DESIGN OF HIGH TEMPERATURE LIQUID METAL SYSTEMS*

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ABSTRACT

A review of over two million hours of high temperature liquid metal system operating experience gained under the Aircraft Nuclear Propulsion and Nuclear Electric Space Power Plant programs at ORNL during the past 22 years may prove helpful to those who have occasion to design high temperature liquid metal systems for other applications. The nature of the problems involved in material selection, mass transfer and corrosion, heat transfer and heat transport, limitations imposed by oxidation of external surfaces of a system, the performance characteristics of various liquid metals relative to other heat transfer media such as high pressure helium and various molten salts, thermal stress and thermal strain cycling, and problems posed by the fire hazard potential all play obviously important roles in the design of high temperature liquid metal systems. In addition, experience has shown that liquid metal systems are singularly unforgiving of small errors in design, shakedown, and operation. This in turn means that much attention must be devoted to the detail design of components to provide a high degree of leak tightness, reasonable freedom from thermal strain cycling, and a host of special problems such as self welding. This paper reviews the nature of the problems, presents a set of design precepts evolved by the writer over the past 20-odd years, and offers a selected set of references as an aid to those interested in this field.

INTRODUCTION

The high thermal conductivity and low viscosity of liquid metals made them exceptionally fine heat transfer media. However, the fire hazard obviously associated with the use of liquid alkali metals at high temperature, coupled with the frustrating difficulties that many organizations have experienced in attempting to build liquid metal systems, has made many people suspicious of their practicality. It is the writer's belief that, while liquid metal systems require a higher order of competence in their design, the most difficult problem is to get design and operating personnel to recognize the fundamental differences between high temperature liquid metal

systems and conventional water and steam systems. One would hardly think of designing a welded steel structure in the same fashion as he would design gray iron castings, yet perhaps the majority of those who have attempted to design high temperature liquid metal systems have followed essentially the same approach as they would in the design of plumbing for conventional water or steam systems. This paper is intended to highlight these differences and present a sound rationale for the designer. It is important that we do this because the high temperature liquid metal systems offer the potential for major improvements in the thermodynamic cycle efficiency of our power plants; first, by permitting the design of reactors capable of operating at high temperatures and, secondly, by opening the door to new, high temperature, thermodynamic cycles such as that offered by the potassium vapor Rankine cycle system.

Materials Compatibility

Probably the first consideration in the design of a high temperature liquid metal system is the choice of the structural material of which the system is to be built. This in turn raises a set of problems that are vital in liquid metal systems, although of relatively little importance in conventional fluid systems; namely, solution corrosion and mass transfer. Liquid metals tend to dissolve many structural metals and thus yield solution-type corrosion. The problem is greatly aggravated because the solubility of the structural metal in the liquid metal coolant differs widely with temperature.¹ Mercury, for example, tends to take nickel and chromium into solution at high temperature, whereas at lower temperatures their solubility is low. This gives a phenomenon known as mass transfer; in stainless steel systems built to handle mercury the nickel and chromium are dissolved out of the hot regions and deposited as flocculent dendritic crystals in the cold zones. For hot zone temperatures above about 900°F, the mass transferred deposit builds up to block the flow channel and render the system inoperative. This problem has proved so intractable with mercury systems that, although work began on them in 1911 in an effort to develop a mercury vapor Rankine cycle,

some 60 years later we still have no good way of building iron-chrome-nickel alloy systems that will operate well at temperatures over 900°F without difficulties with mass transfer. It is for this reason that efforts to develop the mercury vapor cycle first for stationary and recently for space power plants has proved quite disappointing in practice.

If one turns from mercury to the alkali metals, one finds that in the latter the differential solubility problem becomes highly dependent on the oxygen content of the fluid.^{2,2} Extensive experience shows, for example, that if the oxygen content of sodium or NaK can be kept down to less than a few parts per million, mass transfer in the iron-chrome-nickel alloys can be kept to a negligible level up to at least 1200°F, and, with certain qualifications, to temperatures as high as 1500 or 1600°F. This requires that an extremely high degree of leak-tightness be achieved in the operating systems. In practice, this means that the systems must be essentially hermetically sealed, and that in turn implies the kind of care in the selection of the detailed design elements that one must exercise in the design of high vacuum systems. For example, in these high temperature systems it means that virtually all joints must be welded and the welds must be of very high quality. There must be no oxide stringers either in the weld zone or in the structural walls of the system because the alkali metals have such a high affinity for oxygen that they will dissolve out oxide stringers such as those common in castings or in the centers of forgings and this may lead to leaks. This problem is so important that one should avoid the use of castings in liquid metal systems because there is no means for assuring that the integrity of the casting will be adequate.

Some indication of the character of the mass transfer problem is given by Fig. 1 which shows the solution corrosion rates for some liquid metals with typical structural materials as a function of the peak operating temperature. It should be emphasized that the mass transfer problem is very much dependent on the temperature difference within the liquid metal system, i.e., if the liquid metal stream undergoes a temperature change of only 100°F, the rate of the mass transfer will be of the order of 1/4 as great

Fig. 1. Effects of temperature on the corrosion rate for typical combinations of materials for Rankine cycle systems.

as it would be if the liquid metal temperature rise in the system were 400°F, assuming of course the same peak structural metal temperature. Another important factor is whether or not a change in phase occurs. If a boiling potassium system is employed, for example, the boiler will be the hot part of the loop and the condenser the cold portion. If a recirculating boiler is used, the liquid in the recirculating boiler will become saturated with the alloy elements in the structural material and no further solution attack will occur. The vapor leaving the boiler will, of course, be free of dissolved structural material, and, when the vapor condenses, the structural material it contacts will be at a much lower temperature so that the solution rate will be quite low. As a consequence, the solution attack of the structural material in a boiling potassium system is characterized by the solution rate at the low temperature end of the system, and what mass transfer does occur is from the cold to the hot portion of the system rather than vice versa. Curves are not shown for lithium, but the corrosion rate of iron-chrome-nickel alloys in lithium is excessive above 900°F. However, if the oxygen content of the lithium is kept below about 100 ppm, the corrosion rate of refractory metals is essentially zero at temperatures as high as 2200°F.

Air-side corrosion presents problems in high temperature liquid metal systems. The 300 series stainless steels and the high nickel alloys such as Inconel and Incoloy 600 stand up well in air up to around 1600°F. They also stand up well in combustion gases if the sulphur content of the fuel is below 0.1% and other corrosive materials in the fuel such as vanadium, alkalis, and chlorides are kept to low levels. The refractory metals, on the other hand, are quite subject to attack. Molybdenum is the least sensitive, but there is no known way to obtain ductile welds in molybdenum. Niobium is weldable, but is so sensitive to oxidation at temperatures above about 1500°F that even a few parts per million of oxygen in argon or helium will cause serious attack. It may be possible to develop a suitable coating, but to date the only truly effective approach has been to maintain a vacuum of 10^{-6} torr around the niobium.

Structural Material

As implied above, the first requirement of the structural material for a high temperature liquid metal system is that it be weldable with good ductility in the weld zone. As will be discussed later, thermal stresses and thermal strain cycling in liquid metal systems designed for high temperature application cannot be kept leak tight unless the structure has sufficient ductility to tolerate local yielding. The 300 series stainless steels and Nb-1% Zr have been found to be the best materials from the fabrication standpoint, with Haynes 25 giving less desirable but acceptable characteristics.

The next obvious requirement of the structural material is that it have adequate strength at high temperature. In point of fact, the principal consideration is not ultimate tensile strength but rather the creep and creep rupture strength. The choice of the structural material depends upon the design operating temperature and the pressure in the system. Although in principle one could design a component to have an adequate wall thickness irrespective of the strength of the structural material, in point of fact one finds that the design begins to look awkward if the wall thickness of cylindrical elements such as pipes or pressure vessels exceeds about 10% of the diameter. In pipes, for example, routine handling considerations favor a wall thickness-diameter ratio of about 10% simply to prevent denting and kinking of the pipe walls. Similar considerations apply to components such as pump casings, turbine casings, heat exchanger shells, etc. As a consequence there is little weight or cost penalty associated with a low allowable strength if the design pressure is low. For example, one can get a good idea of the suitability of any given alloy for operation in a metal vapor Rankine cycle system designed for operation at a given temperature by using a chart such as that shown in Fig. 2 which gives the ratio of the stress for 1% creep in 1000 hr to the vapor pressure of the liquid metal as a function of temperature. In general the 300 series stainless steels yield well proportioned structures for temperatures up to around 1500 or 1600°F for design pressures below 200 psia. For higher temperatures one would need to

Fig. 2. Effects of temperature on the ratio of the allowable stress to the vapor pressure in the boiler for typical combinations of materials for Rankine cycle systems.

go to materials such as Haynes 25 for operation at temperatures up to perhaps 1800°F, and a refractory alloy would be required for operation at temperatures 2000°F or higher.

Thermal Stresses and Thermal Strain Cycling

Probably the most difficult and subtle — and one might even say the most insidious — set of problems in the design of high temperature liquid metal systems are those posed by thermal stresses and thermal strain cycling. Everyone knows that a brittle material such as glass must be heated gradually and uniformly to avoid cracking. On the other hand, one can take a metal pan and give it severe thermal mistreatment without cracking — at least for a few times. However, anyone who has worked with combustion chambers for jet engines knows that the fluctuating temperatures in combustion chambers can lead to cracks. These are akin to those that one can induce if he bends a piece of wire back and forth until it breaks. A ductile metal can withstand a number of severe strain cycles, but only a limited number. In point of fact, it has been found that the degree to which a metal such as a 300 stainless steel can withstand plastic strain cycling is actually reduced if its temperature is raised to a red heat. This is certainly contrary to the hopes of those of us who first attempted to design liquid metal systems for operation at 1500°F; our worst fears were realized. Systems deliberately designed so that components were subjected to severe thermal strain cycling to see if they would break — broke. Extensive controlled tests showed that the total integrated amount of thermal strain cycling that a given material will withstand increases somewhat as one reduces the amount of strain per cycle. Figure 3 shows a curve for a typical material.⁴ The ordinate is the summation of the amount of plastic strain while the abscissa is the number of cycles. Note that the first point is for a quarter-cycle, that is, simply pulling the material until it breaks. Note that if one goes to above 100 cycles, i.e., much smaller cyclic strains, the total accumulated strain can be increased to perhaps three times that for a single quarter-cycle.

The designer of high temperature liquid metal systems must force himself to try to envision conditions that will produce thermal stresses and strains.⁵

Fig. 3. Variation of total plastic strain with cycles-to-failure.

Some typical cases are shown in Fig. 4. The first example in Fig. 4a indicates the problem posed by differential thermal expansion between the casing of a heat exchanger and the tubes. Transients in the temperature of either the shell-side or the tube-side fluid will cause the heat exchanger tube to change its length substantially relative to the shell. The accumulation of this change in length will tend to build up at the weak (i.e., hot) end and impose severe plastic strains near the tube-to-header joint if a simple shell-and-tube heat exchanger is employed, or will impose severe bending stresses in the short length of the tube where it goes into the header if a bent tube arrangement is employed. Figure 5 shows an example of this sort of problem, in this case a molten salt-to-NaK heat exchanger after extensive operation. A third example is given by a thick header sheet in which the fluid on one side of the header sheet may be at a very different temperature from that on the opposite side. This is particularly important in a heat exchanger designed to transmit heat from a liquid metal such as NaK to boiling water (see Fig. 4c). If the liquid metal is kept at a temperature of, say, 800°F and the pressure in the boiler is allowed to drop to, say, 200 psi, the saturation temperature of the water will be 382°F, and the temperature difference across the header sheet will be of the order of 400°F because the liquid water in the boiler will be at the saturation temperature and the boiling heat transfer coefficient at the

(a) Hockey-stick heat exchanger

(b) Thermal sleeve for vessel penetration

(c) Simple shell-and-tube heat exchanger used as a sodium-to-water boiler

(d) Support skirt for a pressure vessel

Fig. 4. Typical geometries likely to give difficulty with thermal stresses and thermal strain cycling.

Fig. 5. Header sheet region of a salt-to-NaK heat exchanger damaged by repeated cycles of differential thermal expansion between the tubes and the casing. One tube cracked and leaked about 0.6 in. from the header sheet.

header sheet-water interface will be extremely high as will the heat transfer coefficient at the liquid metal-header sheet interface. Thus, the two faces of the header sheet will be at widely different temperatures and severe thermal stresses will result. Similarly, the juncture of pipe carrying a hot liquid with a pressure vessel or tank can lead to large local stresses in the vicinity of the juncture. These can be relieved through the use of a thermal sleeve as indicated in Fig. 4b. Again, any attempts to support a component whose casing will be at a high temperature poses serious problems. A typical example is a vessel mounted on a skirt as in Fig. 4d. In this instance one good way of coping with the problem is to use vertical slits in the skirt in the vicinity of its juncture with the pressure vessel and the bottom of the skirt which would be at room temperature. It is, of course, also important that the thermal insulation on the skirt be tapered in thickness in such a way as to give a uniform temperature gradient between the floor and the vessel.

Design for Leak Tightness

A high degree of leak tightness cannot be maintained in flanged joints in high temperature piping systems because thermal cycles will result in relaxation of the metal in local, highly stressed regions, and trace leaks will develop. To avoid difficulties of this sort, all joints should be welded with high quality heliarc or TIG welds. The number of flanged joints should be kept to a minimum, and they should be used only in cold zones, i.e., where temperatures are below 300°F so that high-class O-ring joints can be employed. Where practicable, double O-ring seals should be employed with the region between the O-rings connected to a vacuum system. In general, tube fittings in instrument and gas pressurizing lines should be avoided, although it is possible to employ Swagelok fittings in low temperature zones with a fair probability that they will yield an adequate degree of leak tightness.

Where possible, welds should be designed so that they can be made in the shop; the number of field welds should be kept to an absolute minimum because of difficulties in maintaining good quality control. Although elaborate formalized procedures have been worked out, there is no substitute for having highly skilled welders and inspectors with extensive experience.

Provision for leak testing during the shakedown operations should be included in the design. One requirement in the leak test work should be that the system be evacuated, and that the pressure rise in the system be no more than a few microns when the evacuated system is left sealed overnight. A variety of leak testing equipment can be used if the vacuum test reveals the presence of a leak. Of these, helium leak detectors appear to be the most effective means of finding trace leaks.⁶

The system design should also include provision for detection of any leaks that may develop during system operation. Oxygen leakage into sodium or NaK can be detected with a cold plug indicator. This device is sufficiently sensitive so that a buildup of oxygen and sodium or NaK can be detected long before any serious increase in corrosion rate will occur.⁷ This, of course, assumes that the leak will stem from a low cycle fatigue crack and hence will develop slowly. Similarly, a leak of liquid metal into the atmosphere surrounding the liquid metal system can be detected with instruments sensitive to the presence of alkali metal oxides. A leak of a liquid metal into a steam system, or of water or steam into a liquid metal system, can be detected by providing a gas trap with a nickel window kept at a sufficiently high temperature so that hydrogen will diffuse through the window into an evacuated zone where it can be sensed with a vacuum gage.⁸

Fire Hazards

It has been stated that the greatest handicap faced by alkali metal systems is the impression left by thousands of junior high school science teachers who introduced their classes to sodium by throwing a small chunk into a beaker of water. The indelible impressions left by these demonstrations make spontaneous fires and violent explosions almost synonymous in people's minds with alkali metals. In point of fact, if there is no water around, a liquid metal fire is much like a charcoal fire. Unlike hydrocarbons, the liquid metals have a very low vapor pressure, and as a consequence oxidation can take place only at the liquid surface; the liquid metal does not vaporize to yield a combustible or explosive mixture of air and vapor. As a matter of

fact, an oxide blanket tends to form which strongly interferes with the oxidation rate so that, if the liquid metal is in a stagnant pool, the reaction will be snuffed out by the oxide.

If no air is present, the reaction between water and sodium or NaK, while rapid and violent, is not explosive. However, if the hydrogen evolved mixes with air, an explosive mixture is formed and, in fact, once a flame front starts it is likely to develop into a detonation wave and a violent explosion will ensue. This is the usual course of the reaction in a high school science demonstration; the sodium-water reaction commonly proceeds for some time before ignition occurs and then, when a substantial quantity of a hydrogen-air mixture has accumulated, this ignites and is responsible for the explosion.

Experiments by quite a variety of different groups indicate that, if a leak occurs in a sodium- or NaK-to-water heat exchanger fitted with a blow-off valve or a rupture diaphragm and a stack, the peak pressures developed are only a little higher than those for which the valve or diaphragm was designed. A particularly fine series of experiments has been run in the United Kingdom using a full-scale tube bank.⁹ About half of the hydrogen from the water that reacts with the sodium is blown off as gaseous hydrogen, the balance remains combined either as NaOH or NaH. The temperatures that develop in the reaction zone may reach around 1300°C, and this may so weaken adjacent tubes as to lead to failures. Whether or not such failures occur appears to be very much a function of the character of the jet that emerges from the leak. For example, British tests involving 2300 psi water jets in full-scale tube bundles led to failures when the jets impinged at close range on adjacent tubes.⁹ These failures occurred in a matter of a few seconds, and hence provided a mechanism for progressive failures of the sort that occurred in the Fermi reactor plant.¹⁰ This in turn places a strong premium on detecting the development of such a leak very quickly so that the pressure on the water side can be relieved and the water and sodium system pressures brought into pressure equilibrium.⁹ When this has been done, the reaction rate drops sharply and the leak may even plug with sodium oxide.

If steam leaks into the liquid metal side of a steam generator, the reaction between the steam and the liquid metal proceeds at a quite modest rate.¹¹ The reaction proceeds quietly without the violent pressure fluctuations commonly associated with liquid water-sodium reactions. This in turn suggests that steam generators for liquid metal systems should employ a re-entry tube steam generator design of the sort shown in Fig. 6 so that any leak that might develop would consist only of steam with essentially no liquid water. If this were the case, there should be no problem with tube wastage because the latter is a phenomenon that apparently involves both erosion and corrosion and requires the presence of liquid in the jet from the leak.⁹

If water or steam leaks into a sodium or NaK system and the reaction is terminated by cutting off the water pressure, the operator is then confronted with a clean-up problem. This can present serious difficulties because the sodium hydroxide, sodium oxide, and sodium hydride formed are about twice as dense as the sodium and hence tend to sink to the bottom where they will collect in pockets. Their much higher melting point, about 600°F, is likely to be above the temperature to which the component can be raised with electric heaters, and hence removing the residue presents an awkward problem. The liquid metal that remains after the system has nominally been drained can be removed by cleaning the system with alcohol, which reacts at only a mild rate, but the sodium hydroxide residue is not sufficiently soluble in water for easy removal by pumping water through the system. Thus, provisions for cleaning such residues out of components such as heat exchangers ought to be included in the design or else the components should be made so they can be disassembled without too much trouble.

Certain other fire and explosion hazards should be noted. The fluorocarbons can react violently with liquid metals and yield detonation-type reactions. Thus, Teflon gaskets ought never be employed. It is also possible for superoxides of potassium to form, and these can detonate. As a consequence, care should be taken not to leave any small residue of NaK or potassium in the system where it can oxidize while the component or system is out of service and then subsequently detonate if severely jarred.

Fig. 6. Section through a reentry tube for a liquid metal-to-steam generator.

A number of steps can be taken in the design of liquid metal systems to reduce fire hazards. Where possible, liquid metals should be kept in rooms free of any water systems. The liquid metal inventory should be kept to a minimum. If possible, provisions should be made for gravity drainage of the liquid metal from the system into a storage tank. Some designers have gone so far as to provide for inert gas flooding of compartments or rooms housing liquid metal systems. In the writer's experience this is really not necessary because in a well designed system there is no weak element that can act as a frangible diaphragm to give a burst type of failure, hence any leak that may occur will be small and develop slowly.

Pumps

Although it is possible to design liquid metal systems for natural thermal convection, the flow rates are ordinarily so low that a much better and more economical design is given by forced circulation. Electromagnetic pumps afford one means of introducing a pump into a hermetically sealed system without also introducing a leakage problem, but they tend to give a rather poor efficiency. The simple, direct current, conduction type, EM pumps commonly have efficiencies of the order of only 5%. Helical induction EM pumps may yield efficiencies as high as 20%. In the writer's experience the most compact, least expensive, and most efficient pumps are axial flow or centrifugal pumps mounted at the bottom of vertical shafts with an oil lubricated balanced pressure face seal operated in a cool zone above the free liquid surface where it separates the inert cover gas from the atmosphere. This requires a relatively large overhang of the pump impeller, but in practice this has proved to be no serious handicap. For example, five pumps of this type were designed and built at ORNL and operated for periods of 20,000 to 25,000 hr with no difficulty.¹³ Care must be taken in the design to keep thermal stresses in the elastic range in regions of high temperature gradients and provide good operating conditions for the seal, but it is quite practicable to do this. Figure 7 shows a cross section through the pump of this type. A total of over a half million hours of operation with pumps of this type has been obtained at ORNL at temperatures above 1000°F.¹²

Fig. 7. Section through a centrifugal pump designed for operation in liquid metals and molten salts. Note the long overhand of the impeller shaft, the oil-lubricated face seal just below the bottom bearing, and the O-ring flanged joint in a cool zone above the hot pump casing.

Valves

As in vacuum systems, bellows seal valves should be employed. Because of the substantially less than perfect reliability of bellows, three-ply bellows should be employed. Experience has shown that these valves are more likely to give trouble than any other element in the system, hence their number should be kept to a minimum.

Liquid alkali metals are so effective in removing oxide films from materials such as stainless steel that the surfaces of the valve seats are essentially completely free of oxide. Thus, at high temperatures it is not surprising that there should be a tendency toward self-welding. This tendency can be reduced by employing dissimilar metals for the plug and the seat, e.g., molybdenum is very disinclined to weld to stainless steel. It is also possible to make use of stellite coatings on the seat but in nuclear systems it is desirable to avoid cobalt alloys. Under any circumstances it is difficult indeed to get a truly tight seal across the seat of a valve unless its temperature can be kept below about 600°F.

Heat Exchangers

While the problems posed by liquid metal systems as described above place many restrictions on the designer, they also open up some important possibilities. The extremely high degree of cleanliness of the systems, for example, means that one can make use of small diameter tubes and thus obtain a large amount of surface area per unit of volume in the heat exchanger. This is particularly advantageous in high pressure steam generators where the tube weight and wall thickness are dependent primarily on the internal pressure and the tube diameter. Thus, the designer can make use of somewhat smaller diameters than are commonly employed in heat exchangers and not need to be concerned with problems of tube plugging because the liquid metal stream will be singularly free of crud-forming material. Further, there will be no tendency for surface deposits and fouling on the liquid metal side that will interfere with the good heat transfer. If advantage is taken of these possibilities,

the amount of heat transfer surface and heat exchanger weight can be reduced drastically as compared with conventional water systems and the much reduced thermal inertia of the heat exchanger makes possible new approaches to system control that promise to be highly advantageous. Further, important cost savings can be effected.^{13,14}

The most important consideration in the design of heat exchangers for liquid metal systems is that the thermal stresses be kept in the elastic range, and this favors keeping the temperature difference between the two fluid streams to 100°F or less. This is not easy to do, especially in steam generators. If heat is to be interchanged between two liquid metal streams, the temperature distribution in the heat exchanger can be as indicated in Fig. 8, and it is easy to design the unit so that serious thermal stresses can be avoided. On the other hand, in a steam generator the bulk of the heat added to the water in the boiler region must be added at a constant temperature so that the temperature distribution is similar to that of Fig. 9. It appears that the best way to avoid this is to employ a re-entry tube boiler of the type indicated in Fig. 6 so that the region in which the water boils is separated from the high temperature liquid metal by a cushion of steam.¹⁵

Expansion Joints

A major problem in the design of liquid metal systems is associated with the expansion of the pipes between major components such as pumps and heat exchangers. If these major components are anchored, the thermal expansion can be accommodated by making use of large bends in the pipe (see Fig. 10a). However, the length of pipe required and the inventory of liquid metal in the pipes becomes quite large when the pipe diameter exceeds perhaps 6 in. An obvious solution would be the use of bellows (see Fig. 10b), but experience has shown that these are sufficiently subject to occasional failure so that this is not an attractive solution. A somewhat sturdier type of joint can be obtained with a so-called omega expansion joint of the type indicated in Fig. 10c. This type of joint depends on a relatively thin toroidal metal wall whose radius of curvature changes as the two segments of pipe that it connects

Fig. 8. Axial temperature distribution in a typical heat-transfer matrix for exchanging heat between sodium and NaK

Fig. 9. Axial temperature distribution in a once-through steam generator for a sodium-cooled reactor.

(a) Large radius loops in the piping

(b) Bellows Joints

(c) Omega Joint

Fig. 10. Devices for accomodating thermal expansion in high temperature piping.

move toward or away from each other. The metal wall is in simple tension rather than in bending as in bellows, thus greatly reducing stresses. Although promising on paper, this type of joint has not been very widely used.

Another approach to the thermal expansion problem is to anchor one component and allow the other component to float on constant tension spring hangers. This approach has the serious disadvantage that it is likely to be subject to damage in an earthquake. Yet another approach is to place all or most of the components of the system inside of a single big pot as in the reactor design of Fig. 11. The pumps and heat exchangers can be located in the pot in such a way that the entire outer envelope is kept at a uniform temperature by streams of liquid from the low temperature end of the system. This approach has the disadvantage that it is difficult to avoid a large liquid inventory to fill the interstices between the components in the pot.

Conclusions

The design of liquid metal systems poses many difficult problems, but these systems offer such important advantages that it is eminently worthwhile for the designer to take the time and effort required to become familiar with these special problems and learn to cope with them. The imaginative designer can then exploit the unique advantages of liquid metals as heat transfer and heat transport media, and should be able to achieve sufficient economics in the use of material to offset the higher standards required in quality control. This, in turn, could yield a much higher reliability and lower operating costs.

Fig. 11. Conceptual Design of a Molten Salt Reactor in Which the Reactor, Intermediate Heat Exchangers, and Fuel Pumps are Integrated in a Common Pressure Vessel.

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