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Heat Pipe as a Passive Cooling System Driving New Generation of Nuclear Power Plants

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Abstract

The technology of the Heat Pipe (HP) system is very well known for scientists and engineers working in the field of thermal-hydraulic since its invention at Las Alamos Nation Laboratory around the 1960s time frame. It is a passive heat transfer/heat exchanger system that comes in the form of either a constant or variable system without any mechanical built-in moving part. This passive heat transfer system and its augmentation within the core of nuclear power reactors have been proposed in the past few decades. The sodium, potassium, or mercury type heat pipe system using any of these three elements for the cooling system has been considered by many manufacturers of fission reactors and recently fusion reactors particularly Magnetic Confinement Fusion (MCF). Integration of the heat pipes as passive cooling can be seen in a new generation of a nuclear power reactor system that is designed for unconventional application field such as a space-based vehicle for deep space or galaxy exploration, planetary surface-based power plants as well as operation in remote areas on Earth. With the new generation of Small Modular Reactor (SMR) in form of Nuclear Micro Reactors (NMR), this type of fission reactor has integrated Alkali metal heat pipes to a series of Stirling convertors or thermoelectric converters for power generation that would generate anywhere from 13kwt to 3Mwt thermal of power for the energy conversion system.

Keywords: Renewable, Nonrenewable source of energy, Fusion and fission reactors, Small modular reactors and generation four system, Nuclear micro reactor, Space reactor, Dynamic site, Return on investment, Total cost of ownership.

Abbreviations: HPs-Heat Pipes, LANL-Los Alamos National Laboratory, NASA-National Aeronautics and Space Administration, MWe-Mega-Watt Electric, kWe-kilowatt Electric, FHR-Fluoride-salt-cooled High-temperature Reactor

Introduction

With new generation of fission reactors at physical reduction size to and smaller footprint that is known as Nuclear Micro Reactor (NMR), a new door has been opened up for future space transportation and surface power applications [1]. As we have learned from undergraduate nuclear engineering class most of Generation Three (GEN-III) either in form of Light Water Reactor (LWR) or Pressurized Water Reactor (PWR) do need to have access to fresh water for their cooling process, although historically heat pipes system were suggested and used for cooling core as safety system or either as first or secondary loop cooling system. For example, mercury heat pipe for Liquid Metal Fast Breeder Reactor (LMFBR) (i.e. Clinch River Project under Westinghouse Research and Development program around 1970s time frame) was implemented as safety cooling system by the first author of this article [2,3].

One of the aspects of heat pipe application and its integration in Generation Four (GEN-IV) type reactor as means of heat transfer system was suggested by Zohuri et al. was for two type of high temperature reactors such as a Molten Salt Reactor (MSR) and a Fluoride-salt-cooled High-temperature Reactor (FHR) and it is published in Nuclear Technology journal as a critical review article, just recently [4]. The Generation IV (GEN IV) nuclear reactor design and the technology is known as nuclear micro reactors that are currently under development by many nuclear manufacturer and the advantages of nuclear micro reactor applications as sources of renewable energy, their use in military applications and department of defense requirements. The nuclear industry's trend toward the design of small and micro reactors for remote areas with no access to fresh water continuously is investigated by their engineers and scientists as well. Nuclear Micro Reactor (NMR) safety, security issues, and cost concerns even for space journey are also explored [1].

One important edge and niche for nuclear energy as we stated in is the demand for power production at remote locations far away from reach to a reliable electrical grid. Nuclear power energy has excellent potential applications at overseas strategic defense locations, theaters of the remote battlefield, providing power to remote communities, as well as emergency locations for tribe's way away from any general population and communities. The mobility of these types of reactors is another advantage of NMRs. With proper safeguards, a 1 to 10 Mega-Watt electric (MWe) output, a mobile reactor system could provide robust, self-contained, and long-term power in any environment. The integration of an Nuclear Air Combined Cycle (NACC), not only makes these reactors to be more efficient from Total Cost of Ownership (TCO), there would be no need for any external means of cooling media such as fresh water in respect to "traditional" reactors of Generation Three or GEN-III [5,6]. Heat pipe-cooled fast-spectrum nuclear reactors have been identified as a candidate for these applications. Heat pipe reactors, using alkali metal heat pipes, are perfectly suited for mobile applications because their nature is inherently simpler, smaller, and more reliable than "traditional" nuclear power plants.

Reactors come in a range of sizes. The size fits a variety of applications as shown in **Figure 1**. Los Alamos National Laboratory (LANL) has traditionally designed reactors for applications in the 1 to 200 kilowatt electric (kWe) range as shown in the first two columns in Figure 1. Most of LANL's designs have been for space applications for the National Aeronautics and Space Administration (NASA) Almost all of these reactor designs are based on a small highly reflected fast reactor concept that uses heat pipes as the means of heat removal from the reactor core. This is an ideal technology for space where reliability and simplicity are key requirements [7].

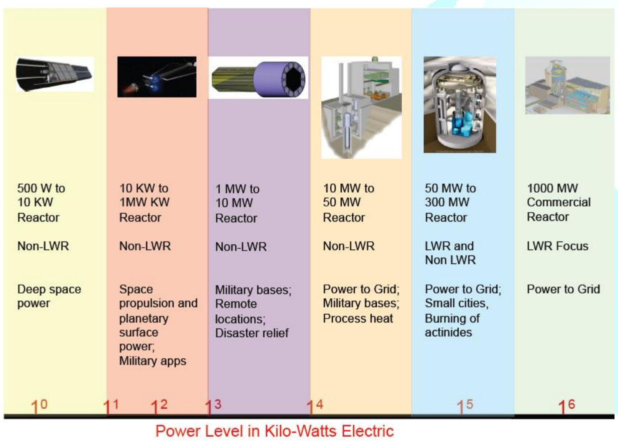

Figure 1: Sizes range of reactor applications [7].
(Courtesy of Las Alamos National Laboratory)

LANL performed a study to examine the issues of scaling heat pipe reactor technology to the low MWe range (shown in the third column of Figure 1.) The low MWe range is an area that was examined in the 1950s through 1970s by the U.S. Army for power at remote locations such as the Arctic, Antarctica and the Panama Canal. Power at remote locations removed from a reliable electrical grid is a potential future niche for nuclear energy. Remote locations include strategic defense locations (such as pacific island bases), theaters of battle, remote communities (such as northern Alaska), and emergency locations (e.g., earthquake relief). This was, in part, the goal of the Army Nuclear Power Program that ran from 1954 through 1977 [7].

An important key technology for Heat pipes driven nuclear reactors is that the HPs are used as a first loop heat exchanger to cool the core of reactor. Reactors that are situated in a remote area with augmented heat pipes as part of their cooling system are perfect for such an application and they have characteristics such as self-regulation and high reliability.

A heat pipe transfers heat between two bodies with no temperature change from end to end (isothermally.) A schematic of a heat pipe is shown in **Figure 2**. The heat pipe makes use of the phase change of the fluid as it moves from boiling at one end to condensation at the other end. This ability makes heat pipes an ideal means to extract thermal power from a nuclear reactor [7].

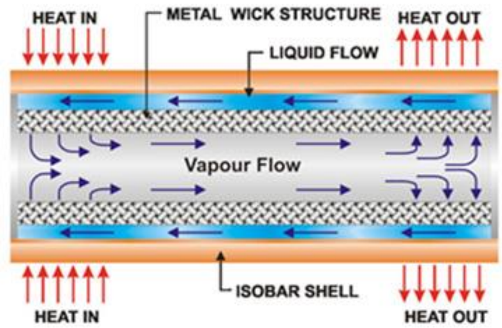

Figure 2: The main regions of the heat pipe.
(Courtesy of www.acrolab.com)

Fundamental of Heat Pipe

A Heat pipe is a two phase heat transfer device with a very high effective thermal conductivity. It is a vacuum tight device consisting of an envelope, a working fluid, and a wick structure. As shown in **Figure 3**, the heat input vaporizes the liquid working fluid inside the wick in the evaporator section. The saturated vapor, carrying the latent heat of vaporization, flows towards the colder condenser section. In the condenser, the vapor condenses and gives up its latent heat. The condensed liquid returns to the evaporator through the wick structure by capillary action. The phase change processes and two- phase flow circulation continue as long as the temperature gradient between the evaporator and condenser is maintained.

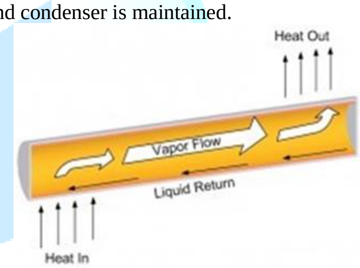

Figure 3: A simple physical configuration of heat pipe cut-away [2].

Heat pipes function by absorbing heat at the evaporator end of the cylinder, boiling and converting the fluid to vapor. The vapor travels to the condenser end, rejects the heat, and condenses to liquid. The condensed liquid flows back to the evaporator, aided by gravity. This phase change cycle continues as long as there is heat (i.e. warm outside air) at the evaporator end of the heat pipe. This process occurs passively and there is no external electrical energy required.

At the hot interface of a heat pipe a liquid in contact with a thermally conductive solid surface turns into a vapor by absorbing heat from that surface. The vapor then travels along the heat pipe to the cold interface and condenses back into a liquid-releasing the latent heat. The liquid then returns to the hot interface through capillary action, centrifugal force, or gravity, and the cycle repeats. Due to the very high heat transfer coefficients for boiling and condensation, heat pipes are highly effective thermal conductors. The effective thermal conductivity varies with heat pipe length and can approach 100 kW/(m•K) for long heat pipes, in comparison with approximately 0.4 kW/(m•K) for copper.

Heat pipes employ evaporative cooling to transfer thermal energy from one point to another by the evaporation and condensation of a working fluid or coolant. Heat pipes rely on a temperature difference between the ends of the pipe and cannot lower temperatures at either end below the ambient temperature (hence they tend to equalize the temperature within the pipe) (**Figure 4**).

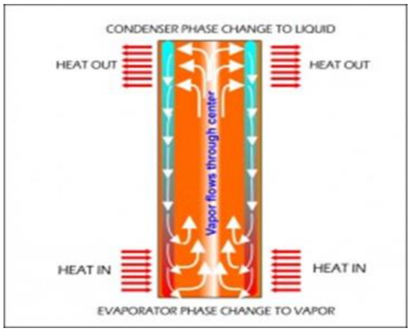

Figure 4: Internal schematic heat pipe structure [2].

Heat pipes have an envelope, a wick, and a working fluid. Heat pipes are designed for very long term operation with no maintenance, so the heat pipe wall and wick must be compatible with the working fluid. Some material/working fluids pairs that appear to be compatible are not. For example, water in an aluminum envelope will develop large amounts of non-condensable gas over a few hours or days, preventing normal operation of the heat pipe.

Heat pipes are manufactured in two types in general, as shown in **Figure 5** and **Figure 6**, depending on their applications as: [8]

1. Constant Heat Pipe (CHP).
2. Variable Heat Pipe (VHP).

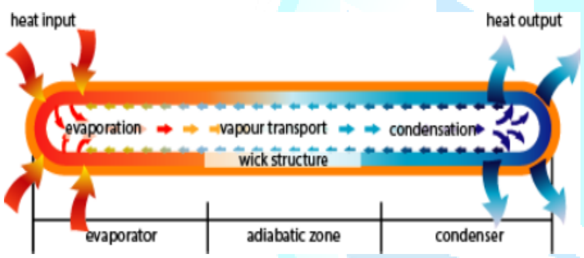

Figure 5: A Simple Constant Heat Pipe (CHP) configuration [2,4].

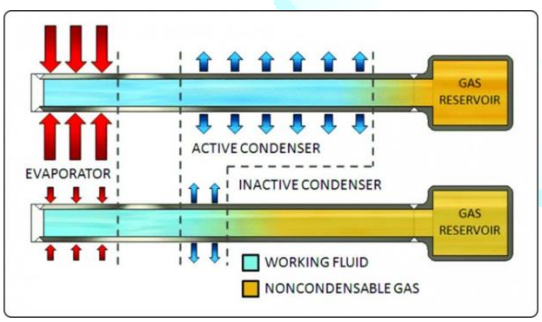

Figure 6: A Simple Variable Heat Pipe (VHP) configuration [2].

Furthermore, In addition to standard, Constant Conductance Heat Pipes (CCHPs), there are a number of other types of heat pipes, including:

- Vapor chambers (planar heat pipes), which are used for heat flux transformation, and isothermalization of surfaces
- Variable Conductance Heat Pipes (VCHPs), which use a Non-Condensable Gas (NCG) to change the heat pipe effective thermal conductivity as power or the heat sink conditions change
- Pressure Controlled Heat Pipes (PCHPs), which are a VCHP where the volume of the reservoir, or the NCG mass can be changed, to give more precise temperature control
- Diode heat pipes, which have a high thermal conductivity in the forward direction, and low thermal conductivity in the reverse direction
- Thermosyphons, which are heat pipes where the liquid is returned to the evaporator by gravitational forces
- Rotating heat pipes, where the liquid is returned to the evaporator by centrifugal forces

Fundamental Operation of Heat Pipe and Thermosyphon Process

The heat pipe shown in Figure 2 is essentially a constant temperature, heat transfer device. It consists of a closed container in which vaporization and condensation of a fluid takes place. The choice of a fluid depends on the temperature range in which the heat pipe will be used. Heat is applied to one end of the heat pipe (evaporator), which raises the local temperature leading to evaporation of the working fluid.

Note: Thermosiphon (alternately. thermosyphon) refers to a method of passive heat exchange based on natural convection which circulates liquid without the necessity of a mechanical pump. Because of the saturation conditions this temperature difference results in a difference in vapor pressure, which in turn causes vapor to flow from the heated section to the cold section of the pipe (condenser). Wicking material is used in regions to facilitate the path of the vapor to the pipe. Typically, a good wicking material maximizes the movement of the fluid, has uniform porosity, has very small pores such that the wick can generate a large capillary pressure, is resistant to degradation by temperature, and does not react or degrade chemically with the working fluid. Heat pipes can have a number of different geometric configurations. These configurations include cylindrical, spherical, square, or any other geometry such that the inner volume of the heat pipe forms a channel from the evaporator section to the condenser section. Metals used to fabricate the heat pipes should be compatible with the working fluid as well as with the external media in contact with the evaporator and the condenser. The outermost shell of the heat pipe is referred to as the container. The container encloses the functioning parts of the heat pipe and provides structural rigidity.

The liquid flow takes place in a porous material usually referred to as wick. The interior space of the heat pipe is called the vapor core, which provides passage for the vapor flow. Heat pipes have been used extensively in a variety of energy storage systems such as chemical reactors and spacecraft temperature equalization. Heat pipes are well suited to thermal storage systems, particularly in the roles of heat delivery and removal, because of their highly effective thermal conductivity and passive operation.

Heat Pipe Operational Limits

As with any other system, the performance and operation of heat pipes are limited by various parameters. Physical phenomena that might limit heat transport in heat pipes include capillary forces, choked flow, interfacial shear and incipient boiling. The heat transfer limitations depend on the size and shape of the pipe, working fluid, wick parameters, and operating temperature. The lowest limit among these constraints defines the maximum heat transport limitation of a heat pipe at a given temperature. The operation limits of a heat pipe as illustrated in **Figure 7**, in the order of increasing power throughput and temperature, are the viscous, sonic, wicking or capillary, entrainment, boiling, and heat rejection. The latter is dictated by the length of the condenser section, surface emissivity and available area for heat rejection in the radiators for space nuclear reactor power systems [8].

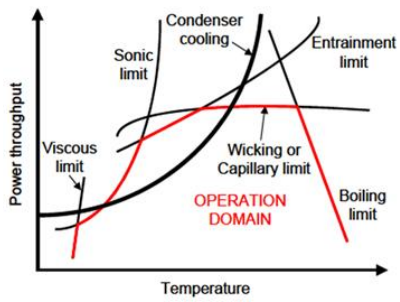

Figure 7: Operation limits of a heat pipe [2].

In the design of heat pipes, consideration must be given not only to the internal structure and fluid dynamics of the pipe but also to the external conditions imposed upon it. By fully operational steady characteristics of heat pipe up to now, we have assumed a steady-state heat pipe, with heat being added to and removed from the heat pipe at a constant rate. Under this condition we mean that the heat pipe is relatively isothermal, and heat is being dissipated over the entire length of the condenser. If the heat pipe input and output rates are then equal, the heat pipe will be functioning in the steady-state condition. If an imbalance between the heat input and output rates, take place, then the temperature of the fully operational heat pipe will continue to change with time to a level at which the balance between heat input and output rates is restored [9].

For any heat pipe design and its application certain criteria have to be met and heat transfer limitations should be considered to make sure the heat pipe works within its design specification and follows its normal operation as they are listed as a main summary of these limitations.

Viscous Limit

The viscous limit dominates at low temperature, near the melting point of the working fluid. The high liquid pressure losses in the wick, due to the high viscosity and low permeability, limit liquid flow from the condenser to the evaporator section. Avoiding this limit requires operating at a relatively low input power until the heat pipe temperature is high enough to decrease the liquid viscosity and hence, the pressure losses in the wick.

Sonic Limit

The sonic limit, also dominant at low temperatures, should be avoided. The vapor pressure of the working fluid is a good indicator of reaching this limit [9]. The vapor pressure and physical state of the heat pipe liquid at ambient temperature, as well as the thermal resistance between the condenser and the adjacent heat sink has significant influence of the startup behavior of a heat pipe.

Prior to start up, the temperature of a heat pipe is equal to the ambient temperature, and its internal pressure is equal to the vapor pressure of the heat pipe liquid at ambient temperature. Also, depending on its freezing point, the heat pipe liquid may be in the liquid or the solid state. The transient behavior and problems of heat pipe startup have been studied by Cotter [10] and Deverall, et al [11]. Tests results reported by latter indicates that the transient behavior of a heat pipe depends on the circumstances mentioned above.

As liquid and vapor move in opposite directions, the vapor exerts a shearing force on the liquid at the liquid-vapor interface. If this shear force exceeds the surface tension of the liquid, liquid droplets are entrained into the vapor flow and are carried towards the condenser section as it is illustrated in **Figure 8**. The magnitude of this shear force depends on the thermo-physical properties of the vapor and its velocity and if it becomes large enough, it causes dry out of the evaporator [9].

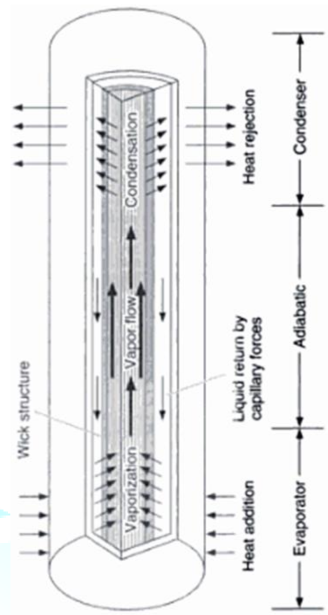

Figure 8: Schematic of heat pipe [2].

Entrainment Limit

The Entrainment Limit at high vapor velocities, droplets of liquid in the wick are torn from the wick and sent into the vapor, which results in dry out. An abrupt wick dry out will take place when entrainment begins and there is a sudden substantial increase in fluid circulation to the point that the return liquid system cannot accommodate this flow increase. This limit was identified by Kemme [12] when he discovered the sound sounds that were made by droplets from media liquid within heat pipe striking the condenser end of the heat pipe and through the abrupt overheating of the evaporator.

The entrainment limit also is known as an axial heat flux, the heat transport rate per unit of vapor space cross-section area. Under this condition, the fluid velocities increase so as the drag force as the heat transport rate through the heat pipe increases. The drag force on the heat pipe liquid is proportional to the liquid surface area in the wick pores, whereas the resisting surface tension force is proportional to the pore width normal to the drag force. Consequently, the ratio of the drag force to the surface tension force is proportional to the pore size and decreases as the pore size diminishes [9].

The entrainment limit is typically encountered during a heat pipe startup, when the vapor flow at the evaporator section exit is chocked (velocity is near sonic). The induced interfacial shear stress at the surface of the liquid saturated wick, by the vapor counter-current flow could not only slow down the liquid flow to the evaporator section, but also break up and entrain tiny liquid droplets back to the condenser. The reduced replenishing of the wick in the evaporator section with liquid could result in a local dry out. The entrainment limit could be raised by employing a small pore size wick and/or increasing the cross-sectional flow area for the vapor in the heat pipe to lower its velocity at the exit of the evaporator section.

Wicking Limit

The "wicking limit" or "capillary limit" is the best understood. This condition is occurring when an applied heat flux causes the liquid in the wick structure to evaporate faster than it can be supplied by capillary pumping power of the wick. Once this event takes place the meniscus at the liquid-vapor interface continues to withdraw and move back into the wick until all of the liquid has been depleted. This action will result the wick to become dry and heat pipe container temperature may continue to rise at the evaporator until a "burnout" condition is reached [13]. The difference in the capillary pressure across the liquid-vapor interfaces governs the operation of the heat pipes. This is one of the most important parameters that affect the performance and operation of a heat pipe. It is usually a major limiting factor in the working of low-temperature or cryogenic heat pipes [9,14].

The capillary limit is encountered when the capillary pressure is not sufficient to pump the liquid back to evaporator causing the dry out of the wick of the evaporator end. The physical structure of the wick is one of the most important reasons for this limit and the type of working fluid affects it. Once limit is encountered, any further increase in heat input may cause serious damage to the heat pipe [9].

The performance and operational characteristics for a given heat pipe and thermosiphons as a function of the mean adiabatic or operating temperature and envelop of these operating limits have been discussed in above (**Figure 9**).

Any design of heat pipe that falls within operation envelop of its function (red color) essentially considered as a good design and will work within specific function of operating temperature that is defined for that design [1]. Thus, The capillary (or wicking) limit is encountered when the net capillary pressure head is less than the combined pressure losses of the liquid flow in the wick and of the counter-current vapor flow in the heat pipe. The capillary pressure head for circulating the heat pipes working fluid increases with increasing the liquid surface tension and decreasing radius of curvature of the liquid-vapor meniscus in the surface pores in the wick, as illustrated in term of Rc in **Figure 9** [8].

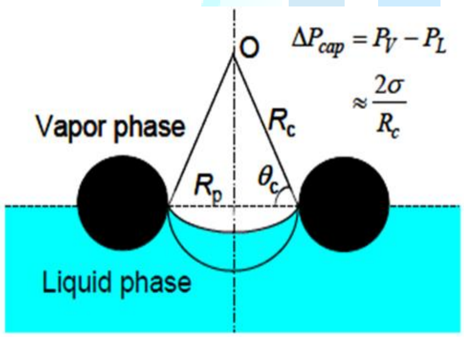

Figure 9: Capillary pumping of the working fluid in heat pipe [2].

Boiling Limit

A boiling at the inside surface of the heat pipe wall in the evaporator section is likely when the local liquid superheat exceeds that for incipient nucleate boiling. The ensuing nucleation and growth of vapor bubbles block the flow of returning liquid to the evaporator section. In alkali-metal heat pipes, the boiling limit is typically encountered at high wall temperatures, beyond those selected for nominal operation [8].

An additional operation limit, often overlooked, is that of heat rejection in the condenser section. In space reactor power systems, the condenser section of the radiator heat pipes is cooled by thermal radiation into outer space. Therefore, the heat removal rate is proportional to the effective surface emissivity and area in the condenser section and the average surface temperature to the fourth power. Metallic surfaces typically have low emissivity, thus are treated with a black coating or paint to improve heat rejection. This operation limit might be encountered late in life, due to the accumulation of non-condensable gases, generated [8].

Heat Pipe Pros and Cons

Heat pipes are tubes that have a capillary wick inside running the length of the tube, are evacuated and then filled with a refrigerant as the working fluid and are permanently sealed. The working fluid is selected to meet the desired temperature conditions and is usually a Class I refrigerant. Fins are similar to conventional coils-corrugated plate, plain plate, spiral design. Tube and fin spacing are selected for appropriate pressure drop at design face velocity. HVAC systems typically use copper heat pipes with aluminum fins; other materials are available.

Advantages:

- Passive heat exchange with no moving parts,
- Relatively space efficient,
- The cooling or heating equipment size can be reduced in some cases,
- The moisture removal capacity of existing cooling equipment can be improved,
- No cross-contamination between air streams.

Disadvantages:

The use of the heat pipe

- Adds to the first cost and to the fan power to overcome its resistance,
- Requires that the two air streams be adjacent to each other,
- Requires that the air streams must be relatively clean and may require filtration.

Heat Pipe Applications

A heat pipe is a passive energy recovery heat exchanger that has the appearance of a common plate-finned water coil except the tubes are not interconnected. Additionally, it is divided into two sections by a sealed partition. Hot air passes through one side (evaporator) and is cooled while cooler air passes through the other side (condenser). While heat pipes are sensible heat transfer exchangers, if the air conditions are such that condensation forms on the fins there can be some latent heat transfer and improved efficiency (**Figure 10**).

Application of heat pipe heat exchanger enhancement can improve system latent capacity. For example, a 1 ^{0}F dry bulb drop in the air entering a cooling coil can increase the latent capacity by about 3%. Both cooling and reheating energy is saved by the heat pipe's transfer of heat directly from the entering air to the low-temperature air leaving the cooling coil. It can also be used to precool or preheat incoming outdoor air with exhaust air from the conditioned spaces.

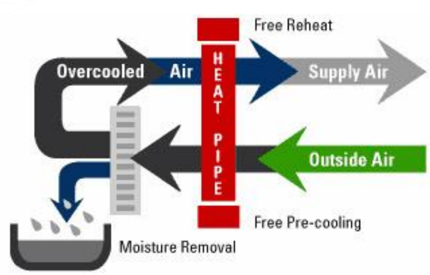

Figure 10: Heat pipe application concept [2].

The best applications of heat pipe are listed below:

- Where lower relative humidity is an advantage for comfort or process reasons, the use of a heat pipe can help. A heat pipe used between the warm air entering the cooling coil and the cool air leaving the coil transfers sensible heat to the cold exiting air, thereby reducing or even eliminating the reheat needs. Also, the heat pipe

precools the air before it reaches the cooling coil, increasing the latent capacity and possibly lowering the system cooling energy use.
- Projects that require a large percentage of outdoor air and have the exhaust air duct in close proximity to the intake can increase system efficiency by transferring heat in the exhaust to either precool or preheat the incoming air.

Moreover, the best possible applications are also mentioned below as well:
- Use of a dry heat pipe coupled with a heat pump in humid climate areas.
- Heat pipe heat exchanger enhancement used with a single-path or dual-path system in a supermarket application.
- Existing buildings where codes require it or they have "sick building" syndrome and the amount of outdoor air intake must be increased,

New buildings, where the required amount of ventilation air causes excess loads or where the desired equipment does not have sufficient latent capacity.

Other aspects of heat pipes that could be taken under considerations are:

Technology Types (Resource)

Hot air is the heat source, flows over the evaporator side, is cooled, and evaporates the working fluid. Cooler air is the heat sink, flows over the condenser side, is heated, and condenses the working fluid. Vapor pressure difference drives the evaporated vapor to the condenser end and the condensed liquid is wicked back to the evaporator by capillary action. Performance is affected by the orientation from horizontal. Operating the heat pipe on a slope with the hot (evaporator) end below horizontal improves the liquid flow back to the evaporator. Heat pipes can be applied in parallel or series.

Efficiency

Heat pipes are typically applied with air face velocities in the 450 to 550 feet per minute range, with 4 to 8 rows deep and 14 fins per inch and have an effectiveness of 45% to 65%. For example, if entering air at 77 ^{0}F is cooled by the heat pipe evaporator to 70 ^{0}F and the air off the cooling coil is reheated from 55 ^{0}F to 65 ^{0}F by the condenser section, the effectiveness is 45 % [=(65-55)/(77-55)=45%]. As the number of rows increases effectiveness but at a declining rate. For example, doubling the rows of a 48% effective heat pipe increases the effectiveness to 65%.

Tilt Based Heat Pipe

Tilt control can be used to:
- Change operation for seasonal changeover,
- Modulate capacity to prevent overheating or overcooling of supply air,
- Decrease effectiveness to prevent frost formation at low outdoor air temperatures.

Tilt control (6 maximum) involves pivoting the exchanger about its base at the center with a temperature-actuated tilt controller at one end. Face and bypass dampers can also be used.

Nuclear Power Conversion

In craft the extreme thermal conditions are encountered. These alkali metal heat pipes transferred heat from the heat source to a thermionic or thermoelectric converter to generate electricity. Since the early 1990s, numerous nuclear reactor power systems have been proposed using heat pipes for transporting heat between the reactor core and the power conversion system. The first nuclear reactor to produce electricity using heat pipes was first operated on September 13, 2012 in a demonstration using flattop fission.

In Nuclear power plant application, heat pipes can be used as a passive heat transfer system for performing as overall thermal hydraulic and natural circulation sub-system in an Inherent Shutdown, Heat Removal System (ISHRS) in the core (i.e. installed on top of the core doom) of nuclear reactor such as molten salt or liquid metal fast breeder type reactors, as a secondary fully inherent shutdown system loop acting like heat exchanger from safety point of view so the reactor never reaches to its melting point in case of accidental events.

Few concepts of heat pipe driving nuclear power reactor currently under consideration and envisioned are that, each of the reactor segments has its own set of heat exchanger. Each segment with its heat exchanger, reflector and shield is fabricated, assembled and shipped separately to the reactor site. They are then assembled into the reactor system, and the secondary sides of the heat exchangers are connected to piping linking them to the power conversion system. A simple schematic of the reactor, shield and heat exchanger is shown in **Figure 11**.

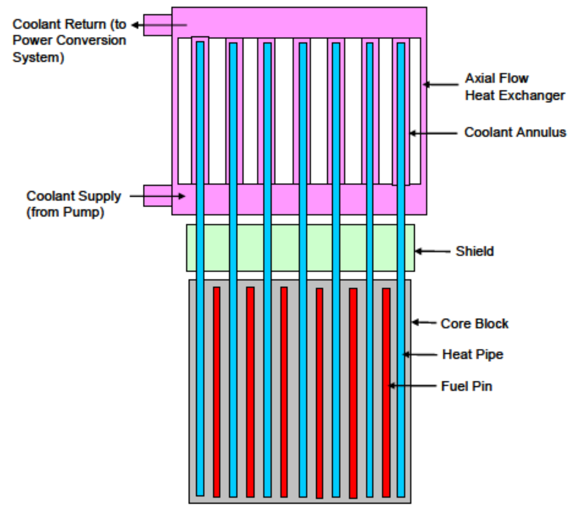

Figure 11: Core to heat exchanger schematic [7].
(Courtesy of Las Alamos National Laboratory)

As depicted in above figure, the heat pipes extend from the reactor core, through the upper shield portion and into the Heat Exchanger (HX). TH HX has an axial flow configuration. The coolant enters into a plenum at the bottom, flows up through annuli formed by the heat pipes and the walls of the heat exchanger, into an upper plenum and exits from a single pipe there. The advantages of the axial flow heat exchanger are that the length and annulus area can be selected to produce a desired pressure drop and a temperature difference between the coolant exit and heat pipe as small as desired. Also, the core can be easily made into orifice by adjusting the flow areas [7].

Overall, the fluoride-salt-cooled high-temperature reactor and some fusion reactors use clean fluoride salts as reactor coolants that have melting points above 450 ^{0}C and generate tritium. The leading salt coolant option for the FHR is flibe ($7Li_2BeF_4$) containing isotopically-separated lithium-7 to minimize neutron adsorption. flibe with lithium-6 is proposed as a fusion reactor coolant to maximize tritium production as a fuel. Some Molten Salt Reactors (MSRs) where the fuel is dissolved in the coolant also use flibe containing isotopically-separated lithium-7. In a recent published paper by Zohuri et al. [4], we examine the use of heat exchangers that contain multiple heat-pipes for transferring (1) heat from the primary salt coolant to steam or air-Brayton power cycles and (2) FHR and MSR decay heat from the primary coolant to the environment. Heat pipes can turn on at preset temperatures and thus reduce the risk of freezing the liquid salt coolant if the reactor shuts down.

Heat pipes can include permeation barriers to recover tritium that diffuses from the salt coolant into the heat pipes and thus prevent tritium releases into the power system or environment for the individual flow annuli. This is especially important for the heat pipes located at the edges of the blocks, which receive significantly reduced power.

In this published paper [4], a clean flibe salt coolant is also proposed for high-magnetic-field fusion machines. For fusion, flibe with lithium-6 is the only salt coolant option because of the requirement to generate sufficient tritium to fuel the reactor. Tritium is primarily generated by neutron adsorption in lithium-6. Tritium is also generated in smaller quantities from fast neutron interactions with lithium-7.

Recent advances in superconductors enable doubling the magnetic field in fusion reactors [6,7]. In fusion systems, the plasma power density increases as one over the fourth power of the magnetic field. Higher magnetic fields can reduce the machine volume by an order of magnitude but creates major challenges. In a fusion blanket the 14-Mev neutrons slow down delivering most of the heat from the fusion reactor. With these higher power densities, it is very difficult to cool solid blankets. As a consequence, it is proposed to use flibe liquid-salt immersion blankets to adsorb the heat from the fast neutrons and breed tritium fuel (**Figure 12**).

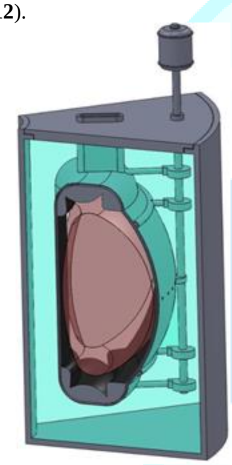

Figure 12: Simplified schematic of fusion liquid-salt immersion. Blanket Source: https://www.wikipedia.org

The blanket has four functions: (1) it slows down neutrons and converts that energy into heat, (2) the neutrons are used to breed tritium, (3) the salt acts as the primary radiation shielding to protect the magnets and (4) high-velocity flibe salt cools the first wall that separates the fusion plasma from the salt [4].

For fission or fusion applications, these salts will typically deliver heat through heat exchangers to the power cycle at between 600 and 700 ^{0}C. The minimum salt temperature is significantly above the melting point of flibe (459 ^{0}C) for two reasons: (1) flibe near its melting point is viscous and (2) a reasonable temperature margin is required to avoid the risk of freezing salt in heat exchangers. The maximum salt temperature is controlled by availability of economic materials of construction.

Flibe salt coolants present two unique challenges for heat exchangers. First, one must prevent salt freezing by systems that (1) prevent the heat exchangers from having cold fluids that could freeze the salt or (2) heat exchanger designs that prevent flibe salt from freezing-the option discussed herein. Second, one must prevent tritium from diffusing through metal heat exchangers to the power cycle or the environment. Heat pipes can achieve these goals [4].

Conclusion

Overall, a heat pipe is a heat-transfer device that combines the principles of both thermal conductivity and phase transition to effectively transfer heat between two solid interfaces (**Figure 13**).

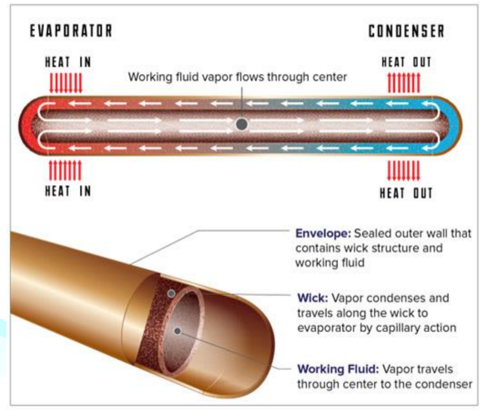

Figure 13: Top view depiction of heat pipe infrastructure [2].

Phase-change processes and the two-phase flow circulation in the HP will continue as long as there is a large enough temperature difference between the evaporator and condenser sections. The fluid stops moving if the overall temperature is uniform but starts back up again as soon as a temperature difference exists. No power source (other than heat) is needed. In some cases, when the heated section is below the cooled section, gravity is used to return the liquid to the evaporator. However, a wick is required when the evaporator is above the condenser on earth. A wick is also used for liquid return if there is no gravity, such as in NASA's micro-gravity applications.

In conclusion, heat pipe reactors could be scaled into the low to mid 10's of MW electric with the right choice of fuel and reactor materials. A recommended power level of about 30 MWe was seen as the upper end of what could be accomplished with current technology. Other reactor technologies would make more sense above power levels approaching 100 MWe or higher. Going forward it makes the most sense to build the first heat pipe reactors with conventional fuel and materials. The easiest path forward would be to stay with a uranium oxide fuel and stainless steel.

A possible reactor concept for remote locations is shown in **Figure 14**. The reactor concept is a heat pipe reactor that would be coupled to an open air Brayton power conversion system. The goal of the concept would be to have a reactor that could be easily deployed by truck or air transport. A concept for transport is shown in **Figure 15**. In this concept the reactor is flown to a military base and then transported to site via a semi-truck. Dirt berms are used as partial shielding and the entire truck is moved into location. The reactor is integrated into the existing power structure by replacing natural gas driven Brayton power conversion with reactor driven power conversion [5].

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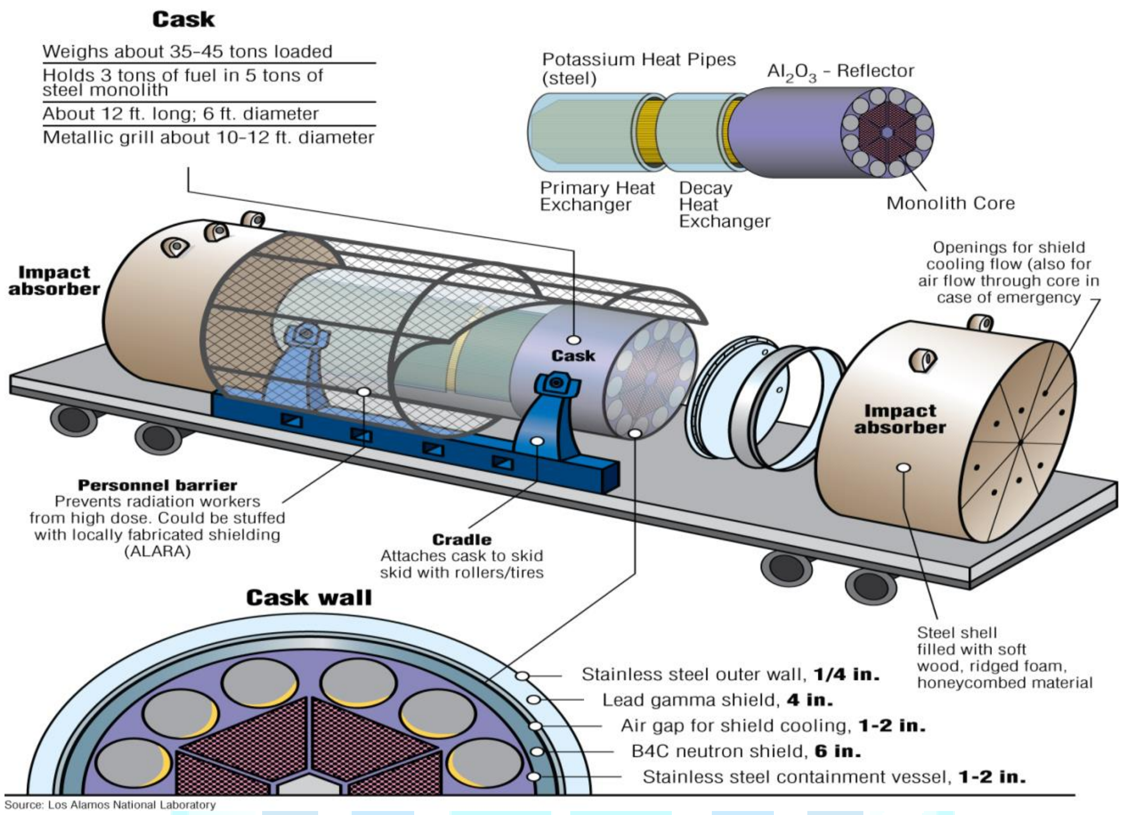

Figure 14: Mobile heat pipe reactor in shipping cask [7].
(Courtesy of Las Alamos National Laboratory)

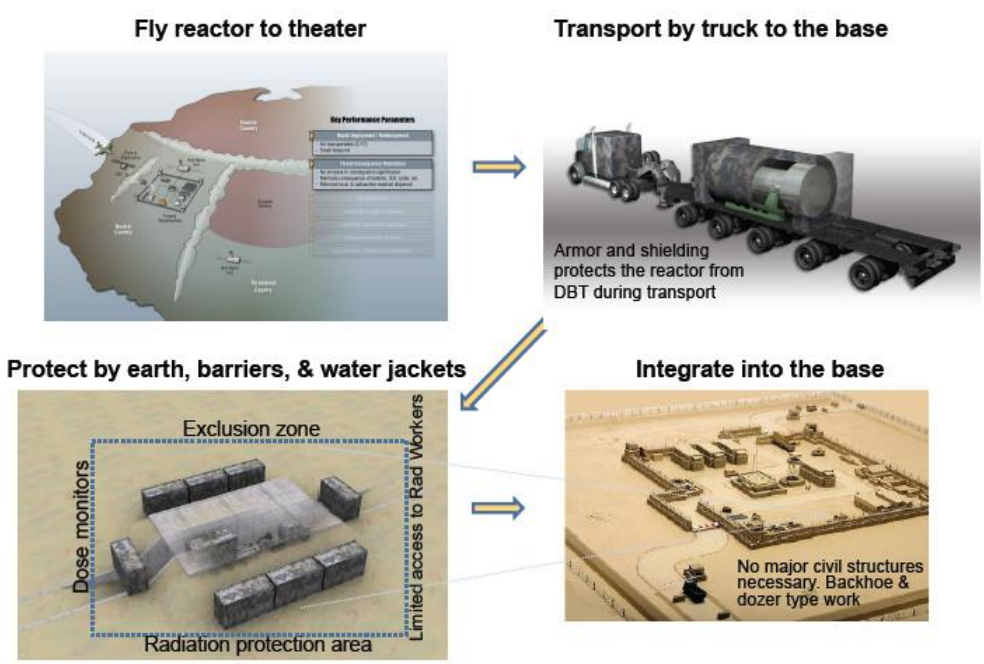

Figure 15: Concept for mobile reactor deployment [7].
(Courtesy of Las Alamos National Laboratory)

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