CONF-840113--4

LIQUID METAL HEAT TRANSFER ISSUES

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CONF-840113--4

DE84 005539

Prepared for publicaton in
SPACE NUCLEAR POWER SYSTEMS
proceedings of
First Symposium on Space Nuclear Power Systems
Albuquerque, New Mexico
January 11-13, 1983

*Operated by Union Carbide Corporation under contract W-7405-eng-26 with the U.S. Department of Energy.

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ABSTRACT

An alkali liquid metal cooled nuclear reactor coupled with an alkali metal Rankine cycle provides a practicable option for space systems/missions requiring power in the 1 to 100 MW(e) range. Thermal issues relative to the use of alkali liquid metals for this purpose are identifed as these result from the nature of the alkali metal fluid itself, from uncertainties in the available heat transfer correlations, and from design and performance requirements for system components operating in the earth orbital microgravity environment. It is noted that, while these issues require further attention to achieve optimum system performance, none are of such magnitude as to invalidate this particular space power concept.

INTRODUCTION

An alkali metal cooled nuclear reactor coupled with an alkali metal Rankine cycle provides an option for achieving desired multimegawatt (electric) power levels for space systems [Jones, MacPherson, and Nichols (1983)]. Proposals have generally linked a potassium boiling/condensing thermodynamic cycle for power conversion with either (1) a single-phase liquid (lithium) cooled nuclear energy supply through an intermediate heat exchanger or (2) a boiling potassium cooled reactor through an efficient liquid-vapor separator. Both concepts were studied extensively in the 1950-1965 period, with the conclusion by the

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Oak Ridge National Laboratory based on extensive analysis and experimentation that the latter (or direct cycle) offered high reliability in a system that was simple and of low specific weight [Fraas (1967)]. Among the factors examined in detail during this period were the thermal characteristics of the alkali liquid metals (thermophysical and thermodynamic properties: heat, mass, and momentum transfer).

In the sections following, this paper describes some of the thermal issues affecting design and performance of the liquid metal system deriving from the physical and chemical nature of alkali liquid metals, discusses existing uncertainties in current heat transfer correlations, and considers the consequence of the microgravity environment on system thermal hydraulics. It should be noted at this point that, while the issues raised regarding the use of alkali metals in power generator and conversion systems are relevent to the development of these systems, none are of such magnitude as to negate the concept. There is need, in some instances, to refine understanding of thermal-hydraulic transport phenomena identified in the earlier work and, in a different aspect, to verify and improve correlations needed for system design and optimization.

ALKALI METAL COOLANT CHARACTERISTICS

The alkali liquid metals attracted early attention as coolants for nuclear reactors because of their excellent heat transfer characteristics. In addition, the capability of operation at high liquid temperatures with low system pressures occasions improved thermal efficiencies while reducing cost/weight penalties associated with use of lower boiling temperature fluids. Pertinent properties for several of the alkali metals of interest in space power application are compared in Table 1. Note particularly the wide liquid range,

Table 1. Alkali Liquid Metal Thermal Parameters

Fluid	Melting Temperature (°C)	Atmospheric Boiling Temperature (°C)	Liquid Thermal Conductivity (at saturation) (W/m.C)
Li	179	1317	45.8
Na	98	883	52.1
NaK (56)	19	826	19.4
K	64	760	31.3
Cs	28	669	18.5

which enables flexibility in cooling design and adds an element of safety (through the high boiling temperature). Being elemental materials, further significant advantage accrues to the alkali liquid metals through their thermal decomposition resistance. However, the alkali metals are, as a class, very reactive chemically, combining energetically with many other materials. Of particular consequence are their flammability in the presence of oxygen and water (liquid or vapor) that dictates care in ground handling for space power systems and less violent reactions giving rise to contamination affecting thermal performance. Isotope activation can be a disadvantage to the extent that shield weights are affected; however, separation to remove the offending isotope will generally minimize this problem. The discussion in the following paragraphs deals with uncertainties that can be ascribed to the chemical reactivity of the alkali metals.

Oxide Effects. A dominant early observation in the study of alkali metal heat transfer was the highly erratic nature of the results. While much was known by the chemist working principally in vitro, the engineer was much less experienced and encountered numerous problems. Thus, the pioneering study by Untermeyer (1949) was victimized by the dissolution of the iron heat transfer test system by the flowing liquid metal, giving data that when correlated in standard form varied with time. Another major problem was the presence of oxide and nitride contaminants associated with poorly understood handling procedures and apparatus design. Results of some exploratory tests [Borishanskii, Zablatskaya, and Ivashchenko (1961)] are shown in Fig. 1, where a plot of the reciprocal of the Nusselt modulus against the Peclet modulus clearly shows the effect of oxide contamination measured in ppm of O_2. A second illustration of the sensitivity of heat transfer to surface contamination is shown in Fig. 2, where data obtained at ORNL during startup of a small lithium forced-convection loop are compared; the sequence of events pictured was as follows:

- Curve 1 - results with initial charge of lithium to system
- Curve 2 - results after dump of initial charge and introduction of a fresh purified charge
- Curve 3 - results after dump of second charge to sump and recharge into system
- Curve 4 - results after some _in situ_ repurification
- Curve 5 (single data point) - results after 2nd dump to sump and recharge into system

While termination of the program funding for this latter study prevented quantification of the results, the data do show that relatively minor amounts of surface contamination by lithium oxides (and possibly nitrides) can cause substantial changes in the heat transfer (a factor of perhaps 2 in Nusselt modulus). Means for obtaining and maintaining system coolant purity need demonstration.

Surface Wetting. In a corollary aspect, the high chemical activity of the alkali metals promotes surface wetting (through reaction to eliminate surface metallic oxides, adsorbed gases, and residual oils/greases). For single-phase heat transfer, this is of some consequence in that data with mercury on wetted surfaces [Friedland (1961)] indicate that heat transfer is not affected by entrained inert gases; while with the surface unwetted, the inert gas blanketing the surface reduces heat transfer by as much as 30%.

Of much greater significance is the effect of surface wetting on two-phase heat transfer. An instructive analysis by Krakoviak (1963) showed that the superheat (wall to saturated fluid temperature difference) required to initiate boiling on a surface was inversely proportional to the radius of the available nucleating cavities. Due to the "cleaning" capability of the alkali liquid metals, as noted above, the population of operable cavities is skewed to the small sizes. As a first approximation, the wall superheat requirement for boiling of the alkali metals can be determined through comparison with data for water, thus circumventing the need to know r_c, the critical cavity radius. Using as a base T_{sat} = 17 °C for water boiling on a commercial metallic surface (a normal cavity distribution) and T_{sat} = 50 °C for boiling on a polished and degreased glass surface (nucleating sites skewed to small sizes) estimated superheats for alkali metals boiling are as given in Table 2.

Table 2. Wall Superheat Estimates for Boiling of Alkali Liquid Metals

Fluid	Superheat for Boiling Initiation (°C) Normal Surface	Superheat for Boiling Initiation (°C) Polished Surface
Water	17	50
Sodium	144	433
Potassium	69	208
Rubidium	56	167
Cesium	39	117

Experimental studies [Hoffman and Krakoviak (1964)] with potassium boiling at high surface heat flux in a vertical stainless steel tube showed the high amplitude surface temperature oscillations predicted by analysis. Extended analysis and further experimentation on surfaces containing artificial cavities [Edwards and Hoffman (1965)] provided quantitative confirmation. Data obtained by these latter investigators for potassium in forced convection boiling on a surface containing reentrant cavities of 2.5 x 10^{-5} cm radius are shown in Fig. 3 (upper data set); note that, in addition to excellent agreement with theory, superheats of the order of 280°C were sustained. Since the radial temperature profile for liquid metals in forced flow is relatively flat, the energy stored in the flow is high; and vaporization on nucleation is very rapid. The associated pressure pulse is intense, and extended operation in this mode could lead to system damage. Means for nucleating at lower wall superheats have been tested, but need demonstration in the microgravity environment of earth orbit.

LIQUID METAL HEAT TRANSFER

Liquid metal heat transfer is described in Fig. 4 in terms of the dependence of the Nusselt modulus on the Peclet modulus (Reynolds-Prandtl product); the limiting cases of constant wall heat flux and constant wall temperature heat transfer in circular tube geometry as derived from theory [Martinelli (1947), Lyon (1951)]are given. Compared with theory are three data sets typical of those obtained in experimental studies on heat transfer with alkali metals in forced convection flow through circular tubes. A generally accepted empirical correlation is also shown [Lubarsky and Kaufman (1956)]. While some of the observed discrepancy between data and theory can be ascribed to the anomolous characteristics of alkali liquid metals discussed in the previous section,

Fig. 4 illustrates the uncertainty that exists in respect to optimizing the design of space nuclear heat exchange systems where weight/volume considerations are paramount. These uncertainties extend into the realm of rod bundle heat transfer, where only limited experimental confirmation of theory exists.

The energy conservation equation for liquid metal heat transfer simplifies to the form:

$$N_{Nu} = A + B\left(\frac{\varepsilon_H}{\varepsilon_M} N_{Pe}\right)^C,$$

where, N_{Nu} = Nusselt modulus and N_{Pe} = Peclet modulus.

The eddy diffusity ratio, $\varepsilon_H/\varepsilon_M$ (thermal/molecular), is generally assumed to be unity. The constants A, B, and C have been developed both theoretically and extracted from experimental data; an abridged listing for several geometries is given in Table 3. Note that these correlations result from substantive

Table 3. Constants for Use in Equation 1

Geometry	Boundary Condition	A	B	C
Tubes	Constant Wall Flux	7.0	0.025	0.8
	Constant Wall Temperatures	5.0	0.025	0.8
	Empirical		0.625	0.4
Parallel Plates	Constant Wall Flux	5.8	0.020	0.8
Rod Bundle	Parallel Flow	a	0.0155	0.86
	Empirical		b	0.45

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[a] $A = 6.66 + 3.126 \left(\frac{P}{D}\right) + 1.184 \left(\frac{P}{D}\right)^2$ for rod pitch (P) to diameter (D) ratios >1.35

[b] $B = 0.58 \left(\frac{D_e}{D}\right)^{0.55}$, where D_e = bundle equivalent diameter.

simplification of the general energy equation; thus, it has been assumed in obtaining Eqn. 1 that:

- flow is incompressible and plug-type
- properties are not temperature dependent
- there are no volumetric heat sources
- turbulent thermal diffusion is represented by the molecular law
- axial thermal diffusion is neglected
- the geometry is symmetrical

An examination of several of these assumptions provides an indication of the state of uncertainty associated with the use of the theoretically derived heat transfer correlations.

Axial Diffusion. For $N_{Pe} \sim 10$, the error in N_{Nu} is estimated to be about 5%; for $N_{Pe} > 100$, this error reduces to about 1%.

Eddy Diffusivity Ratio. From experimental measurements, the eddy diffusivity ratio in Eqn. 1 can be described by:

$$\frac{\varepsilon_H}{\varepsilon_M} = 0.0046 \left(\frac{N_{Pe}}{N_{Pr}} \right)^{0.46} ,$$

where N_{Pr} = Prandtl modulus.

Evaluation for several values of the Peclet modulus indicates $\varepsilon_H/\varepsilon_m$ to vary from 0.32 at $N_{Pe} = 50$ to 1.26 at $N_{Pe} = 1000$.

Plug Flow. The ratio of the Nusselt modulus for fully developed flow to that for plug flow (K^+) if estimated to be:

	K^+	
Geometry	$N_{Pe} = 1000$	$N_{Pe} = 50$
Parallel Plates	1.80	1.04
Circular Tube	1.66	0.94

SYSTEM THERMAL HYDRAULICS

Several liquid metal Rankine cycle options are available which trade off thermal and hydraulic stability problems against system complexity and reliability; four are shown in Fig. 5. The mechanically simplest incorporates a liquid metal boiling reactor and a direct condensing radiator (single loop system); the most complex, a liquid cooled reactor with separate boiler and a tapered tube condenser with separate liquid cooled radiator circuit (3 loop system). It has been estimated that a 20% increase in mechanical reliability and a 30% to 40% decrease in system weight can be realized by utilizing a single loop rather than a three loop system [Fraas (1966)].

Problems associated with liquid metal Rankine cycle systems generally parallel those encountered in other two phase flow applications; principally, control of the liquid-vapor interface. However, in the microgravity environment of the space application, these problems can be more acute. The paragraphs following identify these concerns for the principal system components.

Radiator/Condenser. The largest component (by weight or volume) in the space nuclear power system is the radiator or condenser/radiator. Since liquid metal cycles operate at low pressure with high sink temperatures, radiators for this system will be smaller and lighter than radiators for systems using other thermodynamic fluids. Several radiator types have been suggested: (1) direct where the working fluid condenses within the radiating surfaces, and (2) indirect where the condensing working fluid transfers its thermal load to a separate radiator circuit. The indirect radiator can be either pumped single-phase liquid loops or heat pipe arrays.

The simplest of these concepts, the direct condensing radiator (Fig. 6), utilizes reflectors at the rear surface of tapered condenser tubes to increase the effective radiator area and to act as meteoroid bumpers (thus reducing the armor requirement on the tube surface). Radiating surface temperatures very close to the liquid metal saturation temperature are possible, since temperature drops associated with condensation at the inside surface and conduction through the tube wall are both small. As noted, the attendant higher radiating surface temperature results in reduced radiator surface area and, hence, weight. Control of the two-phase-condensing liquid may be a problem, since the condenser exit must be 100% liquid in order to prevent pump cavitation. The suggested tapered tube geometry generates proper liquid film flow through a combination of surface tension and vapor velocity drag effects, mitigating microgravity effects. Limited analysis of tapered tubes [Korsmeyer (1963)] have shown encouraging results. Vulnerability to loss of the full working fluid inventory through meteor impact exists.

A variant on this concept (Fig. 5d) interposes an intermediate heat exchanger between the cycle fluid and the radiator. The power conversion cycle working fluid condenses again in tapered tubes and transfers heat to a single-phase liquid pumped loop. Some radiator circuit redundancy can be accommodated, thus avoiding catastrophic effects due to meteoroid impact. The introduction of the intermediate heat exchanger (i.e., the condenser) does result in some loss in cycle efficiency by lowering the radiating surface temperature.

A second type of indirect heat sink offers maximum protection against meteoroid impact risks by transferring the condensing heat load to the radiating surface through an array of liquid metal heat pipes (Fig. 7). The alkali metal vapor (e.g., potassium) in the Rankine power conversion cycle condensing on the inboard end of a bank of heat pipes vaporizes the heat pipe fluid (e.g., cesium), thus transporting the reject heat to the radiator surface. The large number of individual heat pipes assures that loss of some through meteoroid penetration will have little impact on overall system performance. Two-phase liquid control in this configuration may be more difficult than in the previous two concepts due to intrusion of the evaporator end of the heat pipes into the two-phase flow in the condenser channels.

A novel radiator concept has been recently proposed [Mattick (1982)] which uses hot liquid droplets as the radiator. The droplets are sprayed as a thin sheet directly into space. Since the droplets can be small (and hence, provide very large total surface area radiating to the space environment) and since the temperature drop associated with a containment surface is eliminated, significant weight savings over conventional radiators is possible. While generally associated with other thermodynamic cycles, the concept can be applied to the Rankine cycle. Thus, Fig. 8, a portion of the working fluid flow extracted upstream of the primary circulating pump would be processed through a "liquid droplet radiator." The collected cooled droplets would be used in a contained spray chamber to condense the turbine exit stream. Substantial mechanical development of the concept is needed. Flash vaporization of the liquid droplets on exposure to the vacuum environment of space may be a significant problem through loss in thermodynamic working fluid inventory; other concerns are with condensation on the cold external surfaces of the power system and/or condensed cloud formation around the space craft. Control of droplet trajectory may also be difficult, particularly under maneuvering conditions (accelerations/decelerations associated with orbital repositioning or reorientation of the system axis).

Boiler. Two conventional boiler concepts have been proposed for space power applications, both of which depend on good liquid control for operational success. The first design uses liquid-vapor separation devices at the boiler exit to extract the liquid from a relatively low quality, two-phase flow and returns the liquid to the boiler inlet; the second is a once-through boiler that evaporates the liquid to high quality in a single pass. For both configurations, nucleate boiling occurs at the heated surface (fuel rods or boiler tubes), and removal of the vapor from the surface and transport of the vapor to the boiler exit in the presence of low-gravity forces must be a concern. Incomplete knowledge with respect to alkali metal boiling inserts a degree of uncertainty into standard operating characteristics of the alkali metal power generation and conversion systems and - to an even greater extent - into any off-normal operation.

For the low quality boiler, the principal issue rests on the performance of the liquid-vapor separator in the microgravity field to assure the necessary high quality flow at the turbine inlet. This can be accomplished by a swirl flow that moves the liquid to the separator surface from which it can be extracted by flow dividers or through porous plugs. Research must address the swirl generation (strength and maintenance) necessary to achieve the required levels of liquid separation and the effects of both thermal and acceleration transients on system performance. In the thermal aspect, while data exist on the critical heat flux with boiling alkali metal and on the superheat required for bubble nucleation, refinement of this information is needed to maximize system efficiency while assuring against heat transfer surface melting or other physical damage.

In the high quality boiler, boiling is accomplished inside tubes heated by single-phase liquid cooling the nuclear core. To achieve complete evaporation within a reasonable boiler length, all liquid must remain on the heated surface. Again, swirl flow inducers are used to suppress the normal (earth surface gravity) flow regime transitions in forced convection boiling and to return any entrained liquid to the tube inside surface. Porous surface coatings using surface tension to retain the liquid are a suggested alternative.

A third boiler possibility is a flash evaporator. In this design, liquid heated to a high temperature would be flashed through nozzles to a pressure below the saturation pressure associated with that temperature. The effectiveness of this process would depend on liquid-vapor heat transfer characteristics and the degree of thermal non-equilibrium introduced into the flow. Nozzle design would be critical in respect to this latter problem and to the avoidance of nozzle erosion. Further systems analysis is needed to establish the viability of this concept.

CONCLUSIONS

Alkali liquid metals have been proposed as nuclear reactor coolant and thermodynamic cycle working fluid in space power applications because of their desirable thermophysical properties and good heat transfer characteristics. However, their high chemical reactivity can occasion degraded thermal performance:

- Oxides/nitrides formed within the liquid flow due to in-leakage of these gaseous contaminants (during ground handling/testing can deposit on cooler surfaces, increasing the resistance to heat transfer in the heat exchangers.
- Solubility of containment materials in the alkali metal coolant can lead to loss in high-temperature mechanical performance due to selective removal of alloy constituents and to flow blockage due to mass transfer (deposition) of the dissolved material into lower temperature (lower solubility) zones.
- Good wetting of metallic heat transfer surfaces by the alkali metals results in skewing of boiling cavity size distributions to the very small sizes, effecting high superheats to achieve bubble nucleation and, in consequence, the possibility of significant temperature and pressure oscillations.

In addition to these phenomenological issues embedded directly in the nature of alkali liquid metals, factors associated with liquid-vapor separation and transport (particularly in the low-gravity environment of earth orbit) and with uncertainties in heat transfer correlations (particularly in rod bundles) can affect the design and performance of the Rankine power conversion cycle.

While problems with liquid metals in Rankine cycle systems/components will generally parallel those encountered with other two-phase fluids in similar equipment, the low-gravity condition will exacerbate liquid-vapor interface control. Uncertainties as to the effect of the microgravity environment on thermal mixing within the reactor core, transient thermal and hydraulic response of the system, and surface blanketing by inert gas must also be resolved. While these issues must receive attention if optimum system performance is to be attained, all of the problems identified are amenable to solution through improvement in the understanding of the thermal mechanisms operant, refinement of correlations for heat transfer in realistic rod bundle geometries, and demonstration that the effects of the microgravity environment on system thermal, hydraulic, and mechanical behavior can be mitigated by proposed concepts.

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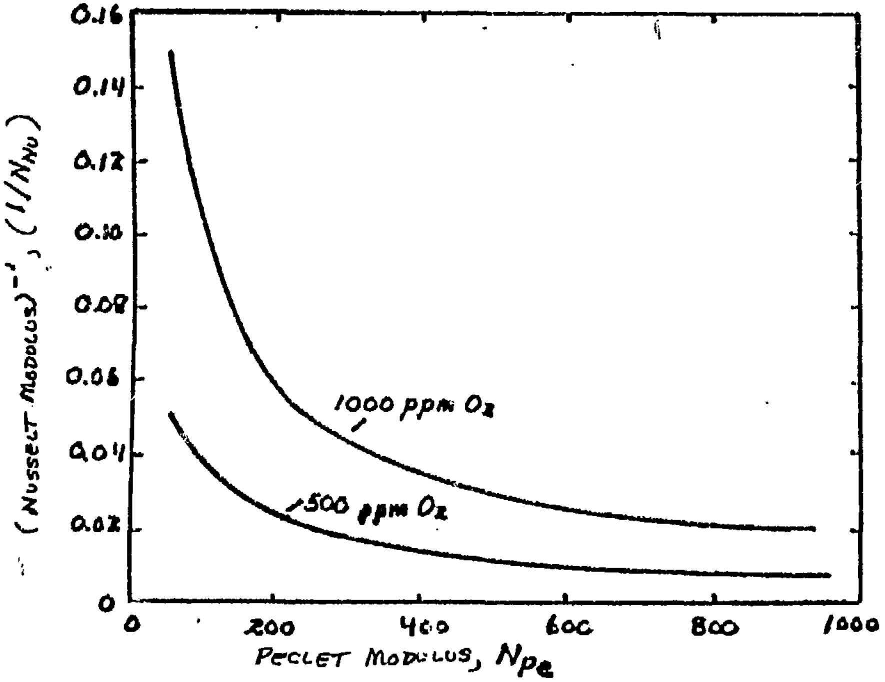
List of Figures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0.10
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0
200
400
600
800
1000
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Peclet Modulus, N_{Pe}
1000 ppm O_2
500 ppm O_2

Fig. 1

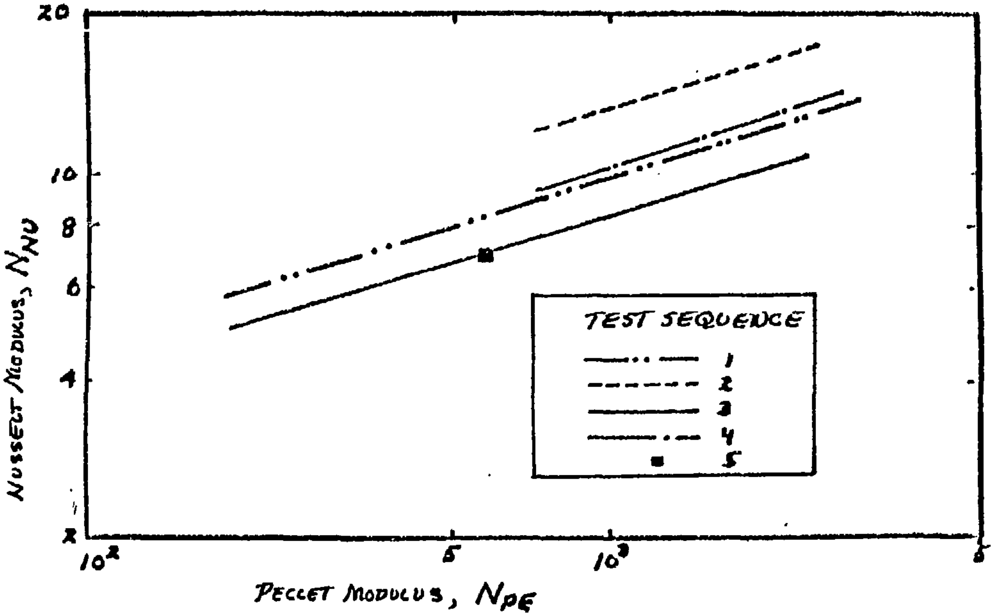
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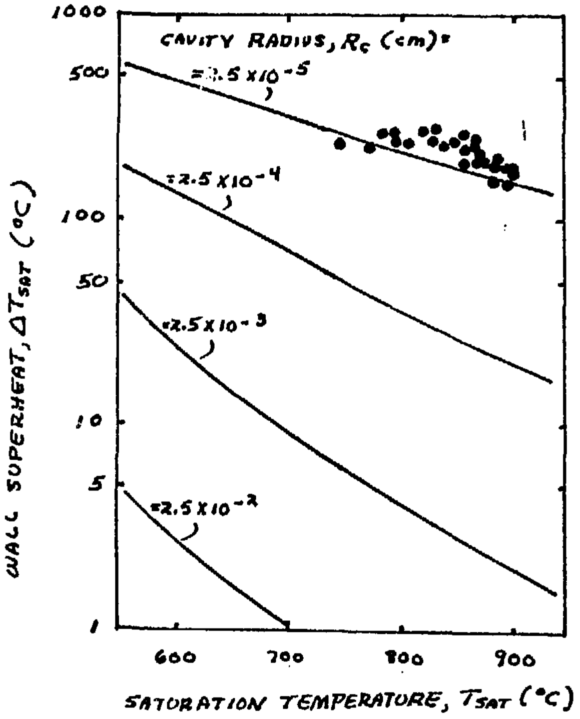
Fig. 2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100
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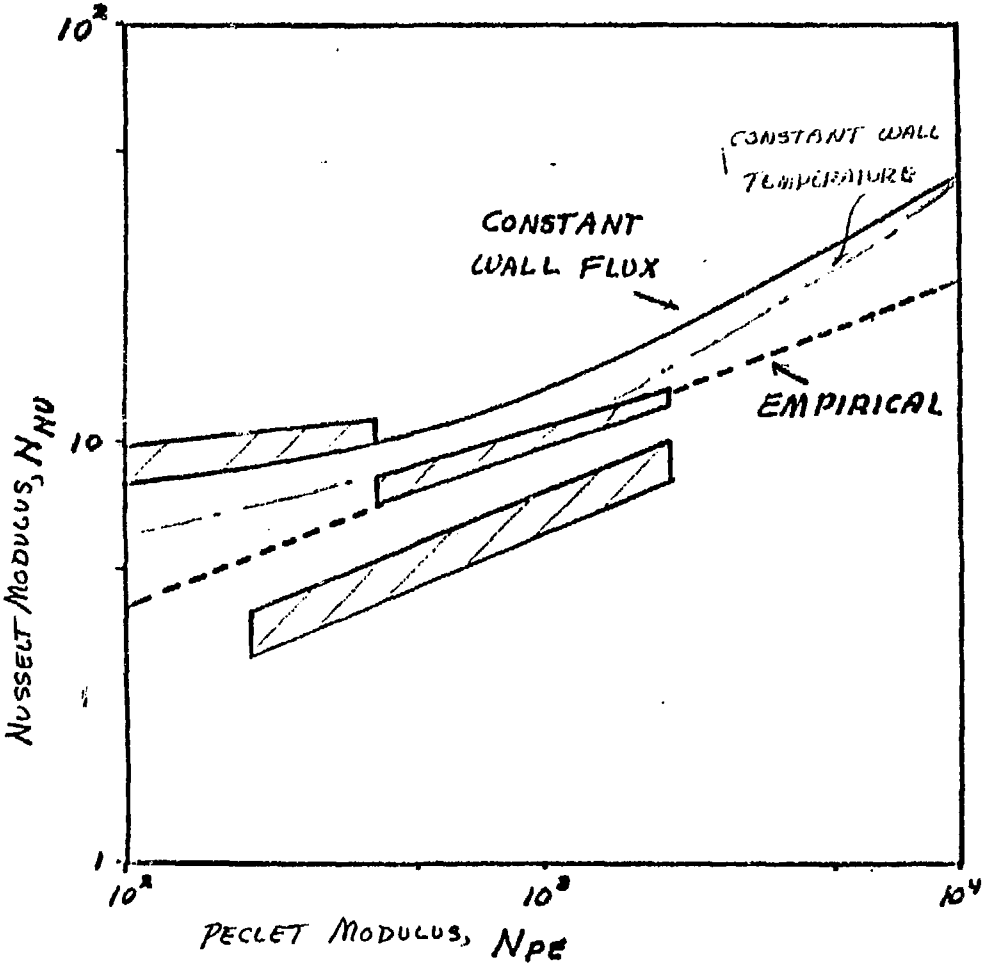
WALL SUPERHEAT, ΔT_{SAT} (°C)
SATURATION TEMPERATURE, T_{SAT} (°C)



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10^2
10^3
10^4
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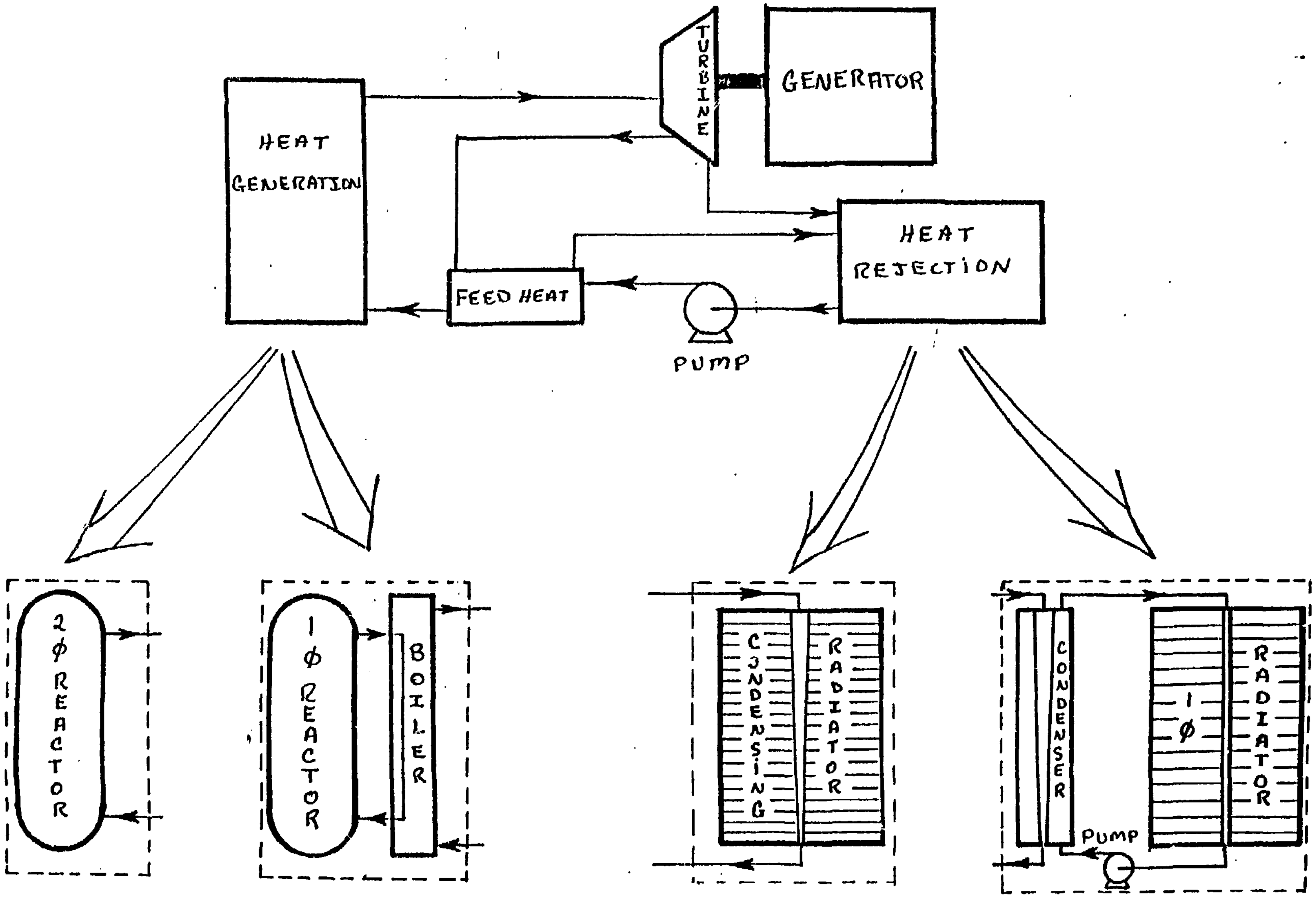
CONSTANT WALL TEMPERATURE
CONSTANT WALL FLUX
EMPIRICAL

Fig. 4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RADIATOR
CONDENSER
PUMP
1 φ
RADIATOR

Fig 5

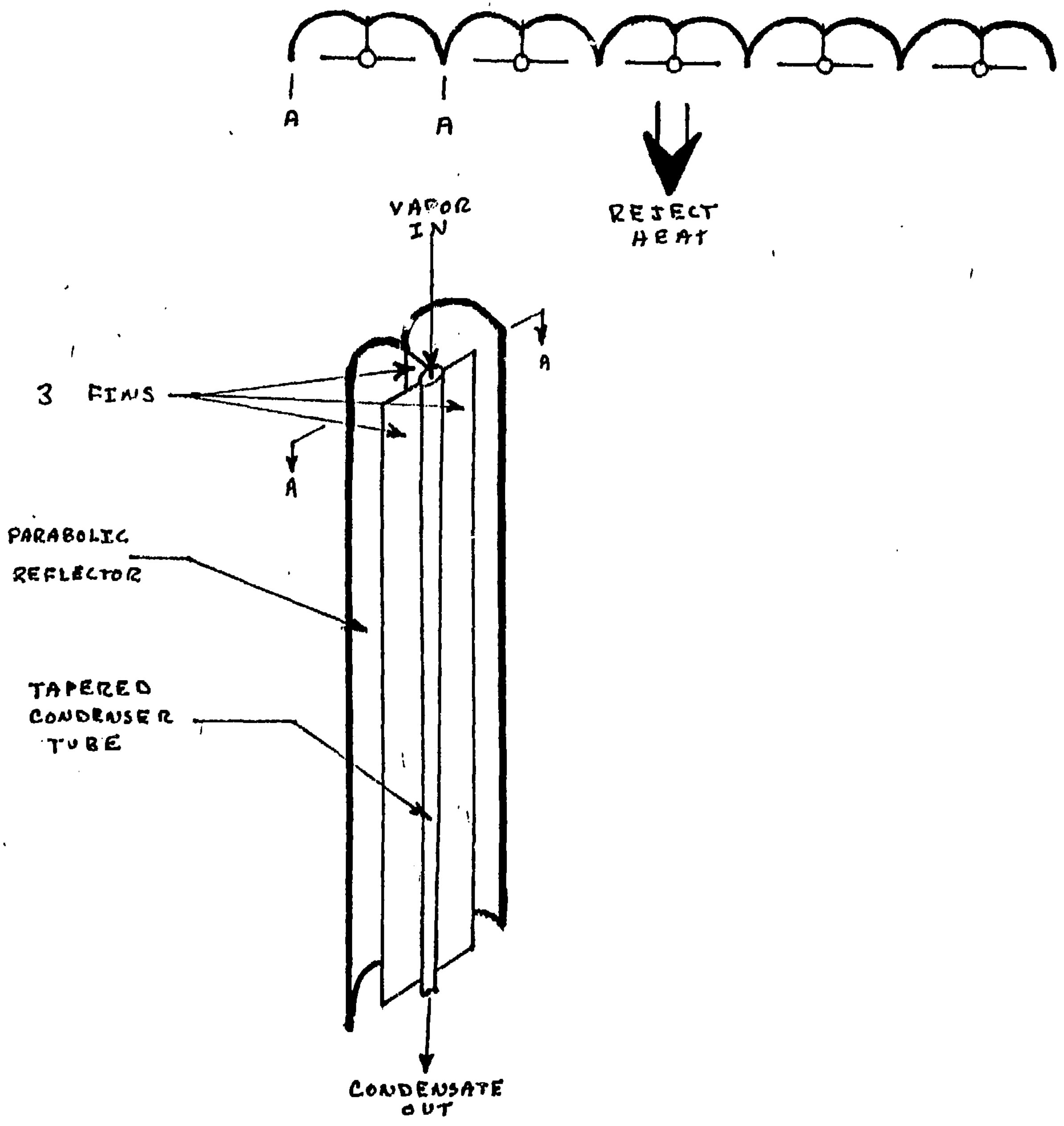
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Fig 6

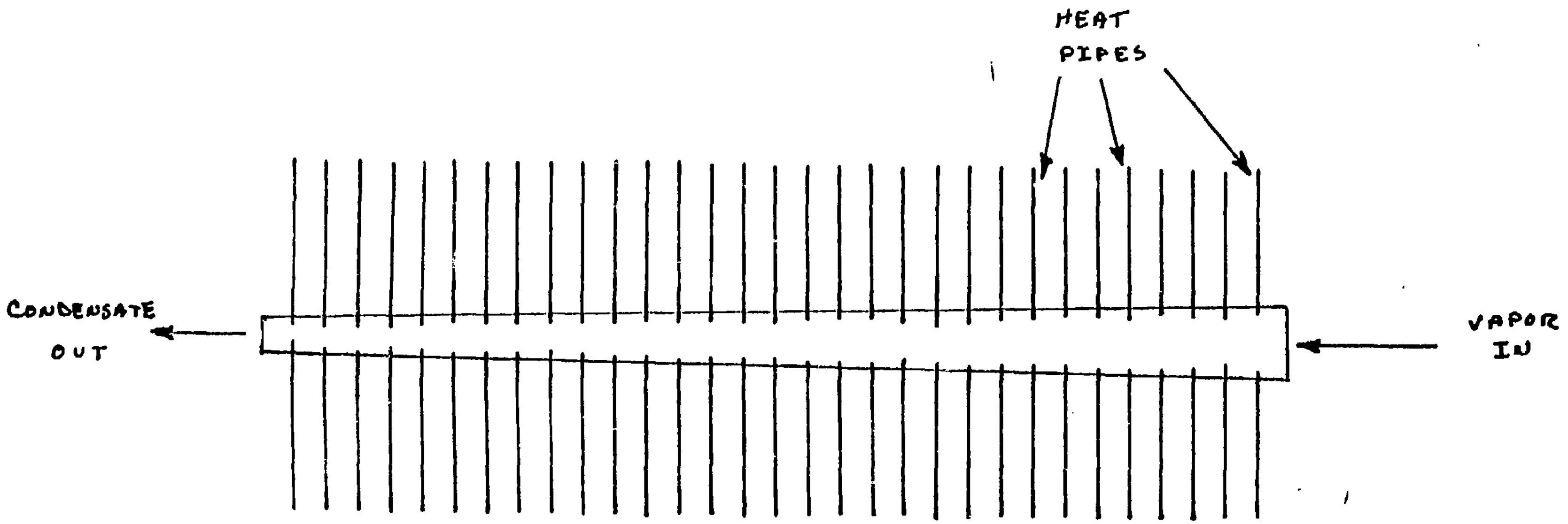

Fig 7

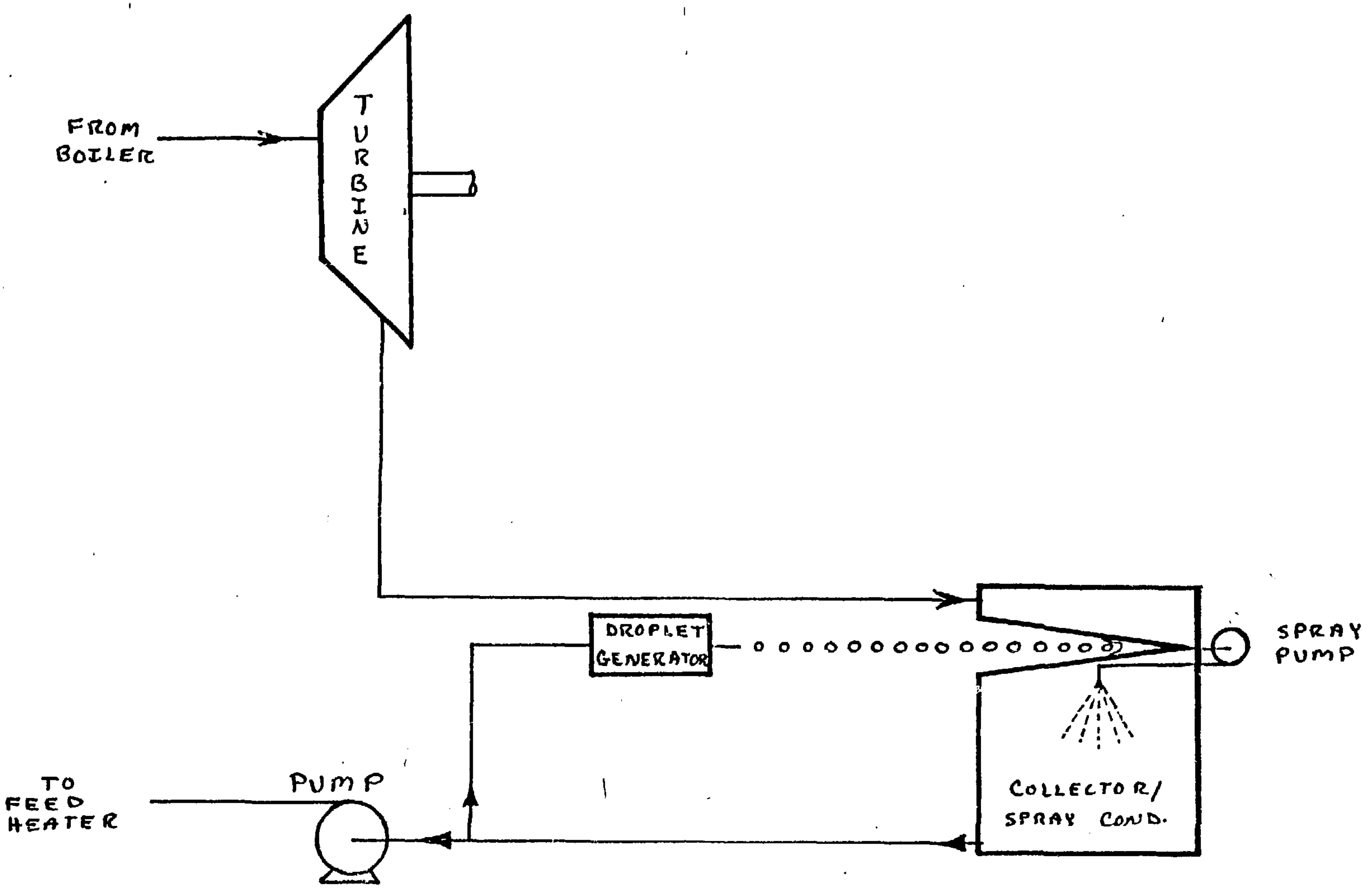
FROM BOILER
TURBINE
DROPLET GENERATOR
SPRAY PUMP
COLLECTOR/ SPRAY COND.
PUMP
TO FEED HEATER

Fig 8