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B-MT(SPME)-24

JUL 1 9 2006

Manager, Pittsburgh Naval Reactors Office
U. S. Department of Energy
Post Office Box 109
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Subject: Hot Leg Piping Materials Issues (U)

Dear Sir:

This letter provides technical information regarding insulation and materials issues for the Hot Leg Piping preconceptual design developed for the Project Prometheus space nuclear power plant (SNPP).

Background

With Naval Reactors (NR) approval of the Naval Reactors Prime Contractor Team (NRPCT) recommendation to develop a gas cooled reactor directly coupled to a Brayton power conversion system as the space nuclear power plant (SNPP) for Project Prometheus (References a and b) the reactor outlet piping was recognized to require a design that utilizes internal insulation (Reference c). The initial pipe design suggested ceramic fiber blanket as the insulation material based on requirments associated with service temperature capability within the expected range, very low thermal conductivity, and low density. Nevertheless, it was not considered to be well suited for internal insulation use because its very high surface area and proclivity for holding adsorbed gases, especially water, would make outgassing a source of contaminant gases in the He-Xe working fluid. Additionally, ceramic fiber blanket insulating materials become very friable after relatively short service periods at working temperatures and small pieces of fiber could be dislodged and contaminate the system. Consequently, alternative insulation materials were sought that would have comparable thermal properties and density but superior structural integrity and greatly reduced outgassing.

Discussion

The hot leg piping from the reactor outlet to the turbine inlet will transport He-Xe gas at approximately 1150K and a pressure between 1.38 and 4.0 MPa. The external pipe material (the pressure boundary) is expected to be a nickel-base superalloy. The ultimate and creep strengths of these materials are reduced with increasing temperature. For temperatures higher than 900K, this loss of strength is critical for the hot leg pipe application. Therefore, to avoid unreasonable wall thickness and attendant mass penalty, the pipe wall has a temperature limit of 900K. To accomplish this, a double wall pipe-in-pipe configuration with an inner pipe of a refractory metal alloy was evaluated. This makes the use of internal insulation necessary to limit the outer superalloy pipe wall temperature to 900K or less. The internal insulation should have thermal properties similar to ceramic fiber blanket and be compatible with other materials in the system. Previous attempts to use fibrous materials as internal insulation in a closed loop have revealed major difficulties with outgassing (Reference d), particularly water vapor, even during very short runs. It might be feasible for ceramic fiber blanket insulation to be baked out and degassed in situ under vacuum, but it is unlikely that this process would completely remove the adsorbed gases in a reasonable time and would engender additional design, manufacturing and processing complexity. The use of foams was envisioned to address these problems. Foams can be made of metals or ceramics. Metallic foams have the advantage that they can be made of materials very similar or identical in composition to other plant materials eliminating additional compatibility issues. Metallic foams might also have a lower heat transfer coefficient at the nominal operating temperature because metals are opaque to thermal radiation. Ceramic foams are thermally and chemically stable and have a lower heat transfer coefficient at low temperatures. However, their heat transfer coefficients typically increase rapidly at higher temperatures because most ceramic materials are translucent to infrared radiation.

Additional details regarding the issues relevant to the internal insulation, merits of various insulation concepts that were considered, and the proposed development plan are presented in the Attachment to this letter.

Conclusions

Ceramic fiber blanket insulation was considered unlikely to be suitable for internal use in a closed loop gas system such as that selected for Project Prometheus by the NRPCT. Insulation with lower surface area and similar thermal properties was required and metallic or ceramic closed cell foams based on bonded individual hollow microspheres were identified as the primary candidate. Ceramic and metallic materials would have been evaluated and the potential vendor base investigated.

Very truly yours,

Vicente Munne, Senior Engineer
Space Plant Materials Engineering
Advanced Materials Technology

Approved by:

Wayne L. Ohlinger, Manager
Space Plant Materials Engineering
Advanced Materials Technology

Attachments

Enclosure: Statement of Work (U)

References

(a) K. H. Donald, , "Space Nuclear Power - Reactor Coolant and Power Conversion System Concept - Approval Of, "NR Letter I#05-01228 dated 4/20/05
(b) D. R. Riley, "Space Nuclear Power Plant Concept Selection, For NR Approval," KAPL Letter SPP-67110-0005 / Bettis Letter B-SE-0077, dated 3/4/05
(c) A. Gribik, "Hot Leg Piping Concept for Further Development, For NR Approval" Bettis Letter B-SE-0124 dated 6/30/05
(d) J.P. Nehrbauer, "Helium Loop Operational/Design Experience" KAPL Advanced Concepts Technical Quick Note # 120696-JPN, dated 12/6/96

Attachment

Hot Leg Piping Materials Issues (U)

Author:
Vicente Munne

Reviewed by:
Wayne Ohlinger

1. **Description of the Engineering Problem:** Upon NR approval of the direct gas Brayton concept for the space nuclear power plant (SNPP), preconceptual design and materials development were initiated. There was a desire to utilize nickel-base superalloys for the pressure boundary, including piping, due to the fact that both the reactor pressure vessel and the Brayton turbine housing were considered likely to be fabricated from a superalloy. Use of superalloy piping potentially would simplify the joining of the piping to other parts of the system. A potential problem was identified with the piping connecting the reactor outlet to the turbine inlet (the hot-leg piping). The problem arises at the reactor outlet because the temperature there is expected to be on the order of 1150 K. Nickel-base superalloys were judged unsuitable with regard to creep strength at the expected pressure induced stress and temperatures above approximately 900K. The nominal pressure was assumed to be 1.94 MPa with a range between 1.38 and 4.0 MPa possible. Preliminary calculations revealed that a wall thickness in excess of two inches would be necessary to withstand the pressure of the gas at the design temperature if a superalloy was used as the pressure boundary and was in direct contact with the hot coolant exiting the reactor. This would incur an unacceptably large mass penalty as well as complicating fabrication and joining issues.
   a. **Pipe in Pipe Design Description:** To circumvent the wall thickness problem a pipe in pipe design was considered in which an internal pipe or liner carries the gas while an external superalloy pipe serves as the pressure boundary. The two pipes are separated by thermal insulation to reduce the external pipe temperature so it can be fabricated with a wall thickness similar to the balance of the SNPP piping. The basic dimensions of the piping are an outside diameter of 16 cm, a wall thickness of 0.48 cm, a thickness of insulation of 1.5 cm and an inner liner thickness of 0.1 cm.
   b. **Required Insulation Physical Properties:** The insulation needed for this application should have a heat transfer coefficient of 0.25 W/mK or lower and should have enough mechanical strength to support shock and vibration forces applied during launch without settling or moving.

2. **Pipe Materials:** The main design issue regarding the hot leg pipe material selection was that an early decision was made to try use an all Ni-base superalloy reactor plant pressure boundary. For the hot leg piping the disadvantage of this material is its strength at high temperatures. The inner liner could be made of the same or a different material dependent upon requirements for strength, chemical compatibility, temperature tolerance . The potential Ni-based superalloys, as well as some alternatives, likely applicable for the inner pipe, are:
   a. **Superalloys:** Nickel-base superalloys were the preliminary design material selection. The nominal pipe material was Inconel 617 with Haynes 230 and Nimonic PE-16 also being considered. The principal potential advantage of superalloy piping for the outer wall was that the remainder of the pressure boundary was envisioned to be superalloy which minimized materials compatibility concerns for these components as well as joining issues
   b. **Refractory Metals:** The inner pipe of the hot leg piping was preferably to be made of an alloy of tantalum, molybdenum, or niobium. Refractory metals have the advantage that they have superior strength at high temperatures. The main issues for this application would be joining and chemical reactivity issues. A welded or bonded joint between a refractory metal and a Ni-base superalloy is problematical because fusion welding is not possible and formation of brittle intermetallics in high temperature service could lead to degradation of joint integrity. For the case of the inner liner it might be more appropriate to use a refractory metal alloy of the same composition as the reactor core in which case the inner liner could be directly joined to the core with minimal difficulty.

3. **Insulation Materials:** There are various commercially available insulating materials that are suitable for external insulation; however, there are not many candidates considered suitable for use as internal insulation in the preconceptual SNPP. The following outlines the candidate materials considered:
   a. **Fibrous Insulation:** Ceramic fiber blanket is an excellent thermal insulator with low mass and is available in a variety of chemical compositions and service temperature ranges. It is widely used but demonstrated disadvantages for internal use in closed loops are that it is friable and that it is extremely difficult, if not impossible, to completely remove all the adsorbed gases, especially water vapor, that it collects just by being exposed to the atmosphere. The high surface area of these materials exacerbates this problem.
   b. **Foil Insulation:** Multilayer foil insulation should also be considered. It consists of several layers of thin foils separated by a short distance that act as radiation shielding and convection barriers for the gas. Its main disadvantages are that the thermal conductivity is higher than other alternatives and that fabrication is very complex for many geometries (like elbows and T's). Mechanical strength is also poor and dependent on stents or other mounting techniques to maintain separation between foils.
   c. **Foam Insulation:** The most promising insulation material for this application was judged to be ceramic or metallic foam (Figure 1). There are a variety of foam materials that may be appropriate. Ceramic materials are lightweight and have low intrinsic thermal conductivity. Potential problems are material compatibility issues, heat transfer coefficient at operating temperatures, and mechanical properties. Metallic materials may have better mechanical properties and potentially lower heat transfer coefficients at operating temperatures. Moreover, they can be made of very similar materials to the piping and other structural metals in the system minimizing potential compatibility issues. Foams can be made in two main morphologies namely closed cell and open cell. Closed cell foams have the advantage of smaller surface area and less possibility of convection through the foam. Preliminary evaluation indicated that foam made of thin-walled, hollow, bonded microspheres of around three millimeters in diameter would be the most desirable morphology given its closed cell structure as well as flexibility of fabrication. Such microspheres have been successfully fabricated using a process consisting of slurry coating, by dipping or spraying, of uniformly sized polystyrene spheres using ceramic oxide or metal-precursor oxides (single element or alloy precursor mixtures); burning out the polystyrene beads; and subsequently sintering in reducing and/or vacuum atmosphere to fully densify the sphere wall. This results in uniform size, thin wall hollow spheres whose interior contains the process gas or vacuum. Other alternative foams and insulation materials would also have been evaluated and tested to characterize their suitability for this application. The operating temperature of the insulation was estimated to be on the order of 1150K. At this temperature, both ceramic and metallic materials are good candidates. Ceramic materials like zirconium oxide have low thermal conductivity at these temperatures but they are transparent to IR radiation. At the target temperature, the radiation component is a large part of the total heat transfer coefficient which makes the total thermal conductivity of a ceramic material not as low as would be expected given its room temperature properties. Metallic based foams are also good candidates although their bulk thermal conductivities are higher than the ceramic materials. Metals are opaque at the temperatures of interest so the radiation component is smaller than that for the ceramics which could potentially enable a lower thermal conductivity foam.

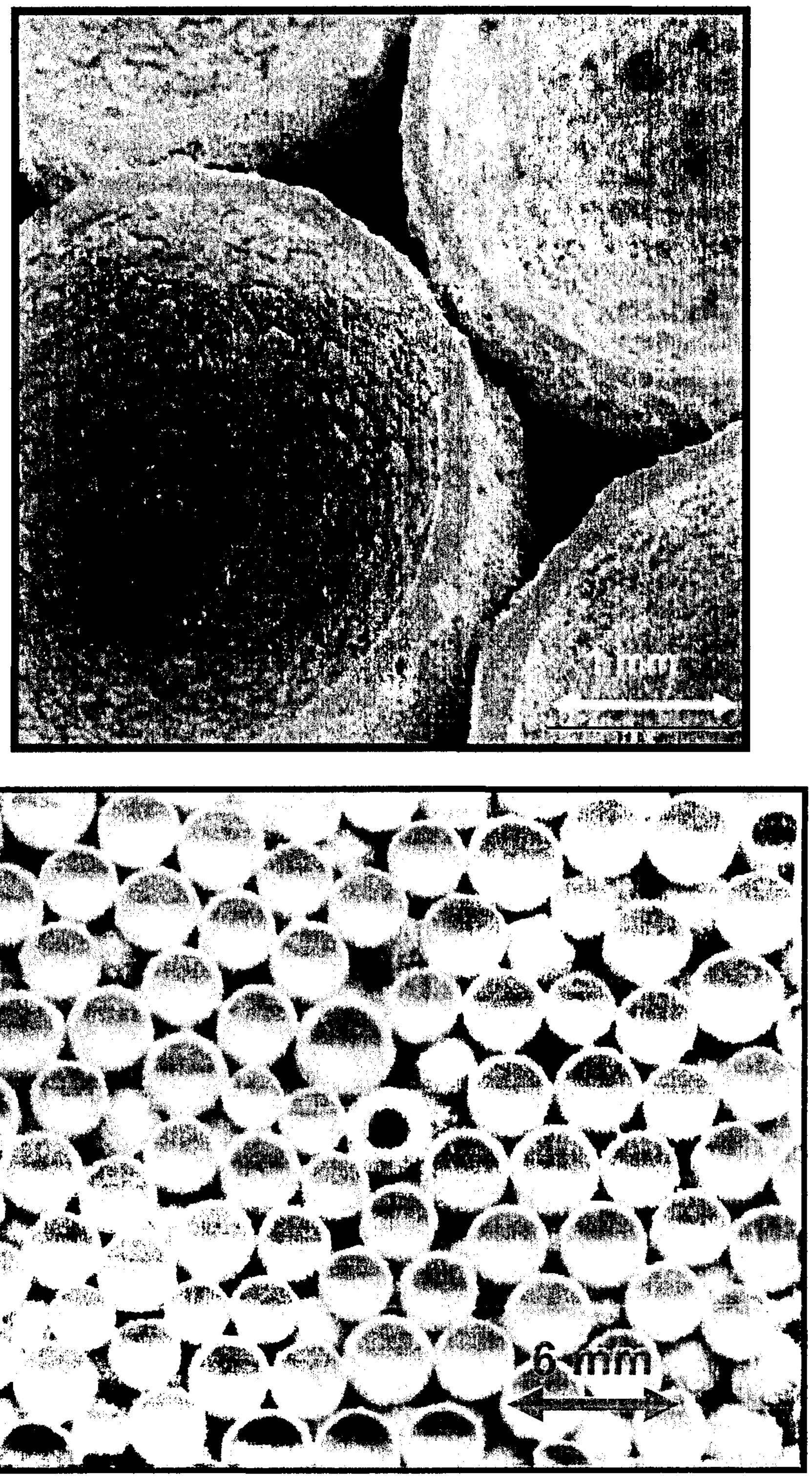

Figure 1: Inconel 617 Foam Insulation Made from Hollow Microspheres

4. **Insulation Materials Compatibility:** The foam insulation must be made of materials compatible with the outer pipe material, the liner, and the balance of the reactor plant components which will be in thermodynamic contact with the insulation. The preliminary foam material selections were zirconium oxide and a nickel-base superalloy. These were expected to have limited compatibility issues with the remainder of the potential SNPP materials. The possibility of using a refractory metal foam was also under consideration.

5. **Proposed Development Plan:** At the time that the NRPCT involvement in Project Prometheus was terminated, a development plan was being defined to investigate the feasibility of using foam insulation as the internal insulation for the hot leg piping. That plan consisted of the following tasks:

   Task 1 -- Sphere Material Selection: Material selection is critical to determination of the heat transfer coefficient at the operating temperature. Cochran[1] et al found that mullite and alumina foams made from spheres had low thermal conductivity values at low temperatures when the main heat transfer mechanism is conduction. However, as temperatures increase and the radiation component of the heat transfer coefficient becomes predominant, the heat transfer coefficient increased rapidly because these materials are translucent to the IR radiation. On the other hand, metals are opaque at these temperatures so heat transfer by radiation is reduced, and the total heat transfer coefficient of the insulating foam is lowered. Moreover, the use of metals similar to other parts of the plant assembly could reduce the materials compatibility concerns. Materials candidates under consideration included zirconium oxide, nickel-base superalloys, stainless steels, and molybdenum and its alloys.

   Task 2 -- Alternate Insulation Choices: In parallel to the development of microsphere based insulation foams, other alternative insulation foams were also going to be evaluated. Screening tests were being developed to determine the suitability of particular insulation materials for this application.

   Task 3 -- Sphere Formation: Among the important variables that affect the properties of the foams fabricated from thin-walled hollow microspheres is the wall morphology. Wall thickness, uniformity, and integrity will have an effect on both the thermal and the mechanical properties of the resulting foam. Walls should be uniform and the thickness should be enough to produce satisfactory mechanical properties but thin enough that low thermal conductivity and low density are retained. Impurities, both from the sacrificial polystyrene beads and from the process gas should be minimized.

   Task 4 -- Processing Issues: Sintering atmosphere and conditions have to be carefully controlled not only to obtain the desired wall density, but also to avoid the presence of unwanted residual contaminants from the polystyrene burn-off or from the process gas. Wall permeability is also an important parameter because it might be desirable to allow diffusion through the sphere walls so as to equalize internal pressure with the environment. Conversely, it might be desirable to have a dense and impervious sphere wall to avoid any mass transfer between the inside of the spheres and the external environment. Vacuum sintering was also planned to be evaluated.

   Task 5 -- Microsphere Characterization: Spheres were planned to be characterized for chemical composition and crystallography. Additionally, metallographic and SEM analysis of individual spheres and sphere wall cross sections was planned. Spheres would also be

[1] A.T. Chapman, J.K. Cochran, T.R. Ford, S.D. Furlong, and D.L. McElroy, "Reduction of High Temperature Thermal Conductivity of Thin-Wall Ceramic Spheres," Insulation Materials: Testing and Applications, 2, ASTM STP 1116, 464-475, (1991).

subjected to pressure tests and mechanical testing, such as crush strength tests, to mimic the high pressure environment and plausible mechanical loads.

Task 6 -- Foam Fabrication: To form a monolithic structure the spheres would need to be bonded together. Bond strength and its effect on sphere wall integrity was to be studied. The effect of processing on bond formation and integrity was to be evaluated by mechanical testing.

Task 7 -- Foam Characterization: Much like the individual spheres, the bonded foams were to be characterized for mechanical and thermal properties. Metallographic and SEM analysis of bulk specimens and cross sections of the foam were planned to determine the quality and integrity of bond formation between the spheres. Heat transfer coefficients were to be experimentally determined.