption and switching;
3) Voltage step-up; and
4) Production of smoothed DC output.

In the MCNSPS ITR system conceptual design these functions are allocated to separate component groups:

1) The current division conductors will take off from the lower end of heat-pipe-cooled, aluminum bus bars. These conductors will be an integral part of the physical package, and they will divide the primary current into sub-units.

2) Current switching will be done with power MOSFET's. The solid state devices needed for this function have a low tolerance to radiation and temperature. Consequently, they will be thermally separated from the main bus bars into a compact water-heat-pipe-cooled unit that can be efficiently shielded from radiation. The temperature of the MOSFET's will be kept below 420 K.

3) The voltage transformation can be accomplished by components (inductors, capacitors, transformers, etc.) that are tolerant of higher temperature and radiation. The transformers may operate at the main bus bar temperature of 570 K.

4) Rectification and filtering functions would best be accomplished by means of solid state electronics. High-current diodes in a bridge rectifier would be used.

5) All power conditioning functions must be accomplished in a paralleling arrangement that permits independent component failures to occur without having a major effect on the system performance.

A small fraction (<3%) of the power will be produced in 3-phase AC and used to power the electromagnetic pump in the primary coolant loop. Pulse width modulation of the gate drive for the MOSFET switches can be used for load-following or output power pulsing, if desired. However, for steady operation, a shunt regulator with high-temperature, parasitic load is preferred to keep the reactor power level constant.

At the location for the power conditioning unit in the conceptual design, additional gamma ray shielding will be needed to protect the semiconductors, but neutron levels should be acceptable. A large part of the additional gamma flux comes from radioactive coolant circulating in the primary loop coolant ducts and heat exchangers. The bus bars and transformers will be arranged to provide shielding from gamma rays. A small tungsten or depleted-uranium gamma-shield will be placed on top of the compact power conditioning unit to achieve the desired dose rates.

6.2.4 Bus Bar Considerations

The generation of low-voltage, high-current DC by an ITR requires that careful attention be paid to bus bars for transporting the current from the reactor to the PCU. While typical reactor output design voltages are in the range of 10 to 100 volts, voltages near 15 to 20 volts are preferred. For power levels of 5 to 10 MWe, the low voltage reactor output bus bars become extremely massive at 20 volts. Therefore, for the MCNSPS conceptual designs ±25 volt yielding a 50 volt reactor output, which will require the development of the YAG sheath insulators mentioned previously, is assumed. The bus bars for this system are made of two segments: the upper section nearest the reactor is constructed of OFHC copper, and the lower portion is composed of high purity aluminum.

Aluminum is not the lightest bus bar material, in terms of electrical conductivity per unit mass. Metal clad solid sodium bus bars provide minimum mass, but require cooling to about 350 K. Metal clad pure calcium bus bars might be lowest mass at practical temperatures of ~400 to 600 K. However, this complication must be studied before deciding whether to accept the trade-off for lighter weight versus the advantages of aluminum. As a system degrades toward end of life, the power loss will be taken in current rather than in voltage, so that the ohmic heating losses in the bus bar will not become proportionally larger.

The thermal energy produced by the Joule heating of the bus bars is mostly radiated from the outer surface of the bus bars themselves. A small portion of energy is also conducted out of the reactor from the hot end of the TFE's into the bus bars, but their temperature quickly drops to an equilibrium between the Joule heating and the radiation from their outer surface.

For power levels of 100 kWe and above, the mass of the bus bars is substantial, so that the power conditioning system should be located near the reactor. This, in turn, requires a compact power conditioner design, if suitable radiation shielding is to be provided.

The current delivered by the main bus bars would be divided into modules within the power conditioning system, as shown in Figure 6.2.5. Each of these PC modules sees 30 volts DC (some voltage is lost in the primary bus bars). All of the modules are connected in parallel to the primary bus bars, so that failure of any one module does not affect the others.

6.2.5 System Radiator

The thermionic power conversion system has two radiators: the primary radiator, which rejects the waste heat from the thermionic conversion process; and the power conditioning radiator, which rejects the heat generated in the power conditioner. Depending on system design optimization, the primary radiator operates at 950 K or higher. The power conditioning radiator operates at two separate temperatures. The transformers in the power conditioners can reject heat at 570 K and still not exceed the Curie temperature. Present power electronics (e.g., MOSFET's) are capable of rejecting heat at no higher than 420 K. Power electronics capable of efficient operation at >500 K are a critical development requirement for reducing the size of the PCU waste heat radiator.

The thermionic system uses the telescoping radiator concept described in Section 4.3 of Volume II. This radiator is able to fit within the delivery vehicle envelope and is shieldable. Details of the radiator size, location, capacity, etc. are described in the specific 5 MWe and 10 MWe conceptual designs which follow.

6.2.6 Conceptual Design

A computerized parametric analysis of the thermionic system was made using an internally-produced thermionic systems code. Table 6.2.2 displays the logic flowchart of the incore thermionic system algorithm.

The code output for the optimum 10 MWe thermionic system is shown on Table 6.2.3. Data from this particular output has been summarized in Tables 6.2.4 through 6.2.7, in the areas of reactor parameters, component weights, power conversion parameters, and the heat rejection system respectively.

Fig. 6.2.11 shows the fully deployed 10 MWe incore thermionic power system. The 10 MWe system is packagable into the Boeing Shuttle Derived Cargo Launch Vehicle.

The optimum 5 MWe thermionic design code output is shown on Table 6.2.8.

IN-CORE THERMIONIC SYSTEM SOLUTION ALGORITHM

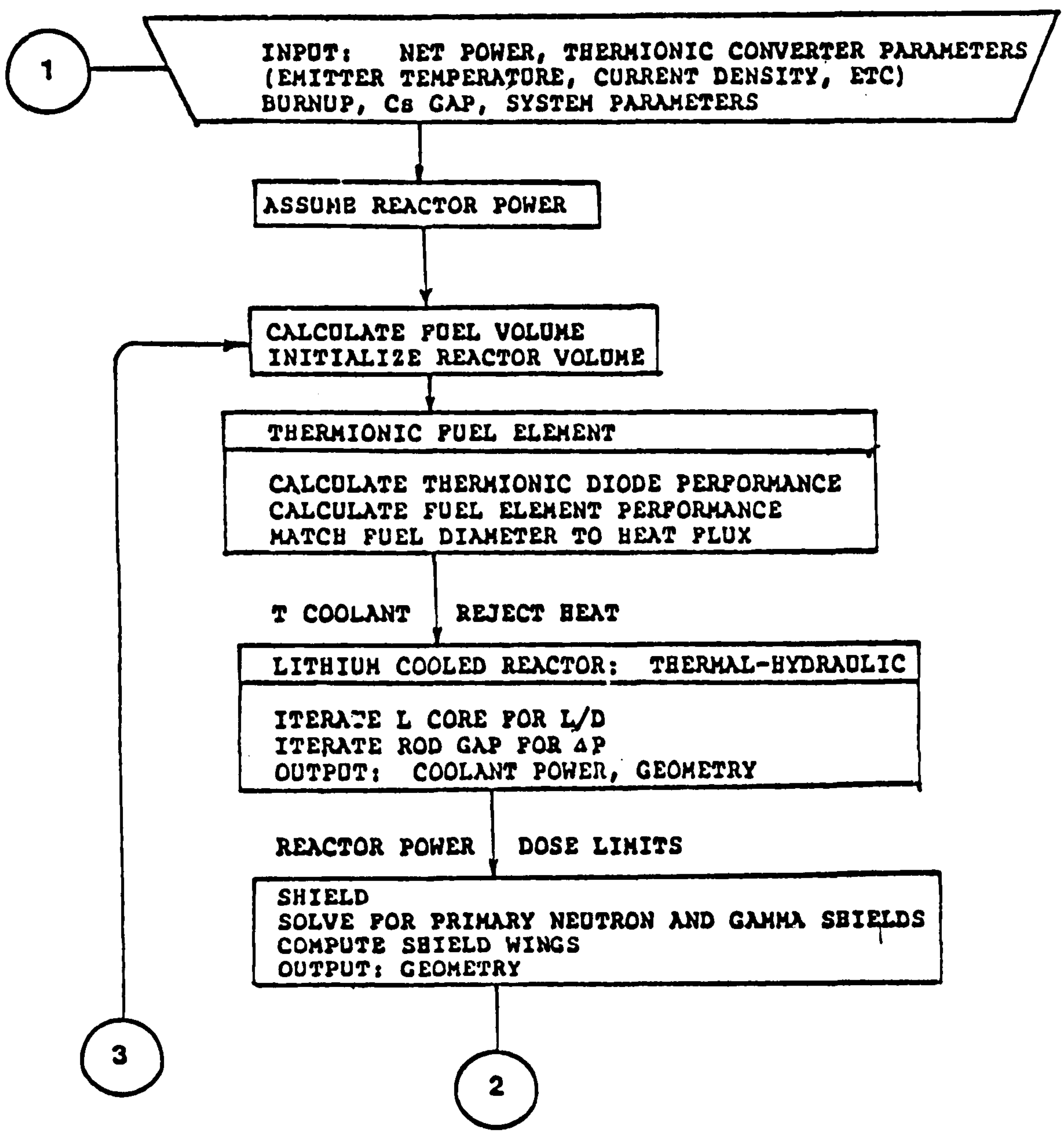

TABLE 6.2.2

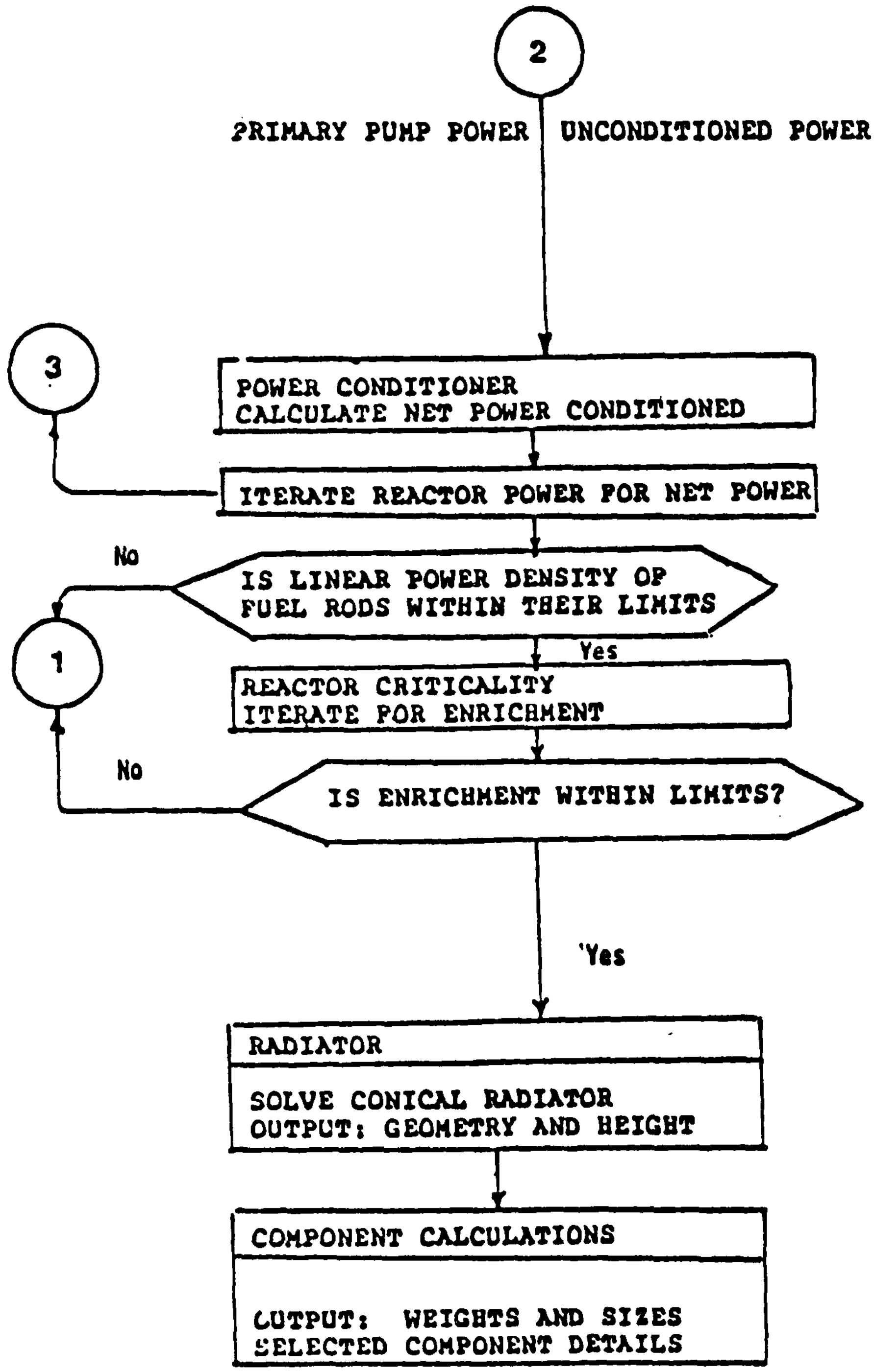

TABLE 6.2.2 (CONT'D)

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10 MWe THERMIONIC SYSTEM CODE OUTPUT

******* HEAT PIPE RADIATOR DETAIL REPORT *******

SKIP TUBE MODEL'

QTOT = 6.84E+7 watts @ 990 K
QTOTcalc= 7.12E+7 watts @ 988.9 K
Total Radiator Weight = 24750 kg Total Radiator Area = 1701 sq m
Overall Radiator Length = 41.72 m with 3 Segments
Section length = 1750 cm

Section Details Follow:

Sect No.	Fluid	Sect Dia. cm	No. Tubes	Tube Dia. cm	Lap cm	Radial Flux W/cm2	Temp. Drops Radial K	Temp. Drops Axial K	Ratio Ax/Rd	dT Sect K	Axial Temp K
1	K	900	293	4.8	146	64.8	8	12	1.5	20	942.9
2	K	890	85	16.4	312	63	8	4	.25	20	966.9
3	K	858	70	19.3	0	0	8	4	.25	20	986.9

THERMIONIC INCORE REACTOR

NET ELECTRICAL POWER =	10 MW	** INPUT
SYSTEM EFFICIENCY =	12.47 %	
REACTOR LIFE =	5 years	** INPUT
URANIUM BURN UP =	6 atom %	** INPUT
PAYLOAD DIAMETER =	18 m	** INPUT
PAYLOAD SEPARATION =	50 m	** INPUT

* THERMIONIC PARAMETERS *

EMITTER TEMPERATURE =	1900 K	** INPUT
COLLECTOR TEMPERATURE =	1050 K	** INPUT
CESIUM RESERVOIR TEMP. =	577 K	
FUEL DIAMETER =	1.18 cm	
EMITTER DIAMETER =	1.36 cm	
THERMAL POWER/LENGTH =	202 W/cm	
DIODE CURRENT DENSITY =	15 A/sqcm	** INPUT
WORK FUNCTION (PHI 0) =	5.1 eV	** INPUT
DIODE SPACING =	10 mil	** INPUT
CELL PD =	20 mil-torr	** INPUT
DIODE VOLTAGE =	.732 volts	
DIODE NET POWER DENSITY =	10.6 W/sqcm	
IDEAL EFFICIENCY =	18.4 %	
CELL EFFICIENCY =	14.6 %	
CELL THERMAL INPUT =	494 W	
CELL L/D-emit RATIO =	1.8	** INPUT
CELL LENGTH =	2.45 cm	
CELL CURRENT =	113 amps	
CELL VOLTAGE =	.638 volts	
CELL POWER OUTPUT =	72.2 W	
NUMBER OF CELLS =	60	
MAXIMUM ROD VOLTAGE =	38.4 volts	
TFE HOOKUP PARAMETER =	.5	** INPUT

* REACTOR PARAMETERS *

REACTOR POWER =	80.16 MW	
REQUESTED PRESSURE DROP =	30 psi	** INPUT
REACTOR PRESSURE DROP =	30 psi	

TABLE 6.2.3

NET COOLANT PRESSURE DROP =	45 psi	
COOLANT MASS FLOW RATE =	164 kg/sec	
PRIMARY PUMP POWER =	.267 MW	
NUMBER OF PUMPS =	1	** INPUT
NUMBER OF FUEL RODS =	2692	
FUEL ROD DIAMETER =	1.74 cm	
THAW TUBE DIAMETER =	.335 cm	
FUEL ROD GAP =	.0576 cm	
FUEL FRACTION =	.281 with VOID FRACTION = .117	
U235 ENRICHMENT =	.576 atom frac. at K-eff = 1.29 **	
NEUTRON FLUX =	.394 at RADIAL EDGE and = .309 at AXIAL EDGE.	

= REACTOR DIMENSIONS =

CORE L/D =	1.5	** INPUT
REACTOR LENGTH =	2.08 m	
REACTOR DIAMETER =	1.3 m	
CORE LENGTH =	1.48 m with CORE DIAMETER = .985 m	
SIDE REFLECTOR THICKNESS =	14 cm	
END REFLECTOR THICKNESS =	12 cm	
FIRST GAMMA SHIELD LAYER =	2.54 cm	

= REACTOR WEIGHTS =

COOLANT =	72.6 kg
THAW TUBES =	353 kg
CLADDING+CONNECTORS =	3560 kg
TRILAYER =	2350 kg
FUEL =	3240 kg vs min FUEL = 3250 kg
SIDE REFLECTOR =	2487 kg
END REFLECTOR =	535.8 kg
PRIMARY TUNGSTEN SHIELD =	649 kg
VESSEL =	604 kg
TOTAL REACTOR WEIGHT =	13850 kg

= SYSTEM WEIGHTS =

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PRIMARY PUMP =	1420 kg
SHIELDING =	8730 kg
HEAT EXCHANGER/PIPING =	494 kg
STRUCTURAL/MISCELLANEOUS =	2470 kg
POWER CONDITIONER&SHIELD =	5540 kg
LOW VOLTAGE BUS BAR =	2500 kg
POWER COND. RADIATOR =	2040 kg
TRANSMISSION BUS & STR =	686 kg
MAIN RADIATOR =	24800 kg
TOTAL SYSTEM WEIGHT =	62730 kg

= POWER CONDITIONER =

P. C. EFFICIENCY =	94 %	** INPUT
FRACTIONAL VOLTAGE LOSS =	2 %	** INPUT
P. C. SPECIFIC WEIGHT =	.3 kg/kWe	** INPUT
TFE OUTPUT VOLTAGE =	19.2 volts	
P. C. & TRANSMISSION LOSS =	1.72 MW	
P. C. RADIATOR AREA =	340 sq m	
P. C. RADIATOR EMISSIVITY =	.85	** INPUT
P. C. DIAMETER =	1.22 m	
LOW VOLTAGE BUS LENGTH =	2.94 m	
TRANSMISSION BUSS VOLTAGE =	500 v	** INPUT
TRANS. BUSS VOLTAGE LOSS =	5 %	** INPUT

TABLE 6.2.3 (cont'd)

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        * SHIELDING PARAMETERS *
NEUTRON FLUENCE LIMIT =          1.E+13 ntrns/sqcm  ** INPUT
GAMMA FLUENCE LIMIT =            5 E+5 Rad-Si       ** INPUT
NEUTRON SHIELD THICKNESS =       68.9 cm
NEUTRON SHIELD WEIGHT =          1440 kg
GAMMA SHIELD THICKNESS =         9.44 cm
GAMMA SHIELD WEIGHT =            1020 kg
SHADOW SHIELD WEIGHT =           2860 kg  with DIAMETER =  2.16 m
SCATTER SHIELD THICKNESS =       53.8 cm
SCATTER SHIELD WEIGHT =          3330 kg  with DIAMETER =  3.29 m

        * RADIATOR PARAMETERS *
REJECT HEAT =                    68.45 MW at  990 K
RADIATOR EMISSIVITY =            .85                ** INPUT
RADIATOR AREA =                  1700 sq m
STARTING DIAMETER =              8.19 m
END DIAMETER =                   9 m                ** INPUT
RADIATOR LENGTH =                41.7 m
NUMBER OF SEGMENTS =             3
MINIMUM TEMP FOR SODIUM =        1100 K             ** INPUT

****************************************************************
```

TABLE 6.2.3 (cont'd)

10 MWE THERMIONIC SYSTEM - REACTOR PARAMETERS (U)

• CORE DIMENSIONS	1.48 M (LENGTH); 0.985 M (DIAMETER)
• REFLECTOR THICKNESS	16 CM - RADIAL (2.5 CM OF POISON); 14 CM-AXIAL (2 CM OF POISON)
• REACTOR DIMENSION:	2.08 M X 1.30 M; L/D = 1.5
• TFE CHARACTERISTICS	1.74 CM OD; 60 CELLS (DOUBLE ENDED OUTPUT)
• UO_2 FUEL	3240 KG (58% ENRICHMENT) IN 2692 TFE'S
• REACTIVITY (BOL)	K EFFECTIVE 1.29 6% ATOM % OF BURN-UP
• LITHIUM COOLANT MASS FLOW	164 KG/SEC (45 PSIA PRESSURE DROP)
• REACTOR THERMAL POWER	80 MW_T (11.7 MWE GROSS ELECTRIC OUTPUT)
• START-UP	FROZEN LITHIUM - THAW PINS - HOT ARTERIES
• OPERATING LIFE	5 YEARS (MULTIPLE SHUTDOWN AND RESTARTS)

TABLE 6.2.4

10 MWe Thermionic System - Component Masses (U) UNCLASSIFIED

• Reactor, Vessel, Primary Tungsten Shield	13850	KG
• Primary E M Pump	1420	KG
• Scatter Shield and Shadow Shield (See Note 1)	8730	KG
• Heat Exchanger and Piping	494	KG
• Structural and Miscellaneous	2470	KG
• PC Unit and Shielding	5540	KG
• Low Voltage Bus Bars (2.76 m)	2500	KG
• Power Conditioning Radiator	2040	KG
• 500 V Transmission Bus/Boom	686	KG
• Primary Radiator	24800	KG
• Total System Mass	62530	KG

Note 1: Payload 10 m diameter at 100 m distance
1×10^{13} nvt and 5×10^{5} Rads

- Shuttle Derived Launch Vehicle

UNCLASSIFIED

TABLE 6.2.5

UNCLASSIFIED

10 MWe Thermionic System - Power Conversion Parameters (U)

• Emitter Temperature	1900 K
• Collector Temperature	1050 K
• TI Cell Dimensions	2.45 cm (length) x 1.36 cm (diameter)
• Interelectrode gap	10 mils
• Current Density	15 A/cm^2 ($\emptyset_0$ = 5.1 eV)
• Reactor Output Voltage	19 volts (Double ended EFE's)
• TI Cell Lead Efficiency	14.6%
• Low Voltage Bus Bar Losses (19V)	2% (8 separate circuits)
• Power Conditioner Efficiency	94%
• E M Pump Power	267 kWe
• 500 volt Transmission Losses (100 m)	5%
• Overall System Efficiency	12.47

UNCLASSIFIED

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TABLE 6.2.6

UNCLASSIFIED

10 MWe Thermionic System - Heat Rejection System (U)

• Telescoping Radiator	3 segments K-Heat Pipes (Skip Tube)
• Primary Radiator Dimensions	(9 m O.D. x 42 m long) 1701 m^2 of Area
• Radiator Temperature	940 K to 990 K
• Emissivity	0.85 - Beryllium Armor
• Total Radiated Heat	68.4 MW_T
• Power Conditioner	340 m^2 of Area (E = 0.85)
• PC Waste Heat	1.7 MW_T
• PC Operating Temperature	PC Radiator has 2 separate temperature sections)

- MOSFETS T_J = 420K (40% of PC waste heat)
- Transformers: 570K (60% of PC waste heat)

UNCLASSIFIED

TABLE 6.2.7

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10MWE MNSPS

FULL SIZE BOEING SDCLV - 90,000 KG

INCORE THERMIONIC SYSTEM

60,000 KG

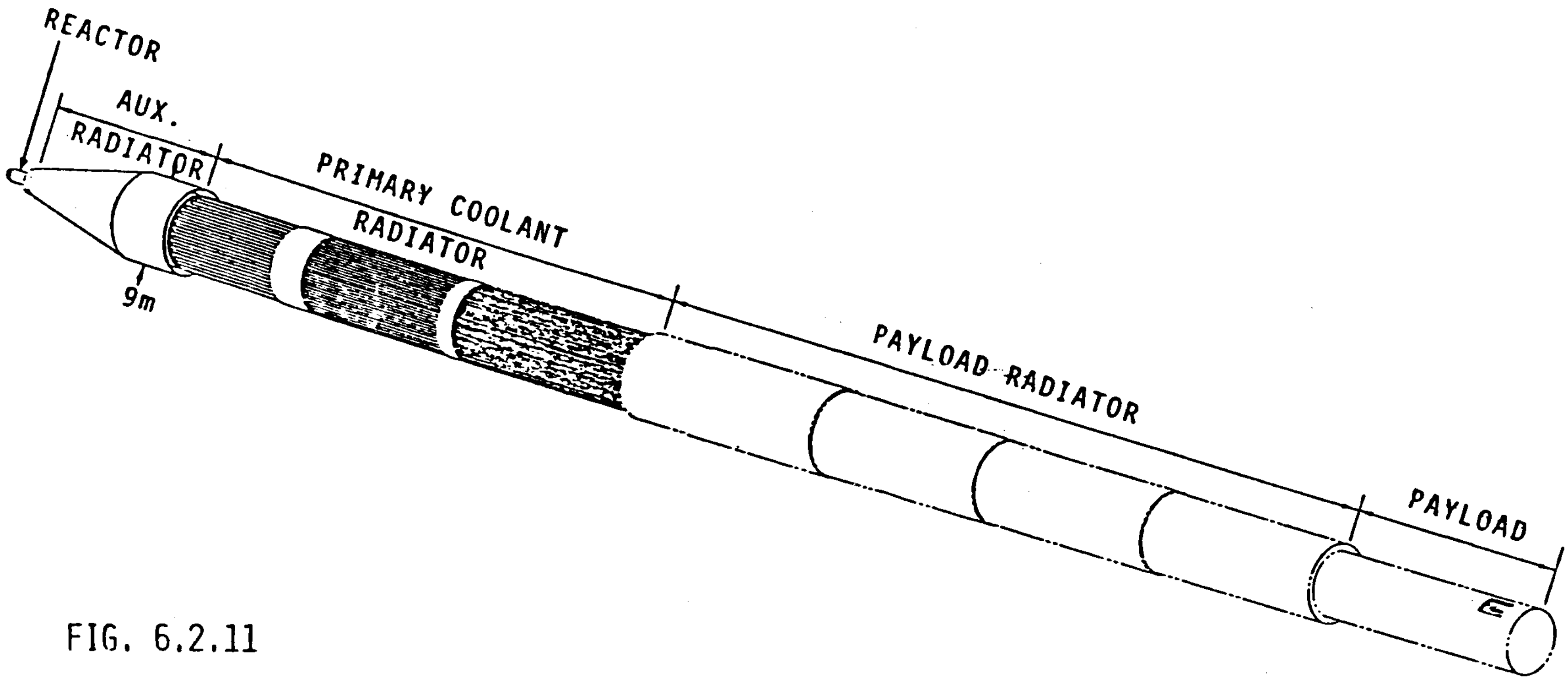

FIG. 6.2.11

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5MWe THERMIONIC SYSTEM CODE OUTPUT

******* HEAT PIPE RADIATOR DETAIL REPORT *******

'SKIP TUBE MODEL

QTOT = 3.34E+7 watts @ 990 K
QTOTcalc= 3.47E+7 watts @ 988.9 K
Total Radiator Weight = 12010 kg   Total Radiator Area = 832.4 sq m
Overall Radiator Length = 41.71 m   with 3 Segments
Section length = 1750 cm

Section Details Follow:

Sect No.	Fluid	Sect Dia. cm	No. Tubes	Tube Dia. cm	Lap cm	Radial Flux W/cm2	Temp. Drops Radial K	Temp. Drops Axial K	Ratio Ax/Rd	dT Sect K	Axial Temp K
1	K	450	146	4.8	146	65.3	8	12	1.5	20	942.9
2	K	440	41	16.7	331	62.2	8	4	.25	20	966.9
3	K	407	31	20.2	0	0	8	4	.25	20	986.9

* THERMIONIC INCORE REACTOR *

NET ELECTRICAL POWER =	5 MW	** INPUT
SYSTEM EFFICIENCY =	12.74 %	
REACTOR LIFE =	5 years	** INPUT
URANIUM BURN UP =	6 atom %	** INPUT
PAYLOAD DIAMETER =	18 m	** INPUT
PAYLOAD SEPARATION =	50 m	** INPUT

* THERMIONIC PARAMETERS *

EMITTER TEMPERATURE =	1900 K	** INPUT
COLLECTOR TEMPERATURE =	1050 K	** INPUT
CESIUM RESERVOIR TEMP. =	577 K	
FUEL DIAMETER =	1.25 cm	
EMITTER DIAMETER =	1.43 cm	
THERMAL POWER/LENGTH =	200 W/cm	
DIODE CURRENT DENSITY =	16 A/sqcm	** INPUT
WORK FUNCTION (PHI 0) =	5.1 eV	** INPUT
DIODE SPACING =	10 mil	** INPUT
CELL PD =	20 mil-torr	** INPUT
DIODE VOLTAGE =	.724 volts	
DIODE NET POWER DENSITY =	11.4 W/sqcm	
IDEAL EFFICIENCY =	18.4 %	
CELL EFFICIENCY =	14.8 %	
CELL THERMAL INPUT =	401 W	
CELL L/D-emit RATIO =	1.4	** INPUT
CELL LENGTH =	2.01 cm	
CELL CURRENT =	93.1 amps	
CELL VOLTAGE =	.639 volts	
CELL POWER OUTPUT =	59.5 W	
NUMBER OF CELLS =	60	
MAXIMUM ROD VOLTAGE =	38.3 volts	
TFE HOOKUP PARAMETER =	.5	** INPUT

* REACTOR PARAMETERS *

REACTOR POWER =	39.24 MW	
REQUESTED PRESSURE DROP =	30 psi	** INPUT
REACTOR PRESSURE DROP =	16.3 psi	

TABLE 6.2.8

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NET COOLANT PRESSURE DROP =	24.4 psi	
COOLANT MASS FLOW-RATE =	79.9 kg/sec	
PRIMARY PUMP POWER =	.0984 MW	
NUMBER OF PUMPS =	1	** INPUT
NUMBER OF FUEL RODS =	1633	
FUEL ROD DIAMETER =	1.82 cm	
THAW TUBE DIAMETER =	.34 cm	
FUEL ROD GAP =	.0508 cm	
FUEL FRACTION =	.256 with VOID FRACTION = .126	
U235 ENRICHMENT =	.567 atom frac. at K-eff = 1.29 **	

NEUTRON FLUX = .764 at RADIAL EDGE and = .689 at AXIAL EDGE.

* REACTOR DIMENSIONS *		
CORE L/D =	1.5	** INPUT
REACTOR LENGTH =	1.76 m	
REACTOR DIAMETER =	1.11 m	
CORE LENGTH =	1.2 m with CORE DIAMETER = .8 m	
SIDE REFLECTOR THICKNESS =	14 cm	
END REFLECTOR THICKNESS =	12 cm	
FIRST GAMMA SHIELD LAYER =	2.54 cm	

* REACTOR WEIGHTS *	
COOLANT =	37 kg
THAW TUBES =	177 kg
CLADDING+CONNECTORS =	2090 kg
TRILAYER =	1260 kg
FUEL =	1590 kg vs min FUEL = 1590 kg
SIDE REFLECTOR =	1749 kg
END REFLECTOR =	353.7 kg
PRIMARY TUNGSTEN SHIELD =	477 kg
VESSEL =	405 kg
TOTAL REACTOR WEIGHT =	8132 kg

* SYSTEM WEIGHTS *	
PRIMARY PUMP =	592 kg
SHIELDING =	2840 kg
HEAT EXCHANGER/PIPING =	252 kg
STRUCTURAL/MISCELLANEOUS =	1190 kg
POWER CONDITIONER&SHIELD =	3050 kg
LOW VOLTAGE BUS BAR =	1030 kg
POWER COND. RADIATOR =	1530 kg
TRANSMISSION BUS & STR =	345 kg
MAIN RADIATOR =	12000 kg
TOTAL SYSTEM WEIGHT =	31090 kg

* POWER CONDITIONER *		
P. C. EFFICIENCY =	94 %	** INPUT
FRACTIONAL VOLTAGE LOSS =	2 %	** INPUT
P. C. SPECIFIC WEIGHT =	.3 kg/kWe	** INPUT
TFE OUTPUT VOLTAGE =	19.1 volts	
P. C. & TRANSMISSION LOSS =	.82 MW	
P. C. RADIATOR AREA =	255 sq m	
P. C. RADIATOR EMISSIVITY =	.85	** INPUT
P. C. DIAMETER =	.967 m	
LOW VOLTAGE BUS LENGTH =	2.73 m	
TRANSMISSION BUSS VOLTAGE =	500 v	** INPUT
TRANS. BUSS VOLTAGE LOSS =	5 %	** INPUT

* SHIELDING PARAMETERS *		
NEUTRON FLUENCE LIMIT =	1.E+13 ntrns/sqcm	** INPUT
GAMMA FLUENCE LIMIT =	5 E+5 Rad-Si	** INPUT

TABLE 6.2.8 (cont'd)

```
NEUTRON SHIELD THICKNESS =    65 cm
NEUTRON SHIELD WEIGHT =       950 kg
GAMMA SHIELD THICKNESS =      8.59 cm
GAMMA SHIELD WEIGHT =         589 kg
SHADOW SHIELD WEIGHT =        1860 kg  with DIAMETER =  1.87 m
SCATTER SHIELD THICKNESS =    43.5 cm
SCATTER SHIELD WEIGHT =       424 kg  with DIAMETER =  1.3 m

          * RADIATOR PARAMETERS *
REJECT HEAT =                 33.43 MW at  990 K
RADIATOR EMISSIVITY =         .85                 ** INPUT
RADIATOR AREA =               832 sq m
STARTING DIAMETER =           3.67 m
END DIAMETER =                4.5 m               ** INPUT
RADIATOR LENGTH =             41.7 m
NUMBER OF SEGMENTS =          3
MINIMUM TEMP FOR SODIUM =     1100 K              ** INPUT

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TABLE 6.2.8 (cont'd)

REFERENCES

[4] Robert E. Corbett, et al., "High Voltage, High Power (HVHP) Solar Power System", Interim report for Aero Propulsion Laboratories, AFWAL-TR-81-2103 (October, 1981)

[5] Bolling Aerospace, private communication (December 1982).

[6] "Radiation Resistance of HEXFET's "HEXFET Data Book, International Rectifier Publishers, Ed Segundo, California (1982-1983).

7.0 SUMMARY OF DEVELOPMENT REQUIREMENTS AND A PRELIMINARY DEVELOPMENT PLAN

7.1 POWER SYSTEM DEVELOPMENT

All of the systems identified in this study, ranging from the most promising and attractive to the least, have significant technology uncertainties. These uncertainties must be addressed through a directed, limited scope technology development and readiness demonstration program, prior to any large commitment of resources to build and demonstrate a 5 to 10 MWe, 5 year endurance, space qualified system. Most of these technology requirements have been presented in the component and system discussions of the previous sections of this report. In this section the technology development requirements are summarized and grouped according to the areas common to, and specific to, the two most promising system concepts--the potassium Rankine and the incore thermionic. The technology development requirement areas associated with the two backup concepts--Brayton and Stirling are also presented.

All of the systems are complex and involve technologies which are just emerging or for which the feasibility of some of the key components and/or materials still remains to be demonstrated. Based on the experience of the earlier space reactor program and recognizing the length of time required to plan, implement, demonstration test, iterate, and ground test any space nuclear power system, SPI recommends that an orderly approach to the development of an MCNSPS should include a 5 year technology readiness program prior to committing to a specific power system concept. During this 5 year period, the primary goals would be to:

- Resolve all critical technological issues which could impact concept feasibility or seriously compromise system performance or safety;

- Develop and refine mission power profile requirements and the probable launch vehicle constraints;

- Establish the governmental and corporate infrastructures and working relationships which will be necessary to fund, direct, evaluate and manage the development of the technologies, components, materials supply, and the scientific, engineering, and testing capabilities required;

- Pursue and/or support a technologically related, but smaller and less complex space nuclear power system program which has the potential for leading to an early flight demonstration. Such a program would not only assist in the establishment of an industrial infrastructure for the fabrication, qualification, and operation of space nuclear systems, but would also build confidence in, and acceptance for, the nuclear power option.

- Establish a clear definition of the system(s) which will best meet the anticipated applications' requirements and have the greatest flexibility to accommodate new constraints or performance needs.

- Establish program planning and funding intention for the concept-specific development of the MCNSPS, a project which can reasonably be anticipated to require 10 years or more for development to flight prototype.

The following critical technologies, common to several of the possible MCNSPS concepts and specifically to both the potassium Rankine and in-core thermionic systems, should be pursued during the initial 5 year technology readiness period:

- The development of uranium nitride and oxide nuclear fuels capable of achieving high burnup at high surface temperature with low cladding distortion;

- The general development of refractory metals for high temperature, alkali metal environments;

- The general development of ceramics and high temperature insulators;

- The development of control drums, bearings and associated hardware capable of high temperature (900 to 1000 K) operation;

- The demonstration of an acceptable method for starting up reactors containing frozen alkali metal coolants;

- The development of processes for fabricating borated zirconium hydride and lithium hydride in custom shapes for shields;

- The development of the enabling technologies for high temperature molybdenum, large (15 cm) and long (18 meters) cylindrical potassium heat pipes, capable of waste heat loads of up to 1 MWt at 1050 K;

- The demonstration of telescoping heat pipe radiators, addressing in particular the startup and control aspects;

- The development of high temperature (500 K) and high voltage (1000 volts) power transmission and electronics capabilities.

As funding allows or concept selection requirements dictate, the following additional critical technologies for the potassium Rankine and thermionic systems need to be pursued as early as possible:

Potassium Rankine

- The development of refractory metals capable of containing alkali metals at 1500 to 1600 K with a low creep behavior at pressures of 200 to 300 psia;

- The development, including startup and control, of a once through alkali metal boiler;

- The development, including startup and control, of an alkali metal turbine;

- The development of large (3500 to 4000 gpm), long life hot alkali metal electromagnetic pumps;

- A critical assessment and selection between the boiling potassium reactor and the two loop approach, and the associated technologies of the approach selected (jet pumps, zero g boiling, vapor separation, hot control drums, etc.);

- The definition and evaluation of system startup and control;

- The development of an alternator ceramic bore seal which is impervious to alkali metal vapor attack.

Thermionic

- Testing of thoria coated uranium dioxide pellets to 6 to 8% burnup, at representative emitter temperatures (1850 to 1950 K);

- Testing of low creep, high strength emitter materials, such as W-4Re-0.5HfC and silicon carbide fibre reinforced CVD tungsten, at emitter temperatures (1850 to 1950 K);

- Demonstration of the performance and endurance of small diameter (1 cm), vented, series coupled nuclear fueled thermionic cells and series connected TFE's.

- Development of relatively high voltage (30 to 50 volts) sheath insulators capable of high fast neutron fluences ($>10^{22}$nvt) at 1100 K;

- Development and demonstration of satisfactory control for large (80 to 100 cm diameter) cores;

- Development of a compact power conditioner for transforming the high current, low voltage TFE output to load requirements. The solid state devices should be capable of 400 to 500 K operation and the transformers and bus bars of 570 to 650 K;

Following the 5 year technology readiness phase, during which mission power and duration requirements are more clearly defined and launch vehicle type and availability is determined (ie STS versus advanced shuttle derived cargo boosters), the MCNSPS program would initiate a 5 year system development phase, the key elements of which include: the continuation and completion of the readiness phase activities; further refinement and demonstration of key components for the system (or systems) most appropriate to the specified or projected mission requirements; defining, designing, and constructing the necessary test facilities, including those for ground test operation and flight prototype qualification testing; and designing and fabricating the ground test and flight prototype systems.

During the next 5 year period, the primary program components would be: system integration with environmental and performance testing and operation; modification and refinement of the prototype systems; and preparation for the launch of the flight prototype.

The schedule and key milestones for this four phase program are summarized in Fig 7.1. The projected costs for the 5 year technology phase comprised of the common activities, those specific to the potassium Rankine cycle, and those specific to the thermionic concept are presented in Figs 7.2, 7.3, and 7.4, respectively. The cumulative projected costs (in constant 1984 $) are approximately $110M, $175M, and $120M, respectively. The lower cost of the activities specific to the thermionic system reflects both a more advanced state of development for that system and the fact that fuel element behavior and power conversion system performance can be proof-tested simultaneously with relatively low cost TFEs, rather than requiring full-scale system components.

Finally, if launching of a complete 10 MWe power system in a single shuttle launch vehicle becomes a governing criterion for the commitment to MCNSPS, then the development program must be changed to establish the technologies appropriate to that requirement. The only concepts with potential for meeting this requirement are the boiling sodium cooled reactor with sodium Rankine power conversion, operating in the 1800 K or higher temperature range, or an advanced thermionic reactor system which operates with emitter

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10 MWE-5 YR ENDURANCE MEGAWATT CLASS NUCLEAR SPACE POWER SYSTEM (MCWSPS)

CONCEPTUAL DEVELOPMENT SCHEDULE

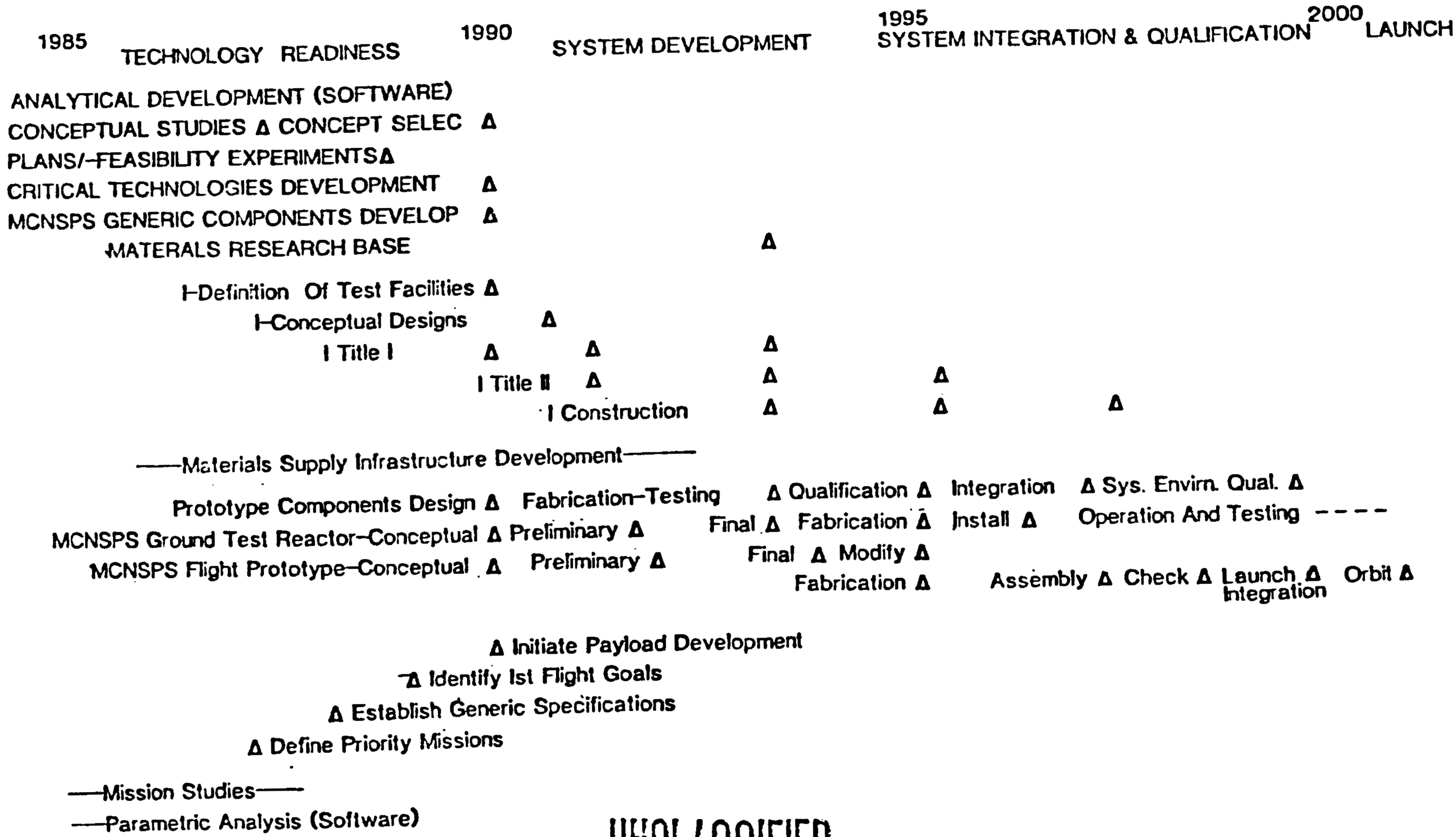

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FIG. 7.1

10MWE - 5 yr. Life MCWSPS

5 yr. Technology Readiness Costs* Common to Either (BKR-KRS) or (LITR)

	1985	1986	1987	1988	1989	1990
. Telescoping Heat Pipe Analysis & Design	.5	.8	1.2	1.4	1.6	1.8
. Vacuum Self Bonding Development	.5	.8	1.2	1.8	2.4	3.0
. MWT - 18 Meter Heat Pipe Development	.4	.8	1.2	1.8	2.4	3.0
. Large Radiator Deployment Model Demo		.6	1.0	2.0	2.2	2.4
. Frozen Lithium Reactor & Loop Startup	.4	.6	.8	1.2	1.3	1.4
. Hydride Shield Development	.2	.4	.6	.8	1.0	1.2
. Control Motor & Drive Mechanism (Bearings & Selfwelding Avoidance)	.4	.8	1.2	1.8	2.4	3.0
. Reactor Physics and Shielding Research	.3	1.0	2.0	2.0	2.0	2.0
. Reactor Control & Safety Research	.2	.8	2.0	2.0	3.0	3.0
. Refractory Metals & Ceramics Research & Development	.6	1.5	2.8	3.2	4.7	5.2
. High Temperature Electronics Research	.5	1.5	2	3	4	5
(1984 MILLION DOLLARS)	4.0	9.6	16	21	27	32

*Contractor Labor and Materials only

FIG. 7.2

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10MWE - 5 yr. Life MCWSPS

5yr. Technology Readiness Costs* BKR-KRS

	1985	1986	1987	1988	1989	1990
System Analysis & Design Studies	1.0	2.0	3.0	4.0	5.0	6.0
. Alternator Bore Seal & Alternator Development	.4	.8	1.3	1.8	2.0	2.2
. Once Thru 0g NAK Boiler-Separator	.4	1.0	1.5	1.5	1.5	1.6
. 0 Gravity Integrated Condenser-Heat Pipe	.4	1.0	1.5	1.5	1.5	1.6
. Bread Board Startup-Restart Demo's.	.4	.8	1.2	1.5	1.8	2.0
. High Temperature Solenoid Valves	1.0	2.0	3.0	3.0	3.0	3.0
. BKR Control Elements Feasibility	.6	1.2	1.8	2.0	2.2	2.4
. Power Turbine	.4	.8	2.4	3.0	3.3	3.6
. Turbo Pump	.3	.8	1.6	1.7	1.8	1.8
. NAK EM Pumps	.2	.4	.6	1.0	1.0	1.2
. Component Test Loop	.4	1.0	3.0	3.0	3.0	3.0
. BKR Critical Assembly Controls Evaluation		.8	1.5	3.0	4.0	4.0
. 1500K-250 psia Refractory Metals Development	.4	1.0	1.5	2.0	2.5	3.0
. Back-up LUNR Feasibility						
.1450-1500K Lithium Pump	.4	.8	1.2	1.5	1.8	2.1
.1600-1650K (surface) UN @ 6% B.U.	.6	.8	1.2	2.0	2.0	2.0
Frozen Startup	.4	1.5	2.0	2.5	3.0	3.5
(1984 Million Dollars)	7.5	16.7	28	35	39.4	44.6

FIG. 7.3

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10MWE - 5 YR. LIFE MCWSPS

5 YR. TECHNOLOGY READINESS COSTS* LITR

	1985	1986	1987	1988	1989	1990
SYSTEM ANALYSIS & DESIGN STUDIES	.6	1.2	1.8	2.4	3.6	4.8
• THERMIONICS RESEARCH SUPPORT	.8	1.2	1.8	2.4	3.0	3.2
• 1900-1950K EMITTER DEVELOPMENTS	.6	1.0	1.6	2.0	2.0	2.0
• 1100K HIGH FLUENCE SHEATH INSULATORS	.6	1.0	1.4	1.8	2.0	2.0
• INTEGRATED TFE FABRICATION DEVELOP.	.4	.8	1.6	2.0	2.4	3.0
• ThO_2 COATED UO_2 FUEL DEVELOPMENT	.4	.8	1.0	1.2	1.2	1.2
• INPILE TESTING FUELS & MATERIALS	.8	1.6	3.0	3.6	4.0	5.0
• CRITICAL ASSEMBLY REACTOR CONTROLS EVALUATION		.8	1.5	3.0	4.0	4.0
• VOLTAGE STEP POWER CONDITIONER	.4	.8	1.6	2.0	2.2	2.4
• 1050K LI EM PUMP DEVELOPMENT	.2	.6	1.2	1.4	1.6	1.8
• 1100K NB-1ZR-.1C LOOP DEVELOPMENT	.2	1.2	1.5	2.2	3	3.6
1984 MILLION DOLLARS	5.0	11	18	24	29	33

*Contractor Labor and materials costs only

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FIG. 7.4

temperatures upwards of 2100 K, and which has advanced emitter surfaces (both for emission characteristics and for high temperature, long duration strength) and higher temperature, higher voltage capability sheath insulators. These are the only two systems with any possible potential for fulfilling a single shuttle launch requirement, and there is little likelyhood that either could be developed to achieve more than one year of full power endurance.

The realization of either of these advanced concepts would represent a significant departure from present or near-term projected state-of-the-art, and their development program schedule and costs would reflect this longer and more expensive program developments. Because these systems do represent such a large departure from present technologies, commitment to their development would be a high risk, expensive undertaking. A more rational approach is to proceed to these advanced systems through the evolutionary process of starting with a system concept at lower power and endurance requirements, which may not have optimized performance or minimum launch requirements, but which does have a high probability for realization.

If a truely comprehensive MCNSPS program is pursued, backup technologies to the potassium Rankine and thermionic concepts may be desired. The two concepts recommended as backup are the gas cooled reactor coupled with a Brayton gas turbine and the Stirling engine system coupled with the lithium cooled, uranium nitride reactor. The critical feasibility issues for each of these approaches are:

<u>Gas Cooled Reactors With Brayton Gas Turbine</u>

- Stability of fuel elements operating with 2000 K cladding temperature.
- Consequences of refractory metals off-gassing impurities into the working fluid (He-Xe) transport system.
- High Pressure (1000 psia), 1800 K gas double wall containment.
- 1800 K high speed ceramic turbine development
- Resolution of large radiator requirement below feasible heat pipe transport temperatures. Requires multiple shuttle loads of radiator per 10 MWe generating plant.
- Assembly of radiator and welding of piping in space.

Lithium Cooled Uranium Nitride Reactor With Free Piston Stirling Engine System

- o Helium containment in no creep cylinder operating at 1000 to 6000 psia and 1400 to 1500 K.
- o High frequency, low mass piston-alternators operating at 240 to 400 Hz.
- o Protection of ceramic cylinder from hot lithium while accomplishing high heat transfer rate through cylinder.
- o Development of a lithium pump capable of operation at 1500 K.
- o Design and assembly of compact radiator and welding of piping in space.

In the following section, the key activities adjunct to the development of the power system are identified.

7.2 ADJUNCT ACTIVITIES

7.2.1 Mission Conceptual Studies

Applications Engineering

Studies are required to ascertain system requirements and performance specifications. These studies include determination of power levels, duty cycles (i.e. pulse heights and durations), voltages, frequencies, total endurance, dormancy status, system maintenance, and shielding, safety, survivability and reliability requirements. The studies must also determine the development, production, operating lifecycle and ultimate disposal costs and relate these to anticipated benefits of application. The studies would be expected to include applications such as:

- o Space based radar - all weather continuous
  - Sea Surveilance and traffic control
  - Air traffic surveilance and control
  - Military ground traffic movement
  - Strategic surveilance and early warning
  - Bi-Static tactical air combat fire control

- Communications
  - GEO-World wide personal mobile communications
  - GEO-Commercial high data rate communication
  - GEO-Commercial TV broadcast to mobile antenna
  - Laser to submarine high data rate communication
  - Strategic BMC^3

- DEW-KEW capabilities with energy storage
  - ASAT & DESAT
  - Mid-course ballistic missile intercept

- Electric Propulsion
  - Low Isp: 100 to 2000 seconds
    1. LEO rendezvous and assembly orbit to operational orbit and GEO transfers.
    2. Tactical change of orbit for strategic assets.
    3. LUNAR Transfers.
  - High Isp: 10,000 to 20,000 seconds
    1. Interplanetary travel.
    2. LEO station keeping.

- Lunar Base Support

Payload Integration Design Studies

These studies are based upon applications requirements and must be conducted in order to validate application potential, to ascertain development requirements, and to determine potential performance adequacy and costs. These design studies will also serve to identify commonality of components to maximize applicability of development. The studies must be updated as technology development progresses and should evolve into preliminary designs, detailed development plans and project implementation.

7.2.2 Launch Vehicles and OTV

1. Large Boosters

Large boosters may be a necessary component for the application of long endurance 10 MWe space power systems. Booster requirements specification must await the results of further applications studies and national commitment. This study indicates that application of 10 MWe space power systems would be enhanced with the availability of greater diameter (9 meters), 100,000 to 200,000 kg launch to LEO (Saturn V) class boosters. Such boosters could launch 10 MWe power systems, fully integrated with their payloads, to operational orbits or at least to 350 to 400 km for safe deployment and initiation of nuclear electric propulsion (NEP) transfer to higher altitudes and/or inclination operational orbits.

2. The STS Shuttle

The STS Shuttle is capable of transporting 3 to 5 MWe long life, fully assembled power systems to LEO for radiator deployment, and for power system rendezvous with the payload and spacecraft. The shuttle could also carry a 10 MWe system to LEO in 2 trips. The radiator would be a load separate from the power system. Power conditioning and bus bars would go up with part of the payload or space craft. The assembly in LEO would be minimal but possibly difficult, because very large masses must be fitted together. Use of the telescoping radiator facilitates this assembly process, since the radiator actually slips over the entire power unit and no welding or pipe joining is required. The system assembly will probably require manned supervision, however. The assembly must take place in a man-safe orbit of low inclination and below about 400 km. The system should be deployed, checked out, operated, tested and flown by NEP to the operating orbit in the deployed configuration.

7.2.3 Miscellaneous Observations

- Spacecraft electronic payloads with 5 to 10 MWe requirements will have radiators exceeding the power plant radiators in size.
- A new approach to electronic and payload design is required. Temperature and radiation sensitive components must be compacted for shielding and thermally isolated from components capable of high temperature and exposure.
- Payloads must be capable of environmental temperatures from 400 to 500 K or more.
- Transfer to operational orbits, repositioning and attack avoidance require up to 0.5g maneuverability in the deployed configuration.
- Nuclear electric propulsion (Isp = 1000 to 2000 sec) appears to be an attractive adjunct development to MCNSPS.
- The large size and cost of MCNSPS class spacecraft, the mission importance and the high payload temperatures will dictate both planned and unplanned maintenance.
- High altitudes and high inclinations of likely MCNSPS spacecraft orbits will present increased natural radiation environments.
- Increased payload operating temperatures and radiation levels will place unprecedented emphasis upon teleoperator robotics for operation and maintenance of the spacecraft, with manned presence likely being limited to brief visitations.

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16. Abstract

This study was conducted in 1984 under the direction of the NASA Lewis Research Center, for the Triagency (DARPA, NASA, DOE) SP-100 program office. The objective was to determine which reactor, conversion and radiator technologies would best fulfill future Megawatt Class Nuclear Space Power System Requirements. Specifically, the requirement was 10 megawatts for 5 years of full power operation and 10 years system life on orbit. A variety of liquid metal and gas cooled reactors, static and dynamic conversion systems, and passive and dynamic radiators were considered. Four concepts were selected for more detailed study. Namely:

1) A gas cooled reactor with closed cycle Brayton turbine-alternator conversion with heat pipe and pumped tube-fin heat rejection.
2) A Lithium cooled reactor with a free piston Stirling engine-linear alternator and a pumped tube-fin radiator.
3) A Lithium cooled reactor with a Potassium Rankine turbine-alternator and heat pipe radiator.
4) A Lithium cooled incore thermionic static conversion reactor with a heat pipe radiator.

The systems recommended for further development to meet a 10 megawatt long life requirement are the Lithium cooled reactor with the K-Rankine conversion and heat pipe radiator, and the Lithium cooled incore thermionic reactor with heat pipe radiator.

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