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Selection Criteria for the High Temperature Reactor Intermediate Heat Exchanger

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Abstract – *The US Generation IV Programme and other similar projects have generated considerable interest for indirect cycle gas cooled reactors. The indirect cycle gas cooled reactor produces heat at temperatures in the order of 1000°C. This heat can be used for power generation, via a Brayton or combined cycle, and hydrogen production, via a variety of high temperature processes. A key component of the indirect cycle gas cooled reactor is the intermediate heat exchanger (IHX). This paper identifies operating fluids and conditions that determine the selection criteria for the IHX. The paper concludes that appropriate material selection will be essential for this high temperature, high pressure application. Candidate materials are reviewed, with consideration given to restrictions on operating criteria, fabrication techniques and design code criteria. In addition to the need for economic fabrication in the identified material, the selection of exchanger type will be heavily influenced by the need for a robust, high integrity, high effectiveness, compact exchanger with low pressure drop characteristics. Several generic exchanger types and their associated construction techniques are considered. It is demonstrated that the features and characteristics of a diffusion bonded exchanger type, such as the Printed Circuit Heat Exchanger (PCHE), are ideally suited to this challenging duty.*

I. INTRODUCTION

The indirect-cycle very high temperature gas cooled reactor (VHTR) is one of the leading contenders for the next generation of nuclear reactor, as it allows a common heat source to be used for both electricity generation and hydrogen production while minimising the complexity and risk associated with the nuclear part of the cycle.[1] It also offers the freedom to select a secondary coolant. Fluids such as helium, nitrogen or helium-nitrogen mixtures are under consideration. The use of nitrogen or helium-nitrogen mixtures allows the use of existing gas-turbine technology. Thus the helium gas turbine development costs, associated with direct cycle, are eliminated. For this type of reactor, heat is transferred from the reactor via an intermediate heat exchanger (IHX).

If the facility, be that for the production of electricity or hydrogen, is to have a high efficiency, the IHX will need to have both a high effectiveness and low pressure drop. While safety consideration, total fluid inventory and the need to place the IHX inside the nuclear containment vessel, dictate compact technology. The need for a compact heat exchanger will probably limit the exchanger selection to a plate type heat exchanger. Thus tubular products are not considered in this evaluation.

Of the currently available technologies, it has been demonstrated that Printed Circuit Heat Exchanger (PCHE) is the most suitable type to undertake the mechanical, thermodynamic and environmental demands of this duty, in a limited space.[2,3] There can be no doubt that the PCHE will be one of the most important candidates for the indirect-cycle high temperature gas cooled reactor IHX.

Operating conditions vary with project, however typical design parameters are:

- Maximum operating temperature 1000°C
- Pressure 50 to 100 bar
- Duty 600MW
- Effectiveness 95%
- Helium or nitrogen environment
- Low pressure drop
- 30 to 60 year design life.

Irrespective of the exchanger type, material selection will be key to this duty. The candidate materials will need to be available in the appropriate product forms, be weldable and be suitable for use at temperatures up to 1000°C. At present there are no “nuclear approved” materials. However, this paper makes the assumption that materials that are already approved for the manufacture of conventional high temperature pressure vessels will be among the leading candidate materials. Candidate materials are therefore selected from those high temperature materials that are approved for use by ASME VIII.

For the selected alloys, the material’s properties, including physical properties, mechanical properties and corrosion resistance, will be discussed in detail. Consideration of these properties will be the basis of selection for successful IHX material.

II. CANDIDATE MATERIALS

II.A. IHX Material Requirements and Primary Selection

As there are no materials approved to ASME III for temperatures approaching 1000°C, primary selection criteria is based on approval to ASME VIII (Boiler and Pressure Vessel Code)[4] for use at a design temperatures equal to or greater than 898°C (1650°F). The alloy must also be available in sheet and plate form, the product forms that are most compatible with the manufacture of compact heat exchangers.

On this basis eight materials are identified. Alloy 617, a nickel based superalloy with chromium, molybdenum and cobalt additions, which is approved to 982°C (1800°F) and seven other alloys approved to 898°C (1650°F) (Fig. 1). These alloys are:

- Alloy 556
- Alloy 800H
- Alloy 800HT
- Alloy 330
- Alloy 230
- Alloy HX
- 253 MA

The allowable design stresses (S) at 898°C, the minimum required mechanical properties (ultimate tensile stress (UTS), 0.2% proof stress (0.2%PS) and elongation (El)) at room temperature together with the nominal compositions of the alloys are listed in Table 1.

Among these alloys, alloy 617, has the highest design temperature (982°C), and therefore immediately becomes worthy of further consideration, as a candidate material for the IHX.

However, design temperature alone is no basis for material selection, consideration must also be given to the allowable design stress at temperature.

If consideration is given to the ASME design stress at 898°C (the highest temperature for which data is available for all of the alloys) we find that design stresses range from 12.4MPa (alloy 617) to 3.3MPa (alloy 330). If a vessel is to contain pressure at temperature, it must have significant strength at temperature. Design to a differential pressure may limit the design pressure to less than individual stream operating pressures (which could be as high as 100 bar), but as the streams are independent in an IHX, prudent design suggests a relatively high differential pressure. Further conventional design philosophy tends towards a design strength that is at least double the design pressure. BERNIE COPSEY, MICHEL LECOMTE, GERD BRINKMANN, ALAIN CAPITAINE AND NICOLAS DEBENE[1] suggest that the candidate alloy should have a design stress of at least 5 MPa at 1000°C.

The need for a design stress of 5 MPa at 1000°C, reduces the list of candidate alloys to just four, which ranked in descending order are:

- Alloy 617
- Alloy 556
- Alloy 230
- Alloy HX

Table 1: Candidate materials for intermediate heat exchangers of high temperature reactor

Alloys	UNS No	T^{Max} °C (°F)	$S^{898°C}$ (MPa)	UTS (MPa)	0.2% PS (MPa)	El (%)	Nominal compositions (wt%)
617	N06617	982(1800)	12.4	655	240	30	52Ni-22Cr-13Co-9Mo-1.2Al
556	R30556	898(1650)	11.0	690	310	40	21Ni-30Fe-22Cr-18Co-3Mo-3W-0.3Al
800 HT	N08811	898(1650)	6.3	450	170	30	33Ni-42Fe-21Cr
800 H	N08810	898(1650)	5.9	450	170	30	33Ni-42Fe-21Cr
330	N08330	898(1650)	3.3	483	207	30	Fe-35Ni-19Cr-1.25Si
230	N06230	898(1650)	10.3	760	310	40	57Ni-22Cr-14W-2Mo-0.3Al-0.05La
HX	N06002	898(1650)	8.3	655	240	35	47Ni-22Cr-9Mo-18Fe
253 MA	S30815	898(1650)	4.9	600	310	40	Fe-21Cr-11Ni-0.2N

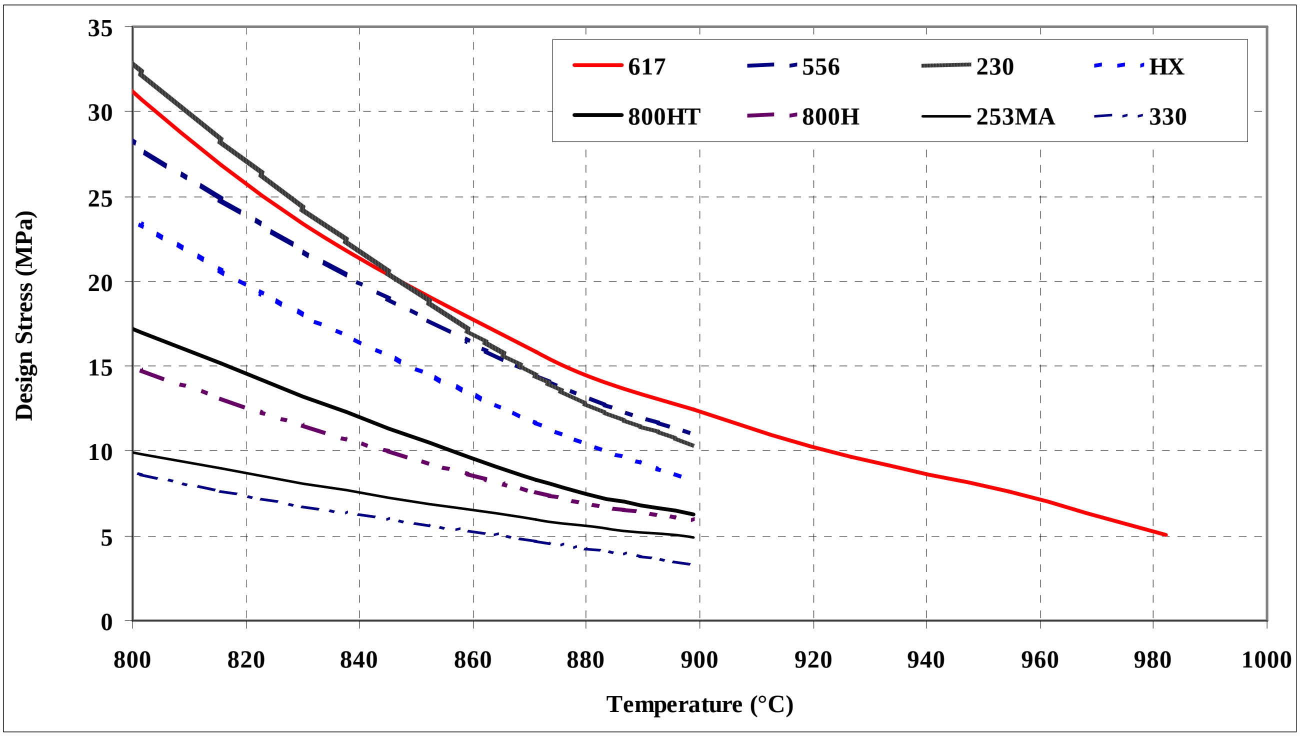

Figure 1: Comparison of ASME allowable stress for high temperature alloys

The design stresses reported in table 1 assume design to ASME VIII, they are based on a creep life of 100,000 hours (about 11 years). Significantly less than the required IHX design life (30 to 60 years), this implies that for IHX applications consideration should be given to design stresses lower than those reported in table 1.

The four alloys above all contain more than 20% Chromium (Cr), which is sufficient to form a protective oxide against future oxidation. They also have Molybdenum (Mo) or Tungsten (W) additions to further improve material performance. The remainder of the report will consider and attempt to rank only these alloys, but will consider; mechanical properties (rather than ASME design stresses), physical properties, corrosion resistance and fabrication.

II.B. Mechanical Properties

The mechanical properties discussed here include short time mechanical properties, thermal stabilities, creep and fatigue properties.

A comparison of 0.2% proof strength against temperature for alloy 617, alloy 556, alloy 230 and alloy HX is given in Fig. 2. Consideration of elevated temperature tensile properties alone would favour Alloy 230, which has the highest 0.2% proof strength at elevated temperatures. At 1000°C the alloys can be ranked in order of descending stress:

- Alloy 230
- Alloy HX
- Alloy 556
- Alloy 617

However, at elevated temperature, time dependent properties are also relevant.

Long-term exposure to high temperatures, may cause alloys to alter their microstructure. Fig.3, shows the phase mole percent as a function of temperature, for alloy 617. This alloy does not exhibit significant intermetallic phase formation, such as sigma phase at high temperature. Such alloys normally exhibit good ductility, even after long-term thermal exposure to high temperatures. The comparison of room temperature ductility for the alloys discussed after exposure at elevated temperature for 8000 hours is given in Fig. 4. Comparison at moderate temperature, below 700°C would rank the alloys:

- Alloy 230
- Alloy HX
- Alloy 556
- Alloy 617

Increase the temperature to 870°C and this comparison changes, the ranking becomes:

- Alloy 617
- Alloy 230
- Alloy 556
- Alloy HX

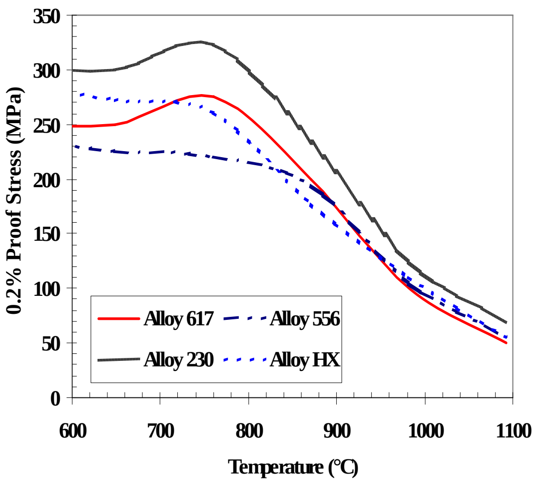

Figure 2: 0.2% Proof Stress for the various alloys at elevated temperatures

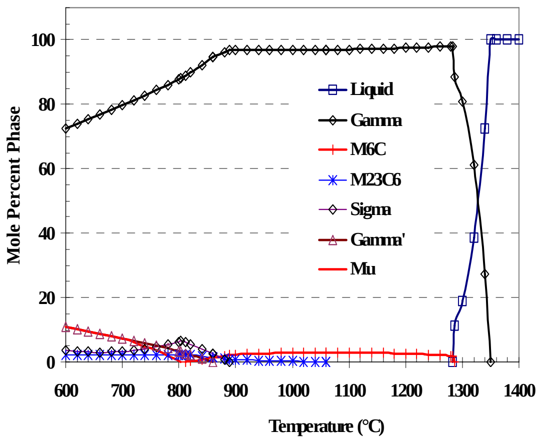

Figure 3: Typical Phase Diagram for alloy 617 showing phase amounts as a function of temperature

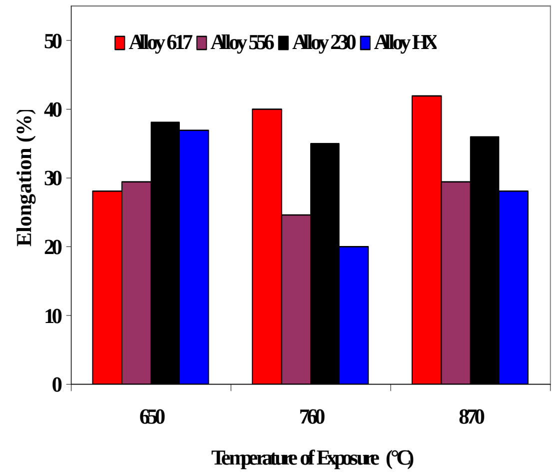

Figure 4: Room temperature ductility for alloys after exposure at temperature for 8,000 hours

The creep rupture stress of these alloys at high temperatures can be associated with the ASME allowable stress as mentioned previously. Alloy 617 exhibits the highest level of creep strength at high temperatures (Fig.1). At a test condition of 982°C and 14MPa, the creep rupture life (based on Larson-Miller Extrapolation) is:

Alloy 617	10,000 hours
Alloy 556	7,500 hours
Alloy 230	5,000 hours
Alloy HX	2,400 hours.

Tested long-term creep properties for modified alloy HX (alloy XR) in a simulated high temperature helium reactor atmosphere are also available.[5] Although alloy XR is not considered in this report, the results suggest this alloy should be given further consideration.

Results from strain-controlled low cycle fatigue (LCF) tests are required to assess the influence of thermal cycling during start-up, shutdown and power changes.[6] According to Haynes International[7] of the alloys considered alloy 230 exhibits the best low cycle fatigue (LCF) properties at a test temperature of 427°C (800°F). This is consistent with superior resistance to crack initiation exhibited by alloy 230 when compared with alloy 617 for the same maximum temperature cycle.[8] The development of alloy 617 was centred on the desire for maximum creep strength at high temperature. Tighter controlled thermo mechanical processing and alloy chemistry are required to achieve the optimized grain structure for both creep stress and LCF strength.

Based on the above an overall evaluation of mechanical properties tends to suggest that an IHX could be manufactured from either alloy 617 or alloy 230.

II.C. Physical Properties and their Influence on IHX Design

The design of the IHX will also be influenced by the selected alloy's physical properties. In particular thermal conductivity and the coefficient of thermal expansion will influence the design. The ideal candidate material will have high thermal conductivity and low thermal expansion.

Thermal conductivity and the coefficients of expansion for the selected alloys are given in Fig. 5 and Fig. 6 respectively.[7, 9, 10, 11]

There seems to be a correlation between nickel content and the coefficient of thermal expansion. Alloy 230 and alloy 617 have the highest nickel content but the lowest coefficients of thermal expansion.

At IHX operating temperatures alloy 556 and 617 have the highest thermal conductivities.

Whatever material is selected thermal conductivities are relatively low and coefficients of thermal expansion significant, when consideration is given to the operating temperature. Both of these properties will impact exchanger selection and design criteria.

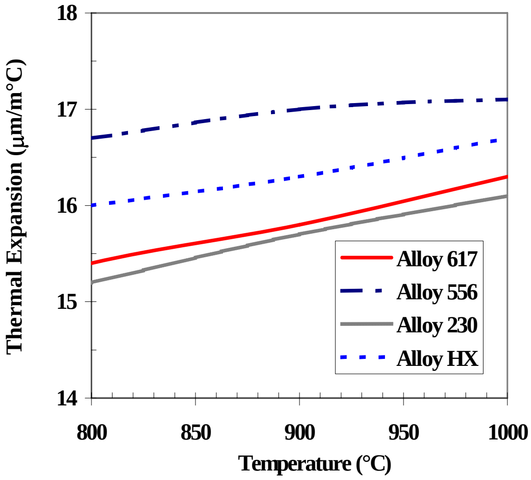

Figure 5: Thermal expansion for the various alloys at elevated temperatures

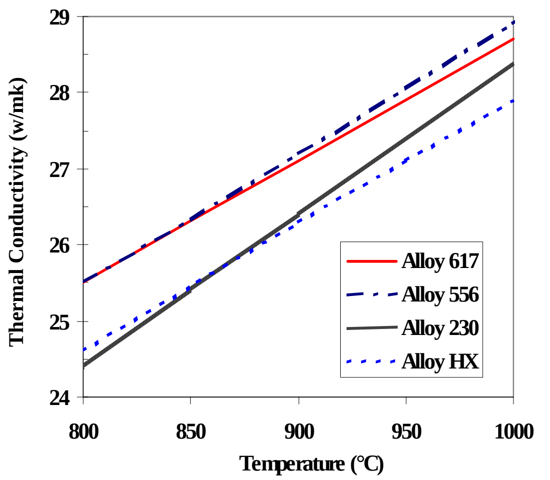

Figure 6: Thermal conductivity for the various alloys at elevated temperatures

The relative low thermal conductivities will reduce the efficiency of any finned structure. As a consequence heat exchangers such as the PCHE, which is considered to be of all primary surface, will have an advantage over heat exchanger types that are dependent upon secondary surface (fins).

Thermal expansion if associated with constraint will translate to thermal stress and therefore limit the fatigue life of the IHX. When designing the IHX it will therefore be necessary to minimize constraint.

If we consider a generic plate type IHX, consideration will need to be given to:

- the interaction of side margins (spacer bars) and the active core.
- the interaction of headers (or collectors) and the core.
- contact arrangement.

The latter is of considerable importance as any non counter-current flow region (including distributors) can result in non-linear temperature profiles. This results in thermal stress and in particular high local thermal stresses in transient cycles (start-up, shutdown and power changes) and therefore limits fatigue life.

Heatric have been developing the PCHE to address all of these issues. The latest ‘platelet PCHE’ derivative has:

- Integrated internal headers
- Minimum side margins
- Near pure counter flow contact arrangement
- Minimum distributor area.

A plate section taken from a platelet PCHE is shown below (Fig.7). PCHE platelet technology is subject to a patent application.

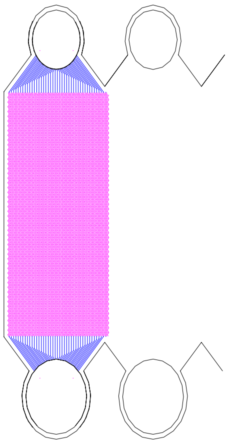

Figure 7: A plate section taken from a platelet PCHE

II.D. Corrosion Resistance

The fluids in an IHX are helium in the primary loop and nitrogen, helium or a nitrogen helium mixture in the secondary loop. Many corrosion issues such as oxidation and carburization are therefore less significant than the high temperature strength issues. Although impurities such as H_2, H_2O, CO, CO_2 and CH_4 may exist in the coolant, they have no influence on the 1% creep strain limit and on the creep rupture strength for material up to 20,000 hours.[12]

However, as the secondary coolant could contain high amount of nitrogen, the nitriding resistance of these alloys need to be considered. Nickel-base alloys generally have good nitridation resistance due to the low solubility of nitrogen in these metals. Iron tends to be detrimental, as does low concentration aluminium or titanium. Silicon forms a brittle intermetallic compound with nitrogen and can contribute to scale spallation, especially in applications with low oxygen concentrations and during thermal cycling. Fig. 8 shows nitrogen absorption after 168 hours at 648°C (1200 F) in flowing ammonia. Although this ammonia data is not directly comparable with the IHX environment, it demonstrates that alloy 230 has the best nitriding resistance of the alloys considered.

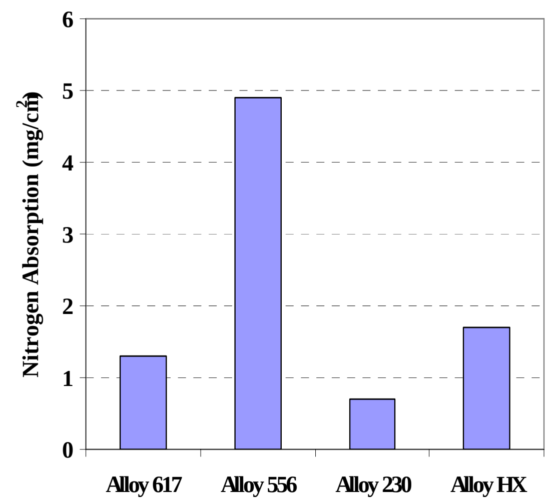

Figure 8: Comparison of Nitriding Resistance

II.E. Fabrication

The behaviour of an alloy during fabrication activities such as forming, machining and welding can be one of the most critical factors in whether or not an alloy is chosen for IHX service. Techniques and equipment for some operations may be influenced by the alloy's hardness and working hardening rate. Generally, the higher the 0.2% proof stress, the higher the hardness value and the higher the working hardening rate.[13] This may put constraint on some plate forming or fin forming techniques, associated with some plate type heat exchangers, when these high strength alloys are considered. It is not anticipated that the PCHE, where traditionally fluid passages are formed by non-mechanical techniques, such as etching, will suffer such constraints.

The combination of low design strength (probably less than 10MPa at temperature) and relatively high design pressure (as a percent of the design stress) will further limit the type of plate heat exchanger. Edge welded plate or any exchanger type with large unsupported areas will be mechanically unacceptable. This limits selection to either a brazed plate fin type structure, a diffusion bonded structure, such as the PCHE or a plate derivative with an internally braced core structure.

However, a design temperature of 1000°C for any metallic material must be considered high. Further any braze alloy must have a melting point and therefore strength below that of the parent alloy. Thus for a brazed product exchanger core strength and time dependent properties become a function of the braze material, and not the parent alloy. Only a diffusion bonded product, such as the PCHE, is of all parent metal construction, with demonstrated parent metal properties.

III. CONCLUSIONS

The review of materials would suggest that either alloy 617 or alloy 230 is the most suitable material for an IHX. These being the only commercially available alloys that have the appropriate combination of mechanical, physical and corrosion resistance properties. Further they are alloys that are available in appropriate product forms and lend themselves to traditional fabrication techniques.

The paper assumes that by necessity any IHX will have to be a compact exchanger. Of the commercially available compact exchangers, the all diffusion bonded and welded PCHE seems to be the most appropriate technology, for this demanding high temperature application.

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