Reactor Boiler and Auxiliaries - Course 133

HEAT TRANSPORT FLUID COMPARISONS

No single substance, or mixture, can be found which satisfies all the heat transport fluid requirements which have been discussed. It is for this reason that several possible fluids have been and are being tried in reactor systems. The general characteristics of the most likely fluids will now be reviewed.

Light Water

Ordinary or light water is attractive, as a heat transport fluid, because it is readily available at low cost. It has a high specific heat and fair thermal conductivity. Its thermal conductivity is about 100 times lower than that of liquid metals but its value is well above those of organic liquids or gases. Hence the heat transfer characteristics of water are far superior to those of gases and organic liquids and are not much poorer than those of liquid metals and molten salts. Because of its good heat transfer coefficient, it is possible to decrease the flow rate of water and, since its density is relatively high, the pumping power required is low. The pumping power with water, for equivalent heat removal, is roughly in the order of one-tenth of that required with a gas at 10 atmospheres pressure.

Another basis for the comparison of heat transport fluids is the volumetric heat capacity, which is defined as the product ρc_p (in Btu/ft^3 - $^\circ$F). Water has one of the highest volumetric heat capacity and this enables a high rate of heat removal to be attained without an excessive rise in the heat transport fluid temperature. This helps to reduce thermal stresses in the system.

A further advantage of using light water as a heat transport fluid is that it can be used simultaneously as a moderator, which results in a fairly compact core. It melts at 32°F and, so, will not solidify during reactor shutdown.

The use of light water, however, has many drawbacks. The thermal neutron capture cross-section is too large to allow light water to be used as a heat transport fluid with any moderator unless some fuel enrichment is used. Water boils at 212°F under normal atmospheric pressure. Therefore, in order to extract the heat from the reactor at a high enough temperature, the heat transport system requires pressurization to prevent the water boiling. If the water is used simultaneously as moderator and heat transport fluid, the reactor can be enclosed in a pressure vessel. This does not involve additional material in the reactor core which increase neutron absorption but it does introduce the disadvantages, discussed previously, which are inherent in a pressure vessel design. If the moderator and heat transport fluids are to be kept separate, as in the pressure tube reactor concept, the additional strength required, because of pressurization, may result in more neutron absorption in the core. Either the pressure tubes must be made of zirconium alloy which has a low neutron capture cross-section but is expensive, or low alloy steel must be used for the pressure tubes thereby increasing neutron capture and necessitating the enrichment of the fuel.

Water at high temperature, even when pure and free from oxygen, becomes quite corrosive. With a pH of 5.5 to 7 the corrosion rates with zircalloy and stainless steel are quite acceptable but the corrosion rates with carbon steel or low alloy steel are not acceptable unless the pH is raised to between 9 and 11. This corrosion problem is more severe because of the presence of oxygen due to radiolytic decomposition of the water. This radiolytic decomposition can be reduced by removing ionic impurities. The decomposition of water is also discouraged by pressurizing and is not, therefore, as severe a problem in the heat transport system as it is in a low pressure moderator system. The cover gas space above the moderator allows the gas to escape from the water and encourages more decomposition. Experience at NPD G.S. has shown that it is better to allow the hydrogen concentration to reach an equilibrium value rather than use a degassifier to remove the decomposition products. The disadvantages with this is that it makes hydrogen available for absorption in zircalloy and this may result in hydrogen embrittlement of the zircalloy.

Radioactive O-19 and N-16 are produced in water as a result of neutron capture. Both these nuclei are gamma ray emitters and the N-16 gamma rays have very high energies. Extensive shielding is, therefore, required around the heat transport system equipment and piping external to the reactor. It also means that the heat transport system is not accessible for maintenance during reactor operation.

Although light water is relatively inexpensive, some cost is involved in maintaining it free of impurities. It is also undesirable to have the containing room and other equipment contaminated by radioactive fluid which could contain fission products from failed fuel elements. Leakage of water out of the system should, therefore, be avoided but the equipment would probably be more conventional than would be possible with heavy water.

Boiling Light Water

There are many advantages to be gained by permitting the heat transport system fluid to boil. If boiling water is used as a heat transfer fluid the large latent heat of vapourization can be used to increase the heat transport coefficient by a substantial amount. Fig. 1 shows how the heat flux, transferred to a fluid, varies with the temperature difference between the heated surface and the fluid. The shape of the graph should be regarded as being generally representative although actual values differ in different cases.

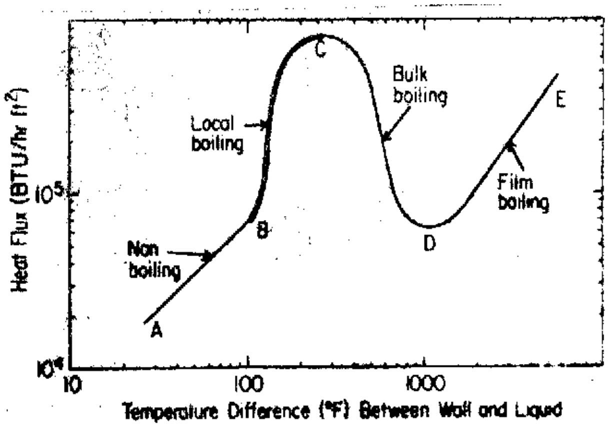

Fig. 1

The graph can be divided into a number of regions, in each of which the mechanism of heat transfer is different. While the heated surface temperature is below the water saturation temperature, (shown as the non-boiling section, AB), heat is transferred by single phase convection, i.e. ordinary convection in water. This is the method of heat transfer already considered.

In the local or nucleate boiling region, BC, the heated surface temperature exceeds the saturation temperature by a few degrees. Bubbles are formed on nuclei, such as solid particles or gas absorbed on the surface. As the bubbles break away, they collapse or continue to grow, depending on whether the bulk of the fluid is below or at the saturation temperature. The large increase in the heat flux in this region occurs as a result of the mixing of the liquid caused by the agitation of the bubbles. This greatly improves the heat transfer characteristics.

The heat flux continues to increase until the heated surface becomes blanketed by an unstable, irregular film in violent motion, with little direct contact between the water and the heated surface. Heat transfer is then by conduction and radiation through the film. The heat flux, consequently, decreases appreciably along CD. At D the film is stable and the heat transfer then improves as the surface gets hotter. However, such high temperatures are required, in the region DE, to attain comparable heat flux to those along BC, that they result in the destruction of the fuel or sheath. This is known as BURNOUT and must, of course, be avoided.

Care must be taken, when operating in the nucleate boiling region, that the operating point is not too near the maximum of the curve. A slight increase in heat flux would then cause a sudden change to film boiling, which usually results in burnout.

It would appear, therefore, that high heat fluxes can be obtained in the nucleate boiling region. This would enable the pumping power to be reduced. Nucleate boiling with the bubbles growing would lead to a net generation of steam in the reactor if the bulk fluid temperature is a little above the saturation temperature. This would allow a direct cycle to be used with the steam being fed directly into the turbine. This, in turn, eliminates the heat loss in the boiler of an indirect cycle. Fig. 2 illustrates two further advantages resulting from the direct cycle. The fuel element temperature, with the direct cycle, is lower for the same steam conditions. Alternatively the steam temperature is higher for the same fuel temperature. Secondly, the direct cycle can be operated at a much lower pressure than that required to prevent boiling in the indirect cycle using water as a heat transport fluid. This reduces thickness of pressure vessels or tubes and results in lower capital costs.

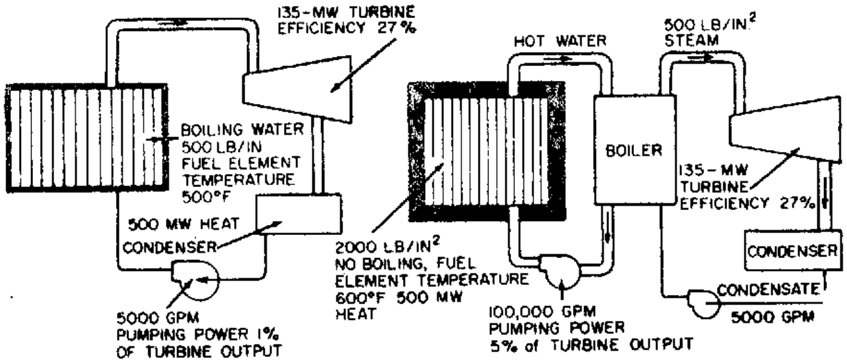

Fig. 2

The overall effect of void formation through boiling in a reactor using light water moderation and cooling is a decrease in reactivity. A reactor using boiling light water would, therefore be self regulating. The reduction in the high enthalpy water content of the heat transport system would also ease the containment problem should a rupture occur in the heat transport system.

There is one final advantage of using boiling light water which is of particular significance to the CANDU concept. If boiling occurs about half way along a fuel channel in a pressure tube reactor, the decrease in neutron capture, by the light water, is sufficient to allow boiling light water to be used in a natural uranium-heavy water moderated system. This would result in reduction in heavy water capital cost and in operational costs resulting from heavy water losses from the heat transport system.

The following are some disadvantages of using boiling light water as the heat transport fluid: -

(1) Because of carry over of radioactive nuclei with the steam, the turbine and associated equipment may have to be shielded to avoid personnel exposure. This also restricts access to the equipment during operation.

(2) The carry over of radioactive nuclei also necessitates the reduction of leakage from the turbine and auxiliaries to avoid general contamination of the building. This is particularly necessary because of the possibility of fission products being present. This leak tightness requirement would lead to higher capital costs for the turbine and auxiliary equipment.

(3) If boiling takes place half way along a fuel channel the latter portion of the fuel channel would be cooled by steam. Further subdivision of the fuel would then be required, to increase the heat transfer area, or the thermal rating of the fuel would have to be raised and this would probably require thicker fuel sheaths. The channel diameter would also have to be increased. The net result would inevitably be poorer neutron economy.

(4) In reactors using a heavy water moderator and light water as the heat transport fluid, there would probably be an overall positive void coefficient especially if the reactor is over-moderated. Formation and collapse of steam bubbles would, therefore cause the regulating system to "hunt" in trying to keep the power steady and a more sophisticated regulating system might be required.

During start up, a large increase in reactivity occurs as more and more fluid boils. Measures, such as poison injection or use of control rods, would be required to balance this reactivity increase and enable the reactor to operate with a full calandria and, therefore, at full power.

(5) If a high pH is required in the heat transport system, pH control may be by ammonia addition rather than by ion exchange resins. This will result in more induced radioactivity.

(6) There is a likelyhood of non-symmetric flux and power distribution axially because of the density variation along the fuel channels.

Fog and Steam

Steam, as a heat transport fluid, suffers from all the disadvantages of a gas. It has low density, low thermal conductivity and poor heat transfer and heat transport properties generally. The fuel elements would therefore require high surface-to-volume ratios such as could be obtained with fins. However, stainless steel would seem to be the only structural and cladding material that could be used with steam since it has adequate corrosion resistance at 1000°F Stainless steel has a low thermal conductivity and little advantage would be gained from using stainless steel fines. Thus, extensive subdivision of the fuel elements would be required. There seems no advantage to be gained, therefore, in producing steam outside the reactor just so that it could be used, in the reactor, as the heat transport fluid.

However, if steam produced in a boiling water reactor could be superheated in a superheating section of the same reactor or in a separate superheat reactor, then the advantages are numerous. Boiling water reactor, even under ideal conditions, produce saturated steam at about 500°F. Only 30% of the heat added to produce this steam can be recovered in the turbine. The poor quality of the steam results in large turbines and low thermodynamics efficiency. Erosion occurs in the turbine unless the blades and diaphragms are made of a material that can withstand this erosion. Superheating of the steam would provide a higher utilization of reactor heat because 60% of the superheat energy added is recoverable. It would also permit the use of standard modern steam turbines.

However, many problems remain unsolved, particularly those arising from material and fuel performances. The use of stainless steel as structural and cladding material and the extensive fuel subdivision that would be required lessen the possibility of superheating in a natural uranium-fuelled reactor. Recent developments indicate that zirconium alloys could be used as sheath material but not as fuel channel material at the higher temperatures that would be possible.

The use of H_2O fog as a heat transport fluid is being seriously considered. Fog is somewhat different from saturated steam. It could be considered to be very wet steam or steam containing suspended water particles. The main advantages of using light water fog are:-

(1) The density of the fog is much lower than that of liquid water. The resulting improvement in neutron economy permits the use of fog, as a heat transport fluid, in a natural uranium - heavy water moderated reactor.

(2) The mean density along a fuel channel, with fog, is less than with boiling water. A smaller reactor core is, therefore possible if fog is used instead of boiling water.

(3) The heat transfer coefficients, with fog, are very high, being of the same order of magnitude as for liquid metals.

(4) The heat transport properties are excellent since evaporation of the droplets takes place and advantage is taken of the energy absorbed in the form of latent heat.

(5) The direct cycle is used as with boiling water.

(6) The fog, behaves as a homogenous medium compared with boiling water, which is in two distinct phases. This would probably eliminate some of the nuclear instabilities associated with the boiling water reactor. The power distribution will also be symmetrical.

(7) Zircalloy appears likely to be acceptable as a structural and fuel sheath material which may mean that UO_2 could be used as fuel in a CANDU type reactor.

The radiation problems, associated with boiling water reactors, will also occur when fog is used as a heat transport fluid.

Heavy Water

The significant differences between ordinary water and heavy water are: -

(1) The appreciably smaller thermal neutron absorption cross-section of heavy water.

(2) The production of tritium (H^3) by neutron capture in deuterium.

(3) The high cost of heavy water.

The low thermal neutron cross-section would permit the use of heavy water, boiling heavy water or heavy water fog as the heat transport fluid in thermal reactors using heavy water as moderator and UO_2 as fuel. High burnups are attainable with low fuel costs.

The tritium produced in heavy water is a serious internal radiation hazard. Leakage must be kept to a minimum to avoid personnel exposure. The leakage problem is particularly severe with the high pressures and temperatures used in the heat transport system and even more so in the direct boiling D_2O or D_2O fog cycles.

The high cost of heavy water increases the capital cost of the station and the operating costs due to leakage. This offsets to some degree the low fuel costs. There is, therefore, an economic reason for reducing leakages as well. Heavy water which has leaked from the system must be recovered and the recovery systems, collection systems and closed ventillation systems required, further add to the capital cost.

One other problem can arise with heavy water. It freezes at around 39°F and it is likely to freeze, in winter, in heat exchangers cooled with river water.

In most other respects heavy water and light water have very similar characteristics with similar advantages and disadvantages.

Organic Liquids

Many of the advantages and disadvantages of organic substances as moderators apply equally well, or more so, to their uses as heat transport fluids. The advantages may be summarized as follows: -

(1) High boiling points and low vapour pressures. Terphenyl boils at 750°F and its vapour pressure is low even at temperatures well above this. Therefore very little pressurization of the

heat transport system is required, to prevent boiling, even when reasonably high temperatures are attained to increase the thermodynamic efficiency.

(2) Low corrosion rates permit the use of standard materials for fuel channel and sheath materials, provided they are otherwise suitable.

(3) Little or no induced activity through neutron capture, since carbon and hydrogen are the only components of the pure material. Radioactive nuclei are only produced if impurities are present.

(4) Fair high temperature stability up to 800°F.

(5) Low cost (15¢ - 20¢ per lb).

The organic material under consideration is a mixture of terphenyls. The probable operating condition are 800°F and 290 psia. This relatively high operating temperature permits the use of a steam cycle with an estimated efficiency of 37.9%. Turbine erosion, due to moisture in the steam, is also greatly reduced. Both the low heat transport pressure and high station efficiency lead to lower capital and fuel costs.

There are, however, some limitations on the use of organics in the heat transport system and there are problems which require solutions. The main disadvantages with organics are: -

(1) High melting point. The melting point of terphenyl is about 250°F and it is, therefore, solid at room temperature. Trace-heating of the system is therefore required.

(2) Low heat transfer coefficients, primarily because of the poor thermal conductivity. Lateral fins may be required, on the fuel elements, to increase the heat transfer area.

(3) Organic compounds suffer radiolytic damage which increases at elevated temperatures. The effect of the radiation is to cause polymerization to longer-chain compounds. This results in the formation of tars, coke or varnish which increase the viscosity. Gases, such as hydrogen, are produced. Continual purification, by distillation under reduced pressure, is required.

It has been found that radiolytic damage is somewhat reduced if the concentration of the higher polymers is kept at around 30%. However, this high concentration tends to cause fouling on fuel element surfaces, but it drops the melting point to such an extent that freezing does not take place even at room temperature.

The major problem associated with organic materials is the development of fuel channel and sheath materials that will enable full advantage to be taken of the higher operating temperatures. The thermal conductivity of stainless steel is too low for it to be used with the poor heat transfer properties of organics. In any case the use of stainless steel also requires fuel enrichment. Zirconium is unsuitable because the hydriding effect of organics leads to hydrogen embrittlement.

A sintered aluminium product (S.A.P.) has been under development. This material consists of 6% to 10% aluminum oxide in an aluminum matrix. A zirconium-Niobium alloy has also been developed which looks promising.

Uranium carbide is being developed as a fuel material since higher temperatures are acceptable with this material than with the oxide.

Liquid Metals

Liquid metals have excellent thermal properties. They have high boiling points, low vapour pressures, high thermal conductivities. Metals of low atomic weights, such as sodium and lithium, also have fairly high specific heats and volumetric heat capacities. In addition, liquid metals are stable at high temperatures and in high radiation fields.

The heat transfer characteristics of several liquid metals are superior to those of water and the same rate of heat removal would, therefore, be possible with smaller heat transfer areas. However, liquid metal volumetric heat capacities are lower than that of water and so the liquid metals require a higher flow rate to remove the same amount of heat. The pumping power required is not too different to that required for water.

These thermal properties of liquid metals make them an excellent choice as heat transport fluids in reactors operating at high temperatures or with high power densities. No pressurization of the system is required. The main disadvantage with liquid metals is their high chemical reactivity at high temperatures. They must be protected from oxidation and must be kept oxygen free to minimize corrosion.

Table 1 lists a number of liquid metals which might be considered as heat transport fluids. Their absorption cross-sections for thermal neutrons are given.

The cross-section for Lithium-7 is very low but Li-7 is only 92.5% of lithium metal. The balance is made up with Li-6 which has a much higher cross-section. Thus, lithium would not be suitable in a thermal reactor unless the lithium-6 were removed by physical separation. The cost of such a seaparation would be excessive. Natural lithium could, however, be considered for fast reactors although it is not attractive because of serious corrosion problems.

TABLE 1

Material	σ_a (barns)
Lithium - 7	0.033
Bismuth	0.032
Sodium	0.5
56% Sodium - 44% Potassium	1.1
Mercury	380

Corrosion problems are not serious with Bismuth and it has an attractively low thermal neutron capture cross-section. Its melting point of 520°F is much too high but alloying with lead produces an eutectic whose melting point is 257°F. Lead also has a low thermal neutron absorption cross-section. A significant draw-back in the use of bismuth and its alloys is the fact that it captures neutrons to form Bismuth - 210. This is a beta emitter, with a 5 day half-life, which decays to Polonium - 210. Po - 210 is an exceptionally insiduous toxic substance which is difficult to contain. The fact that bismuth expands on freezing is an additional complication so that precautions have to be taken to prevent the liquid metal from solidifying at any time.

On the basis of neutron cross-section and heat transfer characterisitcs, sodium appears the most suitable liquid metal heat transfer fluid. It is particularly suitable in fast reactors where its lack of moderating qualities make it attractive. If free from oxygen , it does not attack stainless steels, nickel, many nickel alloys or beryllium, at temperatures below 1100°F. Mass transfer does occur at higher temperatures. It melts at 208°F and may, therefore, solidify during shutdown and requires traceheating of the system. This problem can be overcome by alloying the sodium with potassium to produce an alloy which is liquid at room temperature. However, this Na-K alloy is inferior to sodium as a heat transfer medium.

The major disadvantages with liquid sodium are as follows:-

(1) The formation of sodium - 24 by neutron capture. This is a gamma emitter with a half-life of nearly 15 hours. Consequently shielding is necessary around pipes, pumps and heat exchangers and maintenance problems are increased.

(2) The chemically reactive nature of sodium. It is easily oxidized by oxygen in air and reacts violently with water. Care

must therefore be exercised, particularly at elevated temperatures, to avoid contact of the sodium with air or water. Consideration must be given to providing a secondary sodium or mercury system between the primary sodium loop and the water system. The intermediate mercury loop prevents leakage of sodium into the water system. A secondary mercury or sodium loop prevents transfer of Na - 24 to the steam cycle in the event of a leak occuring and reduces shielding requirements.

The necessity for avoiding water also imposes problems in cooling control or booster rods. Organic coolants may well have to be used.

(3) The problem of sodium leaks. Because of the combination of viscosity, specific gravity, surface tension and wetting characteristics, sodium can leak through very small openings. A system known to be leak- tight at low temperatures may not be so at elevated temperatures. It is very difficult to provide the leak-tightness which is so necessary because of the chemical reactivity of sodium.

It is thought that sodium can percolate through the interface between carbide inclusions in stainless steel and this makes the design of a containing system difficult.

Gases

There is much to recommend the use of a gas as a heat transport fluid. They are generally easy to handle and they have good radiation and thermal stability. However their heat-transfer characteristics are inferior to those of water and liquid metals. With gases the heat transfer area has to be increased by the use of fins and this introduces more neutron absorbing material into the core. The pumping power requirement with gases, are much higher than with other fluid, mainly because of the small densities.

In order to be able to compare gases as to their suitability as heat transport fluids,a merit index is calculated based on the ratio of the heat removed to the pump work expended. The results at 1 atmosphere pressure and a temperature of 212°F are shown in Table 2.

Air is an obvious choice as a heat transport fluid, because of its availability. However, as may be seen from the table, a large proportion of the power produced would be required to pump the air around the system. Furthermore, at high temperatures, both the oxygen and nitrogen in the air will react chemically with core material.

TABLE 2

Gas	Index	Gas	Index
Hydrogen	100	Helium	18
Methane	29	Carbon Dioxide	11
Ammonia	22	Air	7.5

Radioactive Argon-41 is formed by neutron capture in Argon-40 which is found in nitrogen. This is undesirable in a closed system. The thermal properties of nitrogen are similar to those of air and it is, therefore, equally unsuitable as a heat transport fluid.

Hydrogen is the most attractive gas on the basis of the merit index and low neutron absorption cross-section. Unfortunately, it would constitute a serious explosion hazard if it escaped into the air. The containment of hydrogen at elevated temperature and pressure is a difficult problem which requires the use of special material not subject to hydrogen embrittlement.

Helium is less attractive from the heat-transfer standpoint. However, it has a negligible neutron capture cross-section and is chemically inert. It is also stable at high temperatures and in intense radiation fields. It, therefore,has much to recommend it especially in high temperature applications and as the fluid in a closed cycle gas-turbine system. It is in use in the EGCR at Oak Ridge, in Peach Bottom and in the DRAGON reactor in the U.K. High gas pressures are required to reduce pumping power (e.g. 294 psig in DRAGON) and to reduce core size. A closed system would have to be used with special precautions taken to reduce losses, because of the high cost of helium.

Carbon dioxide is inferior to helium as regards heat transfer, pumping power and neutron absorption cross-sections. It is, however, readily available and is relatively inexpensive. The absorption cross-section is small and the gas is free from the dangers of toxicity and explosion. It does not readily attack metals and the reaction rate with graphite appears insignificant below 930°F if an inhibitor is added. It is probably the most practical gaseous heat transport fluid below about 1100°F. It is used, with methane as an inhibitor, up to 1067°F in the Advanced Gas Cooled Reactor in the U.K., with enriched UO_2 fuel sheathed in stainless steel.

Comparison of D_2O Moderated Plants Using Various Heat Transport Fluids

It is not intended that the figures quoted here should be accepted as an indication or a predication of what reactor systems are likely to be adopted in the future. The figures are presented to give some idea of relative costs as they have been estimated by various groups or individuals.

Unit energy costs for D_2O moderated reactors, with various heat transfer fluids, were compared in the 1964 Geneva Paper P-10 (Pon Lewis, Haywood, Primeau, Phillips, Merlo). Their estimated costs are given in Table 3 below:

TABLE 3

	Liquid D_2O	Boiling D_2O (Indirect Cycle)	Boiling H_2O (Direct Cycle)	Organic
Unit Energy Cost (mills/Kwh)	3.829	3.714	3.689	3.580

It is assumed that the water cooled reactors use rod-bundle UO_2 fuel while the organic cooled reactor use a nested annular uranium carbide fuel.

The water cooled reactors have since been reassessed using Tube-in-shell (T1S) UO_2 fuel. The results of this assessment for station outputs of 250, 500 and 750 Mwe are shown in Table 4, which is taken from 1965 CNA Conference Paper 65-CNA-203 (Brooks & Pon) entitled "Conceptual Design of a Nautral Uranium Boiling Light Water Reactor".

Another AECL Report, AECL 1730 published in May 1963, compares unit energy costs with liquid D_2O, boiling H_2O, H_2O fog and organic liquids as heat transport fluids. This comparison is shown in Table 5.

The tables seem to indicate the possibilities of lower unit energy costs with organic liquids or boiling light water .

TABLE 4

		250 MW(e)			500 MW(e)			750 MW(e)		
		Liq. D_2O	Boil. D_2O	Boil. H_2O	Liq. D_2O	Boil. D_2O	Boil. H_2O	Liq. D_2O	Boil. D_2O	Boil. H_2O
D_2O Cost = \$20/lb.										
Specific Capital Cost	\$/kWe	361	344	333	252	236	225	216	200	190
Burnup (Idealized Core)	MWd/teU	9967	10382	9497	10914	11465	10343	11365	11997	10829
Fuelling Cost (@ \$40.84/kgU)	mill/kWhr	0.571	0.503	0.545	0.521	0.454	0.495	0.499	0.433	0.472
Capital Cost	mill/kWhr	3.539	3.375	3.270	2.472	2.315	2.212	2.117	1.965	1.859
Operation & Maint. Cost	mill/kWhr	1.039	1.031	0.943	0.697	0.690	0.643	0.572	0.564	0.531
Unit Energy Cost (UEC)	mill/kWhr	5.149	4.909	4.758	3.689	3.459	3.350	3.188	2.962	2.862
Difference in UEC from Liquid D_2O	mill/kWhr	0	-0.240	-0.391	0	-0.230	-0.339	0	-0.226	-0.326
D_2O Cost = \$10/lb.										
Difference in UEC from Liquid D_2O	mill/kWhr			-0.297			-0.264			-0.258

TABLE 5

Coolant	Liquid D_2O	Boiling H_2O	H_2O Fog	Organic
Net Elect. Output (MWe)	457	457	454	457
Plant Direct Costs ($)	59,020,000	62,080,000	60,921,000	54,953,000
D_2O Inventory (@$20/lb)	14,300,000	12,408,000	10,790,000	10,034,000
1/2 Fuel Charge ($)	2,320,000	3,320,000	3,230,000	3,400,000
Indirect Costs ($)	16,100,000	16,100,000	16,100,000	16,100,000
Contingency ($)	12,000,000	12,000,000	12,000,000	12,000,000
Interest during Constn. ($)	11,400,000	11,600,000	11,300,000	10,600,000
Total Plant Cost ($)	115,140,000	117,508,000	114,341,000	107,087,000
Specific Capital Cost ($/Kwe)	252	257	251.9	234.3
Burnup (Mwd/Tonne U)	8680	8985	7600	11,360
Unit Fuel Cost ($/KgU)	52.00	49.64	52.37	38.50
Fuelling Cost (mills/Kwh)	0.80	0.69	0.86	0.42
Unit Power Cost (mills/Kwh)	3.86	3.77	3.89	3.45
Steam Cycle Eff'cy %	34.6	36.7	36.7	38.0
Net Station Eff'cy %	31.3	33.5	33.5	34.2

ASSIGNMENT

1. List the advantages and disadvantages of using light water as the heat transport fluid.

2. What additional advantages are to be gained by allowing the water to boil?

3. Under what circumstances would steam be used as a heat transport fluid and what advantages would result?

4. Explain why fog is superior to boiling water as a heat transport fluid.

5. What are the significant differences between using ordinary and heavy water as a heat transport fluid?

6. (a) Summarize the advantages and disadvantages of terphenyl as a heat transport fluid.

   (b) Why is it not in use in natural uranium - heavy water moderated reactors?

7. (a) Why would sodium appear to be more suitable than lithium or bismuth as a liquid metal heat transport fluid?

   (b) What are the major disadvantages with liquid sodium?

8. Briefly compare air, hydrogen, helium and carbon dioxide as heat transport fluids.

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