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SODIUM-TO-AIR COOLING SYSTEM

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STATEMENT OF PROBLEM

Provide summary report on information pertaining to Sodium-To-Air Cooling System having applicability to FFTF work effort.

ABSTRACT

This report presents a summary of pertinent information on liquid metal-to-air cooled heat exchangers which will be applicable to the design of the heat dumps required for cooling the main driver and closed loop systems of the proposed Fast Flux Test Facility. It includes present design status, operation history, problem areas and solutions, failures and causes, and past and present day development needs of this type heat exchanger. This work was made in response to Westinghouse Electric Corporation, Power Systems, letter (No. 1048 AT, dated April 10, 1969) to North American Rockwell Corporation Atomics International Division (Reference: Letter Contract, BDR - 362 WAI).

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SODIUM-TO-AIR COOLING SYSTEM

INTRODUCTION AND SUMMARY

This report summarizes information pertaining to liquid metal-to-air cooling heat exchangers, which is applicable to the proposed Fast Flux Test Facility. The following items are included:

1. Present Design Status
2. Operation History
3. Problem Areas and Solutions
4. Failures and Causes
5. Past Development
6. Present-day Development Needs

The FFTF heat dump requires 400 Mwt nominal rating to dissipate the main driver core heat load, and 36 Mwt for the closed loop systems (1). The proposed main driver heat dump system is composed of four units with four heat exchanger modules per unit. The heat load per unit is 133 Mwt, or 33.3 Mwt per module. Six 6-Mwt heat dump units are required for the closed cycle system (2). The use of two 3-Mwt modules per unit is being considered to obtain greater flexibility in control.

The past and present liquid metal-to-air heat exchanger applications have lower rated thermal capacity than that required for the main driver unit. The Sodium Reactor Experiment (SRE) unit has been operated at 20 Mwt (43). The SEFOR unit, now being activated (4), also has a 20 Mwt rating. Thus, the load level of the proposed main driver cooling loop will be greater than that operated to date. The operation summary of installations for the more important reactor and component test facilities are given in Tables 1 and 2. Descriptions of selected units are given in Appendix A.

Although a large number of problem areas have been encountered in past installations, several were completely successful, showing that if proper attention is given to design, satisfactory operation can be obtained. Experience has shown that satisfactory operating life can be obtained with a design similar to that used on the SNAP 8 Experimental Reactor; i.e. 316 stainless steel tubes with circular 430 stainless steel fins, at least 3 U-turns in each tube assembly, unrestrained thermal expansion, and

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REACTOR LIQUID METAL - AIR COOLED HEAT EXCHANGERS

APPLICATION			NUMBER of UNITS	HEAT LOAD Mwt	COOLANT	MATERIAL	PERFORMANCE	PROBLEM AREA	TEMPERATURE ~ °F		OPERATION TIME	
FACILITY	LOCATION	PURPOSE							DESIGN	OPERATIONAL RANGE	HOURS	PERIOD
ART	Tenn.	Aircraft Pro- pulsion Reactor HDX	18	.5	NaK	Inconel Tubes & S.S. Clad Copper Fins	Good on Later Units	Stress failures of tubes and tube header joints, plugging, air bypass	1700	1200-1600	-	1951-1957
			20	1.75	NaK	Same						
EBR I	Idaho	Primary System HDX	4	1.4	NaK	347 SS Tubes, Carbon Steel Fins	Good	Some air recirculation	900	600	-	1951-1963
LAMPRE I	New Mex.	Primary System HDX	1	1.0	Na	316 SS Tubes & Fins	Good	-		1100	-	1961-1965
SRE	Calif.	Primary HDX	1	20	Na	304 SS Tubes & 410 SS Fins	Good	Insulation & control at low heat loads	1200	440-700	-	1956-1960
		Auxiliary HDX	1	1	Na	Same	Good	Same	1200	440-900	> 37,000	1957-1964
SNAP 2	Calif.	*	*	*	*	*	*	*	*	*	*	*
BR-5	Russia	Secondary HDX	1	5	NaK	SS Bare U-Tubes	Good	Leaks at weld joints	-	400-950	16,500 Leakage observed	1959 to Present
SNAP 8	Calif.	Secondary HDX	2	1	NaK	316 SS Tubes & 430 SS Fins	Good	-	1400	1250	14,000 (S8FR) 3,500 (S8DR)	1963-1965 May 1968 to Present
SNAP 8**	Calif.	Secondary HDX	1	1	NaK	316 SS Bare Tubes	Good	Leaks - Thermal Stress	1400	1200	500 (S8DR)	May 1968-Jan.1969
EBR II	Idaho	Pack Up Shut Down	2	.25	NaK	304 SS Tubes, Al. Fins	Good	-	-	700	-	1964 to Present
SEFOR	Ark.	MAIN	1	20	Na	SS Tubes	Just put in Operation	-	-	550-670	-	May 1969-Present
		Aux. Standby	1	1	Na	Carbon Steel Fins						
RAPSODIE	France	Secondary HDX	2	10	Na	Finned SS Tubes	Good	Temperature Control	-	600-950	-	1967 to Present
BOR	Russia	Back Up Shut Down		30	Na	-	Not in Operation	-	-	-	-	-
*See Reference (45)												
** This bare tube unit was replaced by the above S8DR finned tube unit.												

TABLE 2

COMPONENT TEST LIQUID METAL - AIR COOLED HEAT EXCHANGER

APPLICATION			NUMBER of UNITS	HEAT LOAD Mwt	COOLANT	MATERIAL	PERFORMANCE	PROBLEM AREA	TEMPERATURE		OPERATION TIME	
FACILITY	LOCATION	PURPOSE							DESIGN	OPERATIONAL RANGE	HOURS	PERIOD
WMA	Tenn.	Shutdown reactor heat transfer data	1	.01	NaK	Conventional Fin-Tube	GOOD	---	--	600	-	1947- 1949
MSA	Penn.	Primary- Secondary Heat Transfer	1	1.0	Na	316 SS Tubes 4-6 Cr Mo Steel Fins	GOOD	---	1400	-	-	1951-1954
MCR	Indiana	Pilot Model for MCR	2	3.0	NaK	3.6 SS Tubes Type 200 "A" Nickel	GOOD	Crack and leaks in tube to header joint of first unit.	1500	1500	1st-1600 hrs 2nd-4775 hrs	1964
APD-GE	Ohio	Heat Transfer Data	2	.75	Li	310 SS Tubes-Fins*	GOOD	---	1800	1000-1400	-	1949-1953
			5	.75	Li	310 SS Plate-Fin	GOOD	Only one could be made leak proof	1500		-	
SCTI	California	Heat Exchanger Tests	1	8.5	Na	316 SS Tubes 4-6 Cr Mo Steel Fins	GOOD	---	1300	400-1200	-	1962 to Present

*Bismuth Coolers

tube bank and manifolding arranged to allow for gas venting and complete gravity drainage of the unit through the inlet and outlet ports. Uniform heat transfer is not necessary in this type cooler to obtain satisfactory performance and operating life, as this design minimizes thermal stress induced between adjacent hot and cold tubes.

The sources of information on the various test facilities were found to be very limited in respect to liquid metal-to-air heat exchangers; that is, the reports usually emphasized the physics of the nuclear process and the primary heat transfer loop, rather than the heat dump system. In many cases, the problems with the air-cooled heat dump were so small that no note was made of them.

DESIGN CONSIDERATIONS

Air cooled heat exchangers (liquid-to-air) are used in many applications in the nuclear, chemical, and power plant industries. Many of the techniques developed in industry have been used in the design of liquid metal-to-air coolers. The most comprehensive references, relative to air-cooled heat exchanger design, were authored by Fraas and Ozisik (5) and Kays and London (6). These references show a wide selection of configurations that can be used for liquid metal-to-air heat exchangers. However, test data (7,8), and general rule-of-the-thumb design (9) have shown that extended surface heat exchangers are the most suitable for this application, wherein the film coefficient is much higher on the inside than the outside, and the resistance across the metal wall is small. Then the outside film coefficient is controlling.

Several types of extended surface heat exchangers have been used in liquid metal-to-air heat exchangers. They are:

1. Tube-circular fin
2. Tube-plate fin
3. Spiral-tube and plate channel (10)
4. Plate-fin (11)

The more common and successful design was the use of multi-pass, finned U-tube cross-counter flow of the liquid metal in a one-pass forced convection flow of air. This design gives the lowest air pressure loss.

The circular tube-fin design has been found best for power plants in respect to fabrication, cost, inspection, and cleaning (12). It also permits maximum flexibility to reduce thermal stress when one or more U-bends are used. The tube-plate fin is best for designs requiring small weight and volume, such as aircraft and motor vehicles. However, test results show the tube-plate fin design can give thermal stress problems at the high temperature required for liquid metal heat dumps (5). Bare tube heat exchangers have been used (5, 7, 8) but usually require many more welds at the header joints, as more than two to five times more tube length is required (7). The fabrication of plate-fin units was found to be very difficult (11) because this design requires welding and high temperature brazing of a much larger number of joining surfaces.

Heat Transfer and Pressure Loss.

Air Flow Side. The pressure loss and heat transfer film coefficient on the fin side of the tube are functions of the temperature, pressure, and velocity of the air and the hydraulic diameter, surface area, thermal conductivity, tube pitch, and fin dimensions of the heat exchanger.

Kays and London (6) presents heat transfer and pressure loss test data correlation curves on many extended surface heat exchangers. These data are very useful for estimating the optimum heat exchanger configuration, i.e. fin spacing, fin height, and tube spacing. They are based on the following correlations:

Pressure Loss (6)

$$\Delta P = \frac{G^2}{2g} v_1 \left[\underbrace{(k_c + 1 - \sigma^2)}_{\text{entrance effect}} + 2 \underbrace{\left(\frac{v_2}{v_1} - 1\right)}_{\text{flow acceleration}} + f \underbrace{\frac{A}{A_c} \frac{v_m}{v_1}}_{\text{friction}} - \underbrace{(1 - \sigma^2 - K_c)}_{\text{exit effect}} \frac{v_2^2}{v_1^2} \right]$$

Convection (6)

$$St \ Pr^{2/3} (T_w/T_m)^n = f(Re)$$

$$f(T_w/T_m)^m = g(Re)$$

Recommended values for n and m are given in Table 3. The fluid properties are evaluated at the mixed mean air temperature across the coils.

TABLE 3

VALUES FOR n AND m

WITH GAS COOLING (6)

n	m	FLOW CONDITION
.045	.045	Laminar - Flat Plate
.08	-.3	Laminar - In Circular Tube
-.10	-.3	Laminar - Between Flat Plates
.15	.0	Turbulent - In Circular Tubes

Briggs and Young (13) obtained correlations from tests of eleven different fin-tube banks to determine the effect of fin spacing (s), height (L), and thickness (t) and tube pitch and diameter on heat transfer and pressure loss. The correlating equation for heat transfer was:

$$Nu = .134 Re^{.681} Pr^{1/3} (s/L)^{.2} (s/t)^{.113}$$

The correlation for pressure drop requires the use of several curves, given in reference 13. They found that the heat transfer and pressure loss was independent of the number of rows in the direction of flow for most of the configurations tested, and that the tube pitch had a strong effect on pressure loss but little effect on heat transfer. The pressure loss was found to decrease to some minimum value with increasing tube pitch.

The air side cooling is a strong function of the inlet air flow rate and temperature, and a weak function of humidity and atmospheric pressure. In addition, there are several combinations of air flow and surface area that will meet the heat transfer requirements (14). Therefore, the design should be optimized in respect to fabrication, installation, and operating costs, as well as performance. Several calculation methods (14,15,16,17,18) and computer programs (19,20) have been developed to calculate air transport properties as a function of pressure, temperature, and moisture content, and to optimize the design in respect to cost and performance.

Liquid Metal Flow. Several tube side correlations for calculating forced convection liquid metal film coefficients are available (21). Some of these are as follows:

Lyon-Martinelli

$$Nu = 7 + .025(2\psi Pe)^{.8*}$$

Lubarsky-Kaufman

$$Nu = .625 Pe^{.4}$$

Seban-Shimazaki

$$Nu = 5 + .025 Pe^{.8}$$

Skupinski

$$Nu = 4.82 + .0185 Pe^{.827}$$

Dunsmore

$$Nu = 4 + .024 Pe^{.8}$$

The last two correlations are preferred at A.I. as they give the best fit with experimental data. However, since this is not the controlling film coefficient, it is not too important which equation is used.

Radiation. It has been shown that radiation from the fin-tube can be significant (22, 23, 24, 25). It can cause variation in heat transfer between adjacent fin-tubes. This is especially true in tube bundles wherein several rows of fin-tubes are used. Then, the outer rows will radiate a greater amount of heat to the surrounding air duct. This can be significant in comparison to air convection at tube-fin surface temperatures above 600F. This effect can be reduced by the appropriate use of radiation shields around the fin-tube assembly in designs (i.e. compact plate fin-tube) where nonuniform heat transfer will cause excessive thermal stress.

Fin Efficiency. The fin efficiency is approximately given by: (27)

$$\eta_f = \frac{\tanh (L \sqrt{2h/(kt)})}{L \sqrt{2h/(kt)}}$$

If the fin is not bonded to the tube by welding or brazing, this fin efficiency should be corrected for contact resistance (28).

Flow Stratification. Stratification of the flow of either the liquid or the air will cause ineffective heat transfer performance and thermal stress. Therefore, proper attention should be paid to the inlet and outlet header design and to the leakage of air around the tube assembly.

Fouling. External and internal fouling factors should be applied to insure the heat exchanger will have sufficient excess tube surface to maintain satisfactory heat transfer performance with reasonable service time between cleanings. An external fouling factor of $.002 \text{ ft}^2\text{-hr-}^\circ\text{F/Btu}$ is normally recommended for air (26). However this value depends on the local environment and operating conditions. If the temperature of the exchanger is continuously kept near its normal operation range, this recommended external fouling factor should be adequate. For conditions such as frequent shut downs in a highly humid (corrossive) or dusty environment with infrequent cleaning, a much higher fouling factor should be used.

Internal fouling on the liquid metal flow-side (unless nearly plugged) should be of negligible importance to heat transfer, as its film coefficient is much greater than that of the air. However, a small amount could have significant effect on pressure drop. Internal fouling could result from precipitation of liquid metal oxide or mass transport of nickel from hot to cold parts of the heat exchanger through leaching and deposition. Oxide precipitation can be eliminated by adequate cold trapping of the liquid metal oxide in the liquid metal. Mass transport of nickel should be negligible when stainless steel tubing is used at temperatures below 1300F. It has been found to occur with high nickel content alloys such as Inconel when operating at 1500F (40,41).

Fin Design. Fin tubes, as used in air cooled heat exchangers, can be classified as follows:

1. Integral Fins
2. Embedded Fins
3. Brazed Fins
4. Welded Fins
5. Interference Fit Fins

Of these, the brazed and welded type fins have been found most practical in liquid metal heat exchangers in which rapid temperature transients can occur. Since austenitic stainless steels are required for tubing in contact with sodium, the most practical fin material is stainless steel.

Stainless steel-clad copper (29) and nickel (30) fins have been used in liquid metal-air coolers. However, the advantage of a highly conductive or tapered fin is very small in applications where weight is not important because of the high resistance of the gas side film. However, the thickness of the fin is important, when it is made from a low conductivity material (5).

The shape of the fin is normally circular or rectangular. However, in Germany elliptical tubes and fins are quite common, as that design will give lower air pressure loss (31).

High temperature micro-braze of a spiral fin pressed into a plowed groove, is the most common fin-tube joining method used in liquid metal heat exchangers (5). However, the use of fillet or high frequency resistance weld is becoming more common in recent installations. The use of interference fit fins, which is very common in industry, is not recommended with liquid metal heat exchangers, because the contact resistance changes greatly with operating conditions (32).

Arrangement.

Tube Bundle. The tube assembly is normally designed in modular form to facilitate fabrication, installation, and maintenance. The arrangement of the tube bundle may be vertical, sloped, or horizontal. Normal vents and drains at high and low points of the liquid metal in the headers must be provided to eliminate pockets of liquid metal which may solidify following

shutdown. Wherever possible, tubes should be sloped to provide positive drainage by gravity. Tube vibration may occur if long unsupported tubes are used. This situation can be eliminated with the use of sway bar restrainers and snubbers.

Crevices in which liquid sodium may be retained by surface tension or physical entrapment should be eliminated (5, 33). Integral construction of the tubes and headers, by welding or furnace brazing with a high temperature braze material that melts above 2000F, and with thorough inspection (dye penetrant, radiographic, ultrasonic, and leak tests), should be used to insure leak tightness and long operating life. The structure should be designed so that high stress regions are distributed over a large, rather than a localized, zone (5).

Air Movers. Forced, rather than induced, draft fans and blowers have been used on all liquid metal-air heat exchangers because of the high exit air temperature. The type of air mover used is dependent upon propeller diameter and pressure head requirements.

The following design parameters are normally followed: (34,35)

<u>Type</u>	<u>Diameter</u>	<u>Head</u>
Fan	1 to 5 ft	1" WG
Fan	> 5 ft	> .6" WG
Blower		> 1" WG

Since air-cooled plants are installed out-of-doors, fans and fan drives should be durable and designed in such a way that all parts which require maintenance are easily accessible. All motor parts which are subject to wear (bearings, gears, etc.) should be designed for a least 50,000 operating hours (36).

Axial-flow fans up to about 5 ft in diameter are usually mounted on the driving motor shaft. A fan driven directly by the motor is the best solution with respect to operating reliability, but is limited to relatively small fan sizes. Vee-belt fan drive speed reduction is frequently used with large size fans (5 to 11 ft diameter). Such a drive is reasonable in price and sufficiently robust, if the mounting and bearings are carefully designed.

The range of application is usually restricted to a fan shaft power of about 35 hp.

For fan powers higher than 35 hp, reduction gears are normally used (36). Typical arrangements have included a bevel gear coupled to a horizontal driving motor located on the floor, with a vertical fan drive shaft connected with the gearbox through a universal joint. This can be replaced by a more compact construction with a spur gear. The fan wheel is arranged on the drive shaft of the gearbox in an overhung position, and its bearing lies in the gearbox itself. The driving motor is of the flanged type, directly coupled with the gearbox input shaft. Reduction gears for axial flow fans, up to capacities of about 135 hp, have been used.

Since the operating reliability of the gears depends mainly on the perfect lubrication of the tooth surfaces and the bearings, oil circulation pumps have to be installed at the larger capacities. The reliability of the plant can be increased by controlling oil temperature and flow by the use of thermometers with alarm indicators and flow-sensitive relays (36).

Fan noise is a function of the circumferential speed and power level, not the number of units (34,35). Therefore, the noise level can be reduced by using several small units. However, this must be counterbalanced by the resulting increased costs. Noise can also be reduced by screening the air entrance and by suitable use of sound absorbing materials to reduce the sound level and to prevent amplification by the supporting structure and air duct (34).

Reference 58 presents acceptable sound level versus time of exposure.

Environment. Adequate provision must be made for environment such as high winds, sand, dust, rain, and hail. The air blast heat exchangers at SEFOR have been anchored to resist 300 mph tornado winds and surrounded with steel gratings to protect them from flying objects (38). Thus, the requirements for this type of protection will depend on the expected weather variations at the selected plant locations.

Re-circulation of the air flow can occur under high wind conditions (33, 34,39) as the wind tends to force the exit air to flow down the leeward side of the heat exchanger structure. This re-circulation can intermittently raise the inlet temperature by several degrees, thus making control more difficult. This effect can be minimized by the use of an appropriate length stack on the exit, by proper spacing of units, by orientation of heat exchanger units with

respect to the prevailing winds, and by eliminating protrusions above the stack exit. This condition can also be aggravated by the presence of buildings or large obstructions near the air cooler.

Sand and dust can erode the fan blades. At the EBR-I facility the air is passed through a filter to remove dust before entering the fan. Rain and hail can cause rapid changes in heat transfer rate and possible damage to fins. These factors can be corrected by proper design of the fan inlets and stack exhaust, such as orientation, filters, shields, and height above the ground.

OPERATION HISTORY

The operation history of liquid metal-air cooled units that have been designed and used on nuclear reactors are summarized in Table 1. Similar information on units used to test components are summarized in Table 2.

These tables show that several successful installations have been made for operating liquid metal heat exchangers at temperatures between 900 and 1500F. The fin-tube units now in operation at A.I. (SNAP 8 and SCTI); and at NRTS, Idaho (EBR-II); in Russia (BR-5); and France (Rapsodie) have given good performance and long life. These units were the circular tube-fin type (except bare tube at BR-5) with one or more U-turn bends in each tube assembly to permit adequate, independent thermal expansion of each tube between header joints.

The compact heat exchangers, ART, made in a tube-plate fin matrix, had limited life. These units exhibit 3 dimensional variation in thermal expansion when non uniform heat transfer is present. The bare tube heat exchanger used on the SNAP 8 Development Reactor also failed, because there were no flexible turns between tube-header joints to take care of non uniform heat transfer. The Atomic Product Division of General Electric had marginal success in developing compact plate-fin, air-cooled liquid metal heat exchangers. Only one out of five units could be made leak proof (11).

PROBLEM AREAS

The problems with the air mover and facility arrangement have been discussed in the previous section. The following problems have been encountered in heat exchanger design:

1. Control
2. Air leaks through damper louvers
3. Uneven thermal expansion
4. Uneven heat distribution
5. Plugging
6. Rapid temperature transients
7. Liquid metal leaks
8. Free convection loops within the liquid metal tube bundle
9. Liquid metal drainage
10. Trapped gas
11. Monitoring to prevent freezing
12. Preheating

Thermal stress is especially pronounced at the liquid metal inlet between the header and the first fins, where the highest temperature and most rapid temperature transients occur. The thermal stress can be reduced by allowing free expansion of the tube between the inlet and outlet headers, by use of stack dampers to reduce the rate of change in temperature drop across the tube assembly during rapid transients; and by eliminating slugs of hot and cold metal flow, through baffling in the inlet headers.

Plugging was due to uneven heat distribution, liquid metal freezing, possible mass transport of nickel from hot to cold parts of the tube (40,41), and inadequate cold traps to precipitate out the liquid metal oxide in some of the early test units. Plugging normally occurred in the outer rows of tubes which run cooler because of greater air flow around the outer parts of the tube assembly and radiation from the tubes to the duct walls. Plugging can be eliminated by adequate cold trapping, and can be reduced by proper sizing of the air flow passage around the tube assembly, by use of radiation shields by insulation of heat exchanger shell during standby, by use of air preheaters, and by elimination of conductive shorts between the tube assembly and the structure. Mass transport of nickel is not expected to occur in the FFTF HDX because of the lower required operating temperatures and the use of stainless steel.

The control problems were caused by inability to take care of rapid environmental changes and shut down transients. Effects resulting from

rapid changes in environment can be eliminated through use of automatic controls on both the stack and the fan louvers; however, combinations of more than one method of automatic control can cause temperature cycling, if not properly designed (42). Inadequate standby control was experienced in facilities that had air leakage through louvers. This can be corrected by good louver design, insulating the heat exchanger shell, use of air or line preheaters, and uniform flow of liquid metal.

Other problems which can occur but were not mentioned were: drainage of the liquid metal, trapped gas, and tube vibrations.

A discussion of the reported failures and source of the problems encountered at specific facilities follows:

Aircraft Reactor Tests - ART (29, 33, 40, 41)

Several of these compact aircraft nuclear propulsion (ANP) heat exchangers had leak failures at the braze joint between the tubes and the header and in the tubes between the header and the first fin plate on the liquid metal inlet side. It was determined that these failures resulted from excessive thermal stress in these regions and poor brazing techniques in some of the first units. As noted previously, thermal stress was particularly severe in this type of design because of non uniform thermal expansion. The braze joint to the header was improved with the use of back flow brazing technique.

Problems with poor air flow distribution, by-pass flows of air around unit, plugging of outer rows of tubes, and excessive thermal stress from alternate hot cold slugs of liquid metal flow were also experienced.

In developing the test program for the later units it was decided that the most important source of trouble lay in differential expansion between the fins and the header, which occurs because the fins may run cooler than the header drum by as much as 300°F. The difference between the average fin temperature and the average metal temperature in the header drum depends upon the heat load on the radiator, i.e. on the air mass flow through the radiator. This temperature difference is greatest at the inlet air face by a factor which may be as much as 30 to 1, depending on the depth of the radiator in the airflow direction. The thermal strains associated with this differential thermal expansion are cycled each time the airflow is changed. Thus a radiator can be subjected to severe thermal cycles simply by turning it on and off or by

changing the airflow. The adverse effects of this factor were reduced by interrupting the fins at intervals transverse to the air flow in later radiators to reduce air flow over the fins near the inlet header. It was found to be sufficiently effective so that the last unit tested withstood six times the number of severe thermal cycles anticipated for the normal design life.

One of the difficulties encountered in testing the $\frac{1}{2}$ Mwt units was excessive bypass air around the radiator unit. The necessity for avoiding rigid structural restraints on the unit complicated the task of sealing the air duct. In addition, temperature traverses across the discharge air ducts indicated some degree of air flow and temperature asymmetry. In the design of the test stand for the 1.75 Mwt ART radiator units, careful attention was given to the radiator mounting and bypass air seals.

The liquid metal flow pressure drop through these units increased approximately 100 per cent in a 40 day period. It was determined that this increased pressure drop was caused by mass transfer of nickel from hot to cold sections of the Inconel system, rather than by participation of liquid metal oxides. Nickel mass transfer is a function of the tube material, the maximum NaK temperature, the geometry of the tube-fin matrix under consideration (including relative positions of hot sections and cold sections), and the ratio of hot to cold areas in the system.

Military Compact Reactor - MCR (30)

Two compact 3 Mwt rated heat exchangers were tested for the Military Compact Reactor (MCR) at liquid metal temperatures up to 1500F to establish design precepts for the full size unit.

Cracks were seen in the weld of one of the tube-to-header weld joints of the first unit (after 1600 hours operation, 1066 hours at 1500F). Destructive examination after removal from the test loop also showed incomplete bonding of the fins to the tube at several locations.

One of the cracks in the tube-to-header joints occurred where the weld penetration was 54% of the nominal tube wall thickness. Visual examination of the joint also revealed an excessive amount of clearance between the tube OD and the header ID. This clearance in conjunction with the relative thin (.0625 in.) manifold wall permitted movement of the tube to be wholly absorbed in the undersized weld joint, causing excessive strain.

The second unit was fabricated with improved tube-to-fin brazing processes and manual welding of the tube-to-header joints. This second unit showed no signs of failure at the time the program was discontinued. The accumulated operating time on this unit was 4800 hours.

Sodium Reactor Experiment - SRE (43,44).

Both the main (20 Mwt) and auxillary (1Mwt) air cooled units operated satisfactorily during normal operation but had excessive heat loss following a scram. This was resolved by insulation of the entire unit and by utilizing line and component pre-heaters during standby. These units had manual louver controls which could not be operated fast enough to take care of changes in operating conditions. The tube-fin assembly performed satisfactorily under all conditions.

SNAP 8

Three air-cooled heat exchangers were used in the Snap 8 program. One fin-tube unit was used on the Snap 8 Experimental Reactor (S8ER) and two units (one bare-tube and one fin-tube) were used on the Snap 8 Developmental Reactor (S8DR). The two fin-tube assemblies (S8ER and S8DR) performed satisfactorily without failure. The S8ER air cooler was still operating satisfactorily when the reactor was shut down after approximately 14,000 operating hours had been accumulated on the unit. The S8DR fin-tube unit is still in operation with approximately 3500 operating hours at liquid metal temperatures above 1000F. The fin-tube units operated satisfactorily because they featured 3 U-bends in each fin-tube. These U-bends provided sufficient freedom for thermal expansion even though the outer tubes may have run much cooler because of extra radiation and convection heat loss.

The bare tube unit (made with straight tubes between each heater) failed after 500 hours operation because of excessive thermal expansion of the hotter running center tubes. The center tubes buckled and their ends showed signs of metal flow at the tube-to-header joint. The bare tube assembly failed because there were no U-bends in the tube between the header joints. Thus, the whole assembly was held rigid between the inlet and outlet headers, putting the outer cooler running tubes in tension and the center tubes in compression. This resulted in buckling and splitting of the inner tubes. This result

demonstrated the need for U-bends between headers to allow for thermal expansion and more uniform liquid metal distribution through the tubes through use of flow diverters and port nozzles. The bare tube assembly should have operated satisfactorily if proper radiation shields and uniform air and liquid metal flow had been present to insure uniform thermal expansion of all tubes. However, this is not easy to accomplish.

SNAP 2. (45)

The air-liquid metal heat exchanger used on the Snap 2 Development Reactor test program (S2DR) failed after 1700 hours operating time. A description of the heat exchanger design and mode of failure is given in reference 45.

Cadarache. (46)

Two 10 Mwt and one 1 Mwt air-cooled fin-tube heat exchangers were tested at Cadarache to obtain preliminary design feasible data for the 20 Mwt units to be used at Rapsodie. These units performed satisfactorily and had sufficient capacity to dissipate the rated power at the design temperatures for the secondary coolant. However, a liquid metal leak (discovered through the smoke which was produced) occurred in one of the 10 Mwt air-cooled exchangers. This leak was caused by porosity in a weld. It was located at a very inaccessible spot. This led to external corrosion of both the faulty and neighboring tubes. Two tubes (out of a total of 262) had to be cut and sealed off. To avoid incidents of this kind, they recommended that the tube bundles should be manufactured in separate units to make the welds more accessible.

Rapsodie.

The Rapsodie design is similar to that planned for use on the FFTF. Its operation has been satisfactory in respect to heat transfer, but problems have been encountered with structural and mechanical deficiencies of the control louvers (47). They also found that fluctuations in the air environment (temperature, moisture, and wind) feed back into the reactor temperature control, indicating improper design of the louver control mechanism (48).

The identified deficiencies were:

1. Faulty seals on damper blades
2. Binding and seizure of bearings and linkages for damper louves
3. Damper control unstable at low flow conditions and too slow to compensate for rapid change in environment.

BR-5. (49)

A NaK-air heat exchanger and a steam generator are installed in the secondary loop. At the end of 1960 the steam generator was replaced with a NaK-air heat exchanger similiar to that operating in the air network since startup of the reactor in 1959. The bare tubes of the BR-5 air-cooled liquid metal heat exchanger are enclosed. They were not inspected during the first six years of satisfactory operation. When it was inspected in January 1966, it was found that some tubes were covered by outgrowths of alloy oxides of the liquid metal at the point where these tubes were attached into the tube plates of the three bottom sections. At this time 16,500 hours operating time had been accumulated. Inspection of the tubes after removal of the alloy oxides showed that the surface of the tubes was in a satisfactory condition with no significant corrosion damage. No leakage of NaK was observed when the coolant was circulated through the loop after refilling the heat exchanger with NaK alloy. The heat exchanger continued to operate, without replacement of the leaky sections, with constant observation of the condition of the lower tube bank and also with periodic inspection of the condition of the tubes during shutdown.

Inspection of the section tubes, carried out during April to December 1966 and also in February 1967 established that the number of places with oxide formations on the tube plates was reduced considerably in comparison with January 1966. Occassionally there was a small leakage of alloy (dropwise leakage), from individual points where the tubes were fastened to the tube plates, during steady-state and transient temperature conditions in the heat exchanger. However, these leaks were short-lived and 'self-sealing' (50).

PAST DEVELOPMENT

Considerable work has been done to improve the method of brazing stainless steel tubes to the header. The most significant was development of a back brazing technique to eliminate sources of leaks (5). It was found that if joints are first welded, and then back brazed, a very high degree of joint integrity can be obtained. In fact, approximately 7000 welded and back brazed tube-to-header joints were endurance tested without a single instance of a leak through such a joint. Automatic welding was found to produce more consistent and uniform weld joints than does manual welding.

Heliarc welding has been found to be a good method for attaching the tube to the header (30). Fast contact resistance (high frequency 450,000 cycles) welding of spiral fins has been developed by AMF Thermatool Industries, of New Rochelle, New York (51). They report they are able to weld spiral fins onto a tubing as small as 5/8" O.D. at speeds up to 100 ft per minute. The successful use of ultrasonic inspection of the inside surface of a fin tube to determine the integrity of the welded or brazed joint has been reported (52).

PRESENT DAY DEVELOPMENT NEEDS

The primary need for further development is stable automatic control of several units in parallel operation, particularly during periods of low heat dump requirements, and for rapid changes in the air environment. This will be especially critical on units of the size proposed for the FFTF. The development of leak proof damper seals for standby operation is also important. Attention needs to be paid to radiation losses if compact type heat exchangers are used.

Improved methods for detection of local freezing is also needed so that this area can be preheated automatically or isolated from the system for maintenance prior to occurrence of metal possible rupture and subsequent sodium leakage.

CONCLUSIONS

This survey reveals that completely successful air-cooled liquid-metal heat exchangers have been made and tested, showing that if proper attention is given to design, satisfactory operation can be obtained. A large number

of problem areas were encountered in past installation. The primary problems were inadequacy of temperature control during reactor transients and standby, and the prevention of leaks resulting from inadequate inspection during manufacture or excessive thermal stress of the tube-to-header joint. Thus the adequacy of design in respect to control and leak prevention should be especially emphasized.

Excessive restraint against thermal movement of each individual tube was the primary fault in those installations where leaks developed in the tube-to-header joints. Rigid tubing which does not allow for independent thermal expansion and contraction of each tube, due to operating temperature variations and fluctuations, results in high strains being imposed on the tubes and the tube-to-header weld joints, leading to premature failure. The liquid metal plugging and variation in heat transfer will amplify this problem since this results in cold tubes which may not be able to contract if no provisions, such as U-turns, are made for thermal expansion.

NOMENCLATURE

- A - Exchanger total heat transfer area on air side
A_c - Exchanger minimum free - flow area between tubes
f - Friction Factor
g - Acceleration of gravity
h - Film coefficient
G - Air stream mass velocity
Gr - Grashof number
k - Thermal conductivity
K_c - Entrance loss coefficient
K_e - Exit loss coefficient
L - Fin height
Nu - Nusselt number
ΔP - Pressure loss
Pe - Peclet number
Pr - Prandtl number
Re - Reynolds number
s - Spacing between fins
St - Stanton number
t - Thickness
T - Temperature
v - Specific volume
WG - Water gage, inches

Greek Letter

- η_f - Fin efficiency
 σ - Ratio of exchanger free-flow area to frontal area
 β - Ratio of thermal to momentum eddy diffusivities

Subscripts

- 1 Initial
- 2 Final
- m Mean conditions across coils
- w Outside surface

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APPENDIX A

DESIGN SUMMARY OF SELECTED UNITS

ART (29,33)

Testing was performed by the ANP Division of ORNL on compact, high-performance NaK-air coolers for aircraft nuclear propulsion (ANP) applications development. Operation at 1200 to 1700°F was accumulated on 20 coolers which were nominally rated at $\frac{1}{2}$ Mw and employed cross-counter-current air flow over small diameter (3/16 OD) Inconel U-tubes. Rectangular stainless-steel-clad copper plate fins (.006 in. thick copper and .002 in. thick SS) were brazed to these U-tubes.

All fin-to-tube joints in the radiator matrix were micro brazed (melting point above 2000 F). The brazing compound was preplaced during assembly of the units and brazing was accomplished after the units were otherwise completely fabricated.

The high conductivity, stainless-steel-clad copper fin material used in the radiators required edge-treatment after shearing to prevent oxidation of the copper core. This was done by applying slurried aluminum powder to the edges of a stack of fins and heating to alloy the copper and aluminum. This aluminum bronze effectively prevented fin deterioration and loss of heat-transfer effectiveness. The fins were punched and slipped over the Inconel tubes, utilizing the extruded periphery of the punched hole as a spacer between fins.

BOR. (53)

The BOR reactor will utilize air-cooled heat exchangers as backup in their advanced sodium cooled plants.

In each secondary circuit loop of BOR, there is an air-cooled heat exchanger, designed for a thermal capacity of 30 Mwt, which can be connected to any secondary circuit loop instead of the corresponding steam generator.

BR-5. (49)

The heat exchanger consists of nine sections arranged in a casing with dimensions of 1.5 X 1.5 X 2 m. Each section consists of a cluster of 62 U-shaped bare tubes with a diameter of 25 mm and wall thickness of 1.5mm, in a staggered arrangement and sealed into the tube plate of the chamber section. The NaK alloy passes into the upper collector of the heat exchanger, from which it is distributed along three parallel three-section lines and flows out of the heat exchanger through the lower collector. The air for cooling the alloy is fed from bottom to top. The sections of the heat exchanger are made of stainless steel (type 1Kh18N9T).

EBR-II.

An air-cooled heat exchanger is utilized in EBR-II in the shutdown cooling system. NaK flows by natural convection in a closed system, through an immersion type bayonet heat exchanger in the primary sodium system and then through the air-cooled heat exchanger. Hot NaK flow is upward into the finned-tube air heat exchanger, which is located in a dampered air stack outside and above the reactor containment building. Here the heat is transferred to the atmosphere by natural convection of air. The cooled NaK then flows downward into the inlet of the bayonet cooler (.56).

The rate of heat release from the system is controlled by the position of the stack dampers. Normally, the dampers are actuated by automatic control (full open or full closed). Manual control is also incorporated in the event of failure of the automatic system. During reactor operation, the dampers are normally closed and a minimum flow of NaK is maintained in the shutdown cooling system. This method of operation prevents the freezing of NaK in cold weather, provides for positive starting when the dampers are opened, and reduces thermal shock on the system. When the stack dampers are opened the thermal head on both the NaK and air side is increased. This

gives rise to increased flow of both fluids, which in turn results in increased heat removal from the bulk sodium.

MCR (30)

The 3-Mwt Military Compact Reactor (MCR) primary heat exchanger provides the surface for the transfer of heat from the primary system liquid metal to secondary system air. The basic configuration is a cross-counterflow exchanger with four liquid metal passes and one air pass. The liquid metal enters at reactor outlet temperature through the upper center manifold, passes through each bank of finned-tubes (316 SS tubes, 200 A Nickel fins) in four passes perpendicular to the airflow, and is collected in the lower center manifold for discharge to the pump inlet. The air enters at compressor discharge temperature through the bottom of the shell, divides around the lower manifold, and passes vertically up through the core in two parallel paths, then is discharged through the top of the shell.

The core in the 3-Mwt design unit is mounted on rollers inside the shell to allow for the thermal expansion of the primary loop piping. This minimizes thermal expansion stresses induced in the piping or the heat exchanger. The finned tubing is permitted to expand thermally in the direction of its own axis by providing a clearance around the heat transfer tubes in their passage through the baffle wall. The tube bundle was also designed to permit differential thermal expansion between the inlet and the outlet liquid metal manifolds. This expansion occurs as a result of the 300F temperature differential between the two manifolds.

MSA (57)

A 1-Mwt sodium-air heat exchanger was developed to obtain performance data on liquid metal heat exchangers. Sodium passed from a 3-in. double-extra-strong pipe manifold through thirteen 1-in. OD x 16 BWG finned tubes into a discharge manifold. The sodium tubes made 6 passes through the air stream. The fin material was 4 to 6 % chrome-molybdenum steel, 0.024 in. thick and the fins were 2 in. OD. They were spirally wound on the tubes at a pitch of 5 per in. The finned length on each pass was 2 ft 5 in. The

tubes were formed in a serpentine manner with a bare tube U-bend between passes. The unfinned length was not in the air stream.

Air passed upward through the shell side of the cooler at a maximum rate of 27,000 lb/hr. The airflow rate was controlled manually by a damper on the blower inlet.

The overall size of the cooler is 3 ft x 2 ft-8 in. x 2 ft-2 in. The unit was designed for the following conditions:

- 1) Heat load - 3,500,000 Btu/hr
- 2) Heat transfer surface - 426 ft²
- 3) Mean temperature difference - 900F
- 4) Sodium volume - 1.15 ft³

RAPSODIE (59)

The Rapsodie facility has two primary and two secondary liquid metal cooling circuits. Each of the primary circuits transfers its heat to the secondary circuit in an intermediate heat exchanger. The two secondary circuits are identical with each other and each terminates in an air exchanger where the power is passed to atmosphere. The coolant used is sodium, both in the primary and secondary circuits. Each of the circuits can dissipate 10 Mwt thermal power with a rated flow of approximately 370 m³/h. The characteristics of each 10-Mwt terminal liquid metal-air heat exchanger is as follows:

Nests of finned stainless steel tubes.

Number of tubes: 960 (16 nests of 60 tubes).

Tube diameter: 21.4/25.4 mm

Exchange surface: 1145 m²

Exchange coefficient: 53.5 K cal/h m²·C

Temperature: 470C

In the initial stage, the heat will be released into the atmosphere through terminal air exchangers. It is planned to add later an experimental plant for producing energy, with steam generators and turbines (60).

SCTI

The SCTI cooler is rated at 8.5 Mwt (54,55). It is utilized as a heat sink in reducing the temperature of the sodium in order to provide the required thermal transients for the test heat exchangers.

It is constructed of 6 in. 304 SS inlet and outlet sodium headers, with 14 in. long fin tubes, making 14 passes across the air stream. The fin-tubes were fabricated from $1\frac{1}{2}$ in. O.D. type 316 stainless steel with 3.4 in. O.D. x 0.050 in. thick 4 to 6 % chromium-moly steel fins, 5 per inch.

SEFOR (37)

The SEFOR air-blast coolers are forced-air, finned-tube heat exchangers designed for the following conditions:

	<u>Main</u>	<u>Auxiliary</u>
Power (Mwt)	20	1
Sodium inlet temperature (°F)	670	670
Sodium outlet temperature (°F)	550	550
Air inlet temperature (°F)	90	90
Air outlet temperature (°F)	493	403
Heat-transfer Coefficient -		
Design Btu/hr-ft ² -°F	9.0	7.3

The main air-blast cooler consists of the heat exchanger tube bundle, support structure, blower, blower drive, and blower speed control.

The cooler tube bundle surface area of 26,300 ft² consists of 270 finned stainless steel U-tubes, 1.0 in. OD by 0.072 in. wall thickness. The fins are 0.030-in.-thick carbon steel, helically wound at 7 per lineal in. of tube in a plowed groove. The U-tubes are mounted horizontally, 45 across and 6 deep, to produce a tube bundle of 12 layers of tubes. Inlet and outlet manifolds consist of 16-in.-diameter pipe sections, to which tube sheets are welded. The sodium nozzles are located so that the hot secondary sodium enters the top of the bundle to prevent stratification and promote natural circulation. The overall size of the tube bundle is about 13 ft wide, 17 ft long, and 4 ft deep.

The main cooler tube bundle is supported about 16 ft above grade with the blower located at grade and to one side of the tube bundle. Air is ducted from the blower discharge upward through a transition duct, plenum chamber, and the tube bundle. Steel gratings are mounted above and below the heat exchanger tube bundle for protection against flying objects. The tube bundle and support structure are designed for 300-mph tornado wind loads. The bundle may be isolated to maintain sodium temperature during down-time with three sets of pneumatic, remote-operated, insulated doors located above and below the tube bundle. Tube bundle housing is insulated, and cal-rod heaters are mounted between the bottom of the heat exchanger and lower grating to preheat the unit during startup or to maintain temperatures during shutdowns.

Cooling air is supplied by a floor-mounted scroll-type, double inlet centrifugal blower rated to deliver 700,000 lb/hr of air at 6.5 in. of water pressure. The blower has manually-operated, variable inlet guide vanes for control at very low load conditions. A 250-hp motor drives the blower. The sodium outlet temperature from the main air-blast cooler is controlled at a given set point by a temperature indicator controller which adjusts the blower speed through an ampli-speed magnetic drive.

SNAP 8

Three air-cooled heat exchangers were used in the SNAP 8 program. One (S8ER) fin-tube unit was used on the SNAP 8 Experimental Reactor and two (S8DR) units (1 bare tube and 1 fin-tube) were used on the SNAP 8 Development Reactor.

The SNAP 8 design conditions were:

	<u>OPERATING CONDITIONS</u>	
	<u>No. 1</u>	<u>No. 2</u>
Rate Heat Load (Mwt)	.6	1.0
Rated NaK flow (lb/hr)	49,000	49,000
Rated Air flow (lb/hr)	21,350	34,200
NaK temperature, in ($^{\circ}$ F)	1,250	950
NaK temperature, out ($^{\circ}$ F)	1,050	750
Air temperature, in ($^{\circ}$ F)	100	100
Air temperature, out ($^{\circ}$ F)	500	350
NaK design temperature ($^{\circ}$ F)	1,400	1,400
NaK design pressure (psia)	100	100
Maximum NaK pressure drop (psig)	5	5
Air pressure drop (in. of H ₂ O)	1	1

The S8ER Heat Exchanger

A .6 to 1.0 Mwt rating heat exchanger was used as the primary heat sink for the SNAP 8 Experimental Reactor (S8ER) test program. The core was of tube and fin construction with six fins per inch. The tubes were fabricated from 1-1/2-inch diameter Schedule 40 316 stainless steel tubing with 3.4 in. OD by 0.030 in. thick 430 stainless steel fins helically wound and pressed into preplowed grooves in the tubing. The heat exchanger was oriented horizontally with the inlet and outlet manifolds on the same end. The tube bundle arrangement consisted of four rows of four tubes each. NaK entered the inlet manifold at the bottom, split between the four tubes, made four passes through the air stream, and then exited through the outlet manifold at the top. Each four-pass tube assembly had three U-bends which permitted complete freedom for thermal expansion. Air was blown straight up through the heat exchanger by a squirrel-cage blower mechanically operated inlet and outlet louvers and variable fan speed were used to vary cooling as required. A metal

shield was positioned over the air-blast heat exchanger to protect it from direct rainfall. The active portion of the tube bundle was 54 in. long by 20 in. wide by 17 in. high. Destructive postoperative examination of the heat exchanger indicated that considerable life was still available at shutdown.

S8DR - A similar rated bare tube heat exchanger was used as the primary heat sink for the SNAP 8 Developmental Reactor (S8DR). The tube bundle was 48 in. long by 24 in. wide by 8 in. high and was fabricated from 192, 4-ft long by 3/4-in. diameter tubes. NaK entered the inlet manifold on one side to make one pass through the air stream and exited through the outlet manifold on the other side. Each tube was straight and was rigidly attached to the inlet and outlet headers. This unit failed after 600 hr operation because of excess thermal expansion of the hotter running center tubes. The center tubes buckled and their ends showed signs of tube metal flow at the tube-to-header joint.

This unit was replaced with a fin tube assembly identical to the S8ER unit that was successful. This unit has been in use since May 1968, with more than 3500 hr accumulated operating time at temperatures above 1000°F. No problems have been noted with this unit.

SRE (43,44)

The Sodium Reactor Experiment (SRE) used two sodium-to-air coolers (main and auxiliary) to dissipate the reactor heat. (The main cooler was in parallel with the steam generator.) The main air-blast heat exchanger consists of four U-shaped tube bundles installed in a protective housing above the d-c electric-motor-driven fans. The tubes (1 in. OD x 16 BWG wall thickness) have external Type 410 SS fins 2-in. in diameter, spaced 8 per inch.

There are 204 U-tubes 26-1/2 ft in length. They provide 23,600 ft² of heat removal surface (equivalent to 30 Mwt - 20 Mwt nominal). At normal operating power (20 Mwt) the estimated heat-transfer coefficient is 8.3 Btu/hr-ft²°F, and the exit air temperature is 277°F with an inlet air temperature at 100°F. Below the tube bundles there are two 11-ft diameter, five-bladed fans, each driven by a 50-hp variable speed d-c motor.

All tubes are connected in parallel from headers at one side of the assembly. The direction of air flow is normal to the sodium flow. Mechanically operated louvers are installed above the tube bundles to assist in controlling air flow. Tubular electric heaters are mounted below the tube bundles for preheating the system and for providing makeup heat during low-power operation. These heaters maintain a temperature of 350°F during shutdown.

The auxiliary air-blast heat exchanger design is similar, but has only 30 U-tubes 8 ft in length. It has a heat removal rating of 1 Mwt with a design heat-transfer coefficient of 5.8 Btu/hr-ft²-°F. It utilizes a 5-ft diameter fan driven by a 5-hp variable speed d-c motor.