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Why Internal Insulation for the Saturn S-IV Liquid Hydrogen Tank?

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WHY INTERNAL INSULATION FOR THE SATURN S-IV LIQUID HYDROGEN TANK?*

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INTRODUCTION

The development of internal insulation for the Saturn S-IV stage has been a long and difficult program extending over a period of 21 months. The issue of "internal" versus "external" insulation often becomes controversial, since justification or advantages of each type often lie in a grey area. The successful development of either type of insulation is feasible and each have advantages and disadvantages, therefore the particular vehicle design philosophy and its usage must be critically examined to obtain a logical decision.

Vehicle design criteria must obviously affect the philosophy behind each major design decision. Two factors of vehicle design had major influence upon the selection of the insulating technique for the Saturn S-IV stage. The basic design approach for this vehicle was to keep the design as simple as possible and use all possible design experience gained from previous missiles and space vehicles. The greatest knowledge from past experience was structural design. Knowledge of material properties at liquid hydrogen temperature was limited for metals and extremely limited for insulating materials. In order to have a simple design approach, it was advantageous to divorce the problems of metal tankage design from insulation design. The insulation development program could therefore be conducted independently of the tankage design and a redesign in one area would not affect the design in the other area. This also eliminated the possibility of a new design approach, such as a double wall tank, which would integrate the structural and insulating design requirements. Hence a choice of lightweight insulating materials was made available since they could be non-structural. Secondly, no extensive coast phase is required of the S-IV stage. This allowed the investigation of materials which had a wide variation in thermal conductivity values.

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In order to fully appreciate the philosophy for using internal insulation, one must project himself back to the time of the Saturn S-IV proposal in the first quarter of 1960. A few of the factors entering this philosophy have been proven non-critical problems during the actual development of internal insulation. Conversely, some problems associated with internal insulation are now believed even more difficult with external insulation. All of these factors, in conjunction with advantages and disadvantages of each insulating technique, will be discussed.

COMMON BULKHEAD

One of the vehicle design criteria affecting the philosophy of using internal insulation was the use of a common bulkhead separating the liquid hydrogen and the liquid oxygen tanks. Using a stiffened single skin bulkhead necessitated the use of internal insulation on the liquid hydrogen side of the bulkhead to prevent freezing the liquid oxygen. If internal insulation had to be developed for this problem, it was logical to maintain complete internal insulation in the liquid hydrogen tank thus eliminating the necessity of having a dual development program for internal and external insulation.

During the initial design phase, analysis showed that the internal insulation could be eliminated from the common bulkhead if it could be manufactured using fiberglas honeycomb with aluminum faces. It was not known at that time whether fiberglas honeycomb could be bonded to aluminum and successfully withstand the thermal stresses induced at liquid hydrogen temperature. Early in the development program, it was learned that a fiberglas honeycomb common bulkhead would function satisfactorily and the vehicle design was changed to include this feature. Therefore, one of the reasons for using internal insulation no longer existed, but there still remain other reasons why internal insulation was selected.

BONDING AT LIQUID HYDROGEN TEMPERATURE

Another reason beneficial to using internal insulation was that the adhesive necessary to bond the insulation to the tank wall would only have to function successfully at temperatures on the order of -100°F. This would minimize the bonding problem since the adhesive temperature for external insulation would have to function at -423°F. At the time of the Saturn S-IV proposal, it was not known if adhesives existed which would successfully bond an insulating material to the tank wall at liquid hydrogen temperature. This subsequently proved not to be a problem since several commercial adhesives do function adequately at liquid hydrogen temperature.

HEAT LEAKS

When one reviews the vast scope of external equipment that mounts on the tank, such as vent valves, fill lines, engine propellant lines, gas pressurizing lines, external wiring, tunnels, brackets, etc., it becomes apparent that considerable complexity is involved in using external insulation. All the discontinuities which occur with external insulation makes one concerned about heat leaks and thermal stress problems. Manufacturing external insulation so that all these components can pass through it without having a high heat leak requires considerable development effort. Installation of internal insulation is geometrically simpler and has fewer discontinuities. Internal insulation eliminates the direct metal heat leak path into the liquid hydrogen (which external insulation does not) where the interstage structure intersects the tank. Clearly, such leaks can be stopped by insulating heat blocks, but only at the expense of considerable complexity.

TANK CHILLING

Internal insulation minimizes hydrogen loss when chilling the tank during filling. If external insulation is used, it will require approximately 100 percent of the tank capacity of liquid hydrogen boiled off to chill the aluminum walls to -423°F. This, in turn, requires a large launch pad vent system to handle this quantity of hydrogen gas during the fill operation. With internal insulation, the amount of liquid hydrogen boiled off to chill the tank insulation is of the order of 25 percent of the tank capacity. These approximate liquid hydrogen loss values are only applicable to the Saturn S-IV stage but do indicate trends for large liquid hydrogen stages.

HANDLING

Where low density insulation is used, internal insulation minimizes handling problems when compared to external insulation. The necessary shipping and testing of the vehicle would create many opportunities for damaging a light-weight external insulation configuration. An appreciation for the amount of handling required can be gained by considering that a typical Saturn S-IV stage will be shipped from the Douglas plant in Santa Monica to the Sacramento test facility, erected in the test stand for acceptance firing, transported from Sacramento to Florida, undergo check-out procedures in the prelaunch area, and errected on the launch pad.

CRYOPUMPING

When external insulation is used, the insulation must be absolutely airtight and free of cracks. If a crack does occur in the external insulation, liquefaction of air and cryopumping will occur resulting in a significant rise in heat transfer to the liquid hydorgen. If air liquefaction did occur, then liquid oxygen would be in direct contact with organic materials, which may be hazardous. Conversely, if a crack did occur with internal insulation, only gaseous hydrogen would exist in the crack and the heat transfer would only be increased slightly. This point has been proven during insulation development tests in a large tank where debonding has occurred in the insulation with no liquid air formation or degradation in performance.

THERMAL STRESSES OF INSULATION

The most serious problem presented to a bonded insulation, either internal or external, is the ability to structurally withstand the high thermal stresses generated when liquid hydrogen makes initial contact with the warm tank. During the transient of tank filling, the thermal stress level will depend on the coefficient of expansion of the inner wall since it will be at liquid hydrogen temperature while the outer wall is at ambient temperature. With external insulation, the tank wall can only be metal, such as aluminum for the Saturn S-IV stage, which has a high coefficient of expansion. When nonstructural internal insulation is used, more latitude in material selection is available for the inner wall material. While the thermal shock of filling is perhaps a more important stress condition since it is repeated many times, particularly on the static test vehicle, aerodynamic heating during flight also produces a high thermal stress condition. During vehicle exit through the atmosphere, the thermal stresses will be higher for external insulation since it represents a smaller heat sink and experiences a larger temperature gradient than internal insulation.

The thermal stress problem was the most difficult one to overcome during the development program. As is so often the case, an insulating material which had good structural characteristics had poor thermal characteristics and vice versa. By tailoring the insulation materials, designs have been achieved which have both good insulating and structural characteristics.

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HEAT TRANSFER

Assuming internal and external insulation have the same thermal conductivity and thickness, the internal insulation allows approximately 30 percent less heat to be transferred into the liquid hydrogen for the S-IV application due to lower temperature gradient across the insulation. With internal insulation, the temperature gradient across the insulation is approximately 570°F during the flight due to aerodynamic heating. For equal external insulation, the temperature gradient is approximately 825°F due, as mentioned previously, to the low heat sink represented by a lightweight insulating material.

During the insulation development program, it was learned that the thermal conductivity of the internal insulation was degraded due to diffusion of gaseous hydrogen when the insulation was exposed to liquid hydrogen for several hours. It appears feasible to develop a vapor barrier to preclude this problem, but it was not necessary for the S-IV application. The minimum insulation thickness which was practical for tank installation provided sufficient insulating properties even with the higher thermal conductivity value. External insulation is not subjected to this particular problem, unless air leakage and subsequent cryopumping results in a serious degradation, but it is subjected to degradation of thermal conductivity due to heat leaks which are compounded by the number of discontinuities that exist with external insulation. Hence, when all the design compromises are considered in actually insulating large liquid hydrogen tanks, the overall effective thermal conductivity is probably comparable.

GROUND ENVIRONMENT

The vehicle must be protected from various ground environmental conditions such as salt water, rain sand, fungus, etc. With external insulation, adequate protection must be provided to preclude any damage sustained from these environments. With internal insulation, no additional precautions are required since the tank will be fundamentally sealed and kept dry. The internal insulation must only be capable of withstanding a simple cleaning process using soap and water.

STRUCTURAL INTEGRITY

The use of internal insulation requires a very high degree of structural integrity to insure that particles do not get into the engine fuel system which may cause malfunction. This would appear to be an advantage for external insulation; however, during the development of the internal insulation, many failures have occured and in no case were there failures in the insulation of such nature that would affect the fuel flow to the engines or their operation.

METAL STRENGTH

At the time of Saturn S-IV preliminary design, no great knowledge was available on the precise metal strength characteristics, degree of brittleness, and notch sensitivity at liquid hydrogen temperature. Hence a decision was made at that time not to rely on the cryogenic strength of metals for the design of the S-IV hydrogen tank. The statement is often made that the higher strength values of metal at liquid hydrogen temperature is a strong advantage and therefore internal insulation would be a disadvantage, but this must be carefully analyzed before such a conclusion is reached. For aluminum, there is approximately a 40 percent increase in buckling strength when the temperature is reduced to -423° F. The buckling loads often design the tank cylinders and usually tensile loads design the tank domes. Therefore, for tanks having a high ratio of tank length to diameter, only a small gain can be realized. But a comparison must also be made on whether the buckling loads on the launch pad with the tank unpressurized and empty or the flight loads with the tank pressurized and filled design the structure. For the S-IV application these empty tank buckling loads were important, hence the use internal insulation and the resulting higher metal temperatures, between -100° F and -180° F, had a low penalty when compared to tank metal temperatures of -423° F.

CONCLUSIONS

During the development of a liquid hydrogen vehicle, it will be tanked and detanked a number of times. Static test vehicles will be used over a long period of time in which they are exposed to liquid hydrogen many times. One then becomes concerned over the general thermal stress problems and fatigue life of materials. If materials can be maintained at temperatures closer to room temperature, the less critical these problems become. At first glance this philosophy of internal insulation seems inconsistent with the common bulkhead design which does experience all of these cyclic effects. This problem is not as severe because during normal operation the bulkhead is not highly stressed from pressure or external loads. Also, it is chilled gradually since the liquid oxygen tank is filled prior to the liquid hydrogen tank. The strength of metals at cryogenic temperature is not a one to one advantage. Where buckling loads design tank walls, the full advantage of increase strength at cryogenic temperatures cannot be taken.

The limitations of internal insulation are recognized. It does not fully solve the problems associated with orbital storage and extended coast periods. These all require much lower heat flows which can be obtained with high performance external insulations provided all the heat leaks can be stopped. This is a much more complex insulation scheme and perhaps can be used in conjunction with internal insulation. For the Saturn S-IV mission, which is only a boost requirement the internal insulation appears to be the most desirable solution from both the manufacturing and operational point of view.