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What every engineer should know about Vacuum Insulated Tubing:

Michael S. Lombard, SPE, Oil Tech Services, Inc.

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The Petroleum Engineer assigned to the task of designing a thermal well completion using insulated tubing will have a number of questions such as:

- What is the thermal conductivity value?
- What is the thermal performance, heat loss per foot or meter of length?
- What are the mechanical properties and limitations of the insulated string?
- What are my connection options?
- What is the price?

While these are very specific requests the answers may not be the answers that lead the engineer to the best purchase decision. A certain level of knowledge about <u>high vacuum multilayer insulation systems</u> should be known before the Petroleum Engineer specifies and purchases an insulated tubing string.

Once it's decided a steam injection program will benefit from the use of insulated tubing and before the purchase decision is made, it's important that the buyer understand technical matters concerning the type insulating systems that will be installed. This paper attempts to create a level of technical transparency and provide the engineer with a few tools that can be used to evaluate the various manufacturers and technologies.

Multilayered insulated steam injection tubing was introduced in the late 1970's by General Electric Company finding immediate acceptance as a means to lower steam costs, solve wellbore issues, and improve steam oil ratios. The first insulated tubing consisted of an Argon gas backfilled insulating system having thermal conductivity values in the range of 0.015 Btu/Hr-Ft-°F (0.026 w/mK). A flurry of activities on the part of oil producers and manufacturers lead to the introduction of Vacuum Insulated Tubing (VIT) in 1983, by Babcock & Wilcox Company (Ayres, 1982). This multilayer and gettered high vacuum insulated tubing systems (VIT) offered substantially improved thermal performance having conductivity values in the range of 0.0018-0.0023 Btu/Hr-Ft-°F (0.003-0.004 w/mK).

Ayres, (1982). *Patent No. 4,512,721*. USA, Ohio.

Collapsing oil prices in mid-1980's, reduced the incentives to use advanced thermal recovery processes and insulated tubing disappeared from the Petroleum Engineers toolbox causing insulated tubing manufacturers to either disappear or re-organize themselves to survive in a changed environment. 20+ years later, the world has become quite different; globalization has expanded aggregate wealth and enabled developing countries to achieve unprecedented prosperity. One of the consequences is a changed oil market and higher oil prices where heavy crudes can and do sell at a premium compared to lighter oils. This changing world has once again made the economics for thermal enhanced oil recovery (EOR) attractive. Additionally, new recovery processes have been invented, like SAGD completions, and engineers are evaluating many new and old technologies to improve the efficiency of every aspect of their oil production operations.

Vacuum Insulated Tubing (VIT) improves the thermodynamic potential of a well by delivering more Enthalpy (Btu's) to the oil bearing reservoir: Enthalpy is the thermodynamic potential performing both non-mechanical work and the release of heat into the oil bearing reservoir rock. The delivery of higher quality steam to the oil bearing reservoir rock provides substantial benefits, and in deep wells it is indispensable for optimizing the thermal performance of the steam process.

In SAGD completions insulated tubing is used to improve the overall process; starting with the reservoir, through the well design and injection string, and including optimization of the surface facilities. During the initial phase of SAGD well pairs steam is injected down a long (toe) string while produced reservoir fluids are simultaneously returned to surface through a concentric short (heel) string. Insulated tubing is used to gain four primary benefits:

1. Reduce the wellbore heat exchange between the injected and returning fluid streams.
2. Reduce the mass flow of steam delivering the specified enthalpy (Btu's) to the reservoir using less steam volume.
3. Improve the initial steam oil ratio (SOR) due to the reduced mass steam flow needed for the process.
4. Reduce demands on surface facilities allowing for either smaller plant sizes or giving the existing plant spare capacity to circulate additional well pairs.

All the above can have a large impact on payout and return-on-investment. And in both conventional steam injection and SAGD processes Insulated Tubing (VIT) can benefits the overall process by:

- Delivering of the highest rate of Enthalpy (Btu's) to the oil bearing zone.
- Reducing rate and magnitude of thermal expansion and heat transfer occurring in the production casing and cement relieving concerns for thermal induced damage to the well and cement integrity.
- Maximizing injected Enthalpy delivered to the reservoir optimizing viscosity reduction, gas thermal expansion, and the potential for insitu reservoir distillation.

Performance characterizes of insulated tubing can vary to a tremendous degree and there is no such thing as a "generic" or a "standard specification". This paper is a guide and resource covering the general manufacturing processes and selection of raw materials for VIT. Specifically the paper covers getters, cleanliness requirements, the Bakeout process (temperature and time programmed desorption of gasses from raw materials), and other manufacturing and quality control issues and processes.

Borrowing a phrase made popular by a respected financial advisor and popular television show host, her question "show me the money?" is adapted to "show me your raw materials and processes?". These raw material specification and manufacturers processes are the important features the engineer can evaluate, quantify, and use to make an informed purchase decision.

The start of our discussion starts with the core raw material for any high vacuum system, the non-mechanical pump (chemical pump), **getter,** that creates and maintains the high vacuum insulation system and allows the vacuum's superior insulating performance compared to other types of insulation systems.

<u>Getter (the chemical pump within the vacuum envelope):</u>

- Show me your getter manufactures' data sheet.
- Show me how the getter is activated.
- Show me the location and quantity of getter installed into each joint.

1. Getter: The engineer will want to review the technical data sheet for the getter used by the manufacturer. You will look for information on getter capacity, pumping speed, and activation temperature.
2. Getter Activation: The engineer will want to know the process of getter activation and compare the VIT manufacturers procedures to the getter manufacturers published data for activation efficiency (see graph 1).
3. Getter Quantity: It is important to know the quantity and location of getter installed into the annulus of each joint.

<u>What is getter?</u> Getter is a non-mechanical chemical pump converting gas molecules into solids and trapping these solids within the matrix of the getter material. The composition of getter used in high vacuum insulation systems is mostly Zirconium, Vanadium, and Iron mixed to create both granules and pills that are installed in close proximity to the inner tube where they are easily activated by high temperature steam. The getter manufacturer will

form the getter into its final configuration at room temperature where it will immediately start to pump H^2, N^2, O^2, CO, and CO^2. Instantaneously a passivation layer is created on the outer surface because of the getters high affinity for primarily N^2 and CO which coats the getter surface stopping further pumping at room temperatures. Once this passivation layer forms high temperature activation is required to re-start the pumping process.

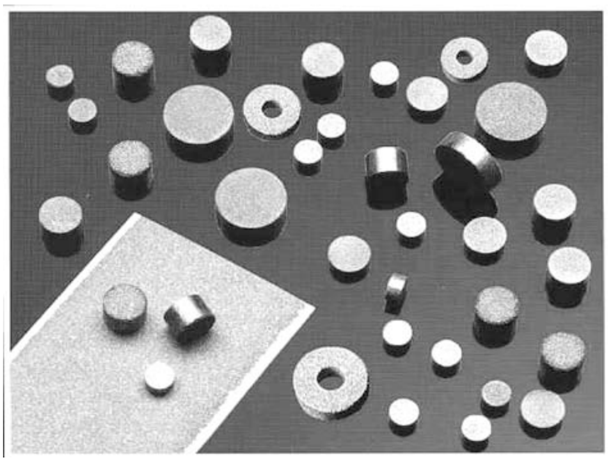


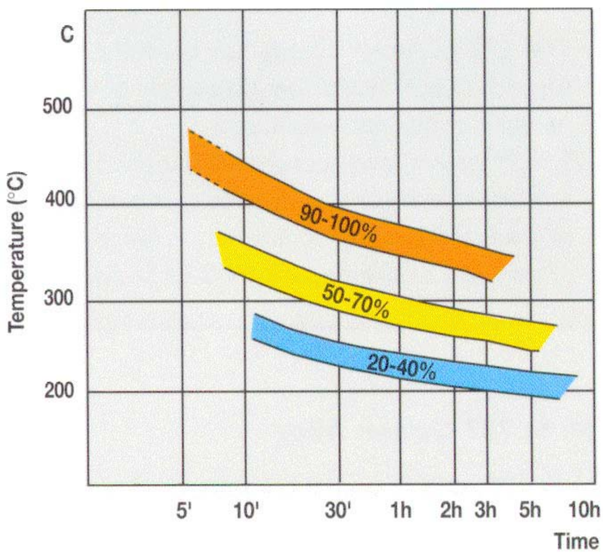
Photo 1: Examples of Non-Evaporative Getter Materials

Getter re-activation for VIT is best and normally done in a temperature controlled oven (bakeout process) this being a critical step in manufacturing a multilayered gettered high vacuum system.

What is a bakeout process? Incorporating a Bakeout is a common and standard practice for high vacuum systems and a critical manufacturing process helping and increasing the getters ability to perform its primary job of maintaining the vacuum over the life cycle of the VIT joint. Outgassing from raw materials, primarily the inner and outer tubes, are a lifelong issue for the vacuum system. Taking a step back to the college physics lab, when a vessel is mechanically evacuated with a vacuum pump we observe it immediately experiences an increase in pressure after the vacuum pump is removed and the evacuation port sealed. This increase in pressure is caused by the residual gases left in the vessel and the evolution of trapped gases from the inner surfaces of the vessel being slowly released (evolved) as soon as the pump is removed. A Bakeout process is a good way to counter this problem. The bakeout causes a cleaning the inner vessel surfaces, helps to remove residual gasses, and releases sorbed gasses from the vessel walls. In a VIT joint the heat applied during the bakeout process makes the gases more active and drives them off the surfaces of the inner and outer tubes where they can be mechanically pumped as they evolve from the interior matrix of the steel tubes. This process is called temperature programmed desorption.

The temperature programmed desorption cycle can be divided into two (2) general procedures. The first is at a lower temperature while getter is kept cool with its surface passivation layer intact and its pumping ability held in reserve. This first step allows surface gases to slowly evolve from raw material where they are pumped and exhausted through the vacuum port by a mechanical vacuum pump. The second general phase is getter re-activation when substantially higher temperature are applied over a predetermined period of time causing the getters passivation layer to be absorbed and become trapped deep into the getter matrix allowing the getter to become a chemical gas vacuum pump.

This timed temperature cycle controls getter re-activation and the establishment of a controlled high vacuum in the range of 10^{-6} to 10^{-10} Torr[1]. Getter manufacturers publish tables of getter activation based on temperature and time. The graph below shows the getter pumping efficiency for SAES st707 expressed as a percentage of the getters rated pumping speed. VIT manufactures will control the temperature programmed desorption cycle to stay within the 90-100% (orange) band. Lower temperatures require longer time periods.



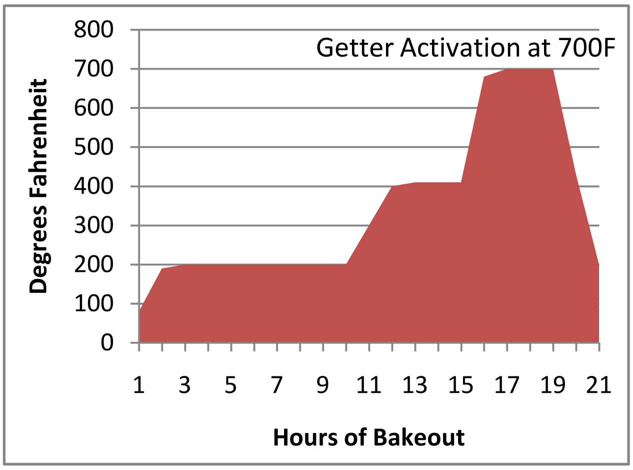
Graph 1: Activation for SAES st707 manufactured by SAES Getters, Milano, Italy[2]

Getters are actually quite forgiving in terms of the activation and re-activation processes. According to

[1] 1 Torr = 1/760 of an atmosphere
1 Torr = 133.322 Pa (Pascal)
1 Torr = 0.00131578935941 atmosphere (1.315 x 10-3)

[2] SAES – st707 non-evaporable getter

SAES Getters standard activation for st707 can be at 450°C (845°F) for a period of 10-15 minutes and longer periods at lower temperatures. There is no magic formula for this process, the objective being to hold the activation process at the selected temperature for a long enough period of time to obtaining the highest re-activation efficiency possible.



Graph 2: Temperature Programmed Desorption Cycle (Bakeout), Oil Tech Service, Inc., SAES Getter st707

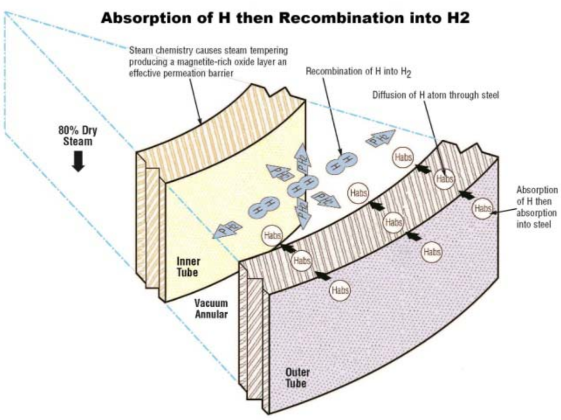
The above graph shows three distinct phases of a typical bakeout process (temperature programmed desorption cycle) for VIT. With a mechanical vacuum pump attached through a vacuum port on the outer tube the oven is set at a low temperature for approximately 10 hours while raw materials (inner and outer tubing and insulating materials) are slowly heated causing a general surface cleaning and diffusion of surface gases. During this phase the getter is kept cool to avoid premature removal of its passivation coating.

In phase 2 while the external mechanical vacuum pump continues to pump annulus gasses the bakeout temperature is increased and held for a period of approximately 5-hours. During this period gas molecules trapped in the inner and outer tubes become very active and rapidly evolve from the steel matrix. At the same time the getter is allowed to slowly heat causing Hydrogen (H^2) trapped in and on the getter surface to evolve and pumped and exhausted by the mechanical vacuum pump.

In the final phase, lasting approximately 5 hours, the reactive gases that created the original passivation layer are diffused permanently into the bulk of the getter material and become permanently trapped within the getter matrix. At this stage the getter pumping ability is extremely active establishing a high vacuum within the annulus. This high vacuum along with the multiple radiation barriers wrapped around the inner tube provide the low thermal conductivity values shown in the VIT manufacturer's literature.[3]

Throughout the life of the joint the function of the getter is to maintain the vacuum in the annulus space between inner and outer tubes. Once the insulted joint is placed into service and steam injection starts, remaining trapped gases inside the steel matrix will continue to slowly release (evolution of gases), and the getter's task is to pump and permanently trap these gas molecules inside the getter matrix.

A good bakeout means cleaner raw materials and lower volumes of sorbed gases residing in the steel matrix of the inner and outer tubes. Because getters have a finite capacity the bakeout is a critical step in giving the VIT joint a controlled long life cycle and for maximizing the residual getter pumping capacity to handle vacuum enemy #1, Hydrogen permeation.

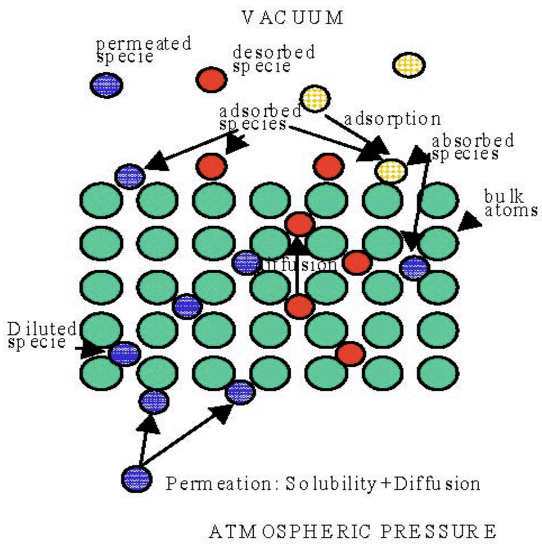


Hydrogen gas will impair thermal efficiency and increases the thermal conductivity of the VIT vacuum system. Hydrogen can permeate through most materials, and in VIT vacuum system whose boundary walls are carbon steel oil country tubulars it can be particularly aggressive. Permeation of gases is a combination of two physical processes: dissolution and diffusion. First, the gas dissolves into the solid steel walls and then diffuses through the steel matrix and desorbs into the vacuum volume. The dissolution phenomenon obeys Henry's law:

$$c = sP^n$$

Where c is the concentration, P the gas pressure, s the solubility, and n depends on the material.

[3] Bakeout is a controlled process with the vacuum pressure being measured at intervals during the bakeout. The timed temperature cycle duration is adjusted according to observed annulus pressure levels.



Getter is an ideal sorbent for Hydrogen and specifically designed to meet this challenge. The task for the VIT manufacturer is to forecast the quantity of getter needed by quantifying the amount of evolving gas from raw materials and forecast the volume of Hydrogen permeation that might occur over the life of the joint. The evolution of gas is normally based raw materials test values, and Hydrogen permeation data is from laboratory and field testing. The manufacturer should be prepared to discuss this matter and inform the buyer about the quantity of getter installed into joints of VIT.

An insulated tube manufactured not using a bakeout cycle will need to install substantial higher quantities of getter to insure a vacuum is maintained once the tubing is put into service.

<u>What to look for (keeping in mind the devil is with the details):</u>

- Getter manufacturer technical data sheets.
- Does the manufacturer us a Bakeout cycle to remove surface gasses and activate the getter? Is this bakeout cycle consistent with the getter manufacturer's recommendations?
- Manufacturer's response to the pumping capacity for getter after the initial re-activation.
- Quantity of getter installed.

<u>Show me your other raw materials:</u>

- **Show me the MTR's on tubulars.**
- **Show me information about your multilayered insulating materials.**
- **How many radiation barriers are installed around the inner tube?**

Other raw materials consist of:

1. <u>Inner & Outer Tubing</u>: View copies of Material Test Report (MTR) obtained from the steel mill.

2. <u>Multilayer Insulation</u>: Consists of layers of aluminum foil separated by layers of insulating material. These materials should have technical data sheets and be rated for vacuum service. Insulating materials for high vacuum systems are without binders that outgas. Aluminum foils meet cleanliness specifications for vacuum service being free of oils and other contamination.

   Storage procedures for raw materials should be reviewed: Multilayered insulating materials for vacuum service are subject to oxidization and are hydrophilic absorbing moisture that is not a good material to have in a high vacuum system. All water vapor found in a vacuum comes from the atmosphere. At 25°C (78°F) and 50% relative humidity air contains 12 torr of water vapor and any material capable of absorbing or attracting water will do so. Fortunately water has a relatively weak attraction bond being easily broken in the bakeout and mechanical pumping process: The removal technique being time and temperature.

3. <u>Number of radiation barriers</u>: Heat transfer through multilayer vacuum insulation systems is dominated by radiation. Manufacturers will optimize the number of radiation barriers having each layer with low conductance insulating material between radiation shields. You want to know how many layers of radiation barriers are installed around the inner tube.

<u>What to look for</u>:

- Materials for and the number of radiation barriers installed around the inner tube.
- Placement of getter. Should be in close proximity to the inner tube.

<u>Show me your manufacturing processes:</u>

There are seven general manufacturing processes used by most manufacturers for the assembly of VIT joints: (1) Cleanliness, (2) fitting of insulating materials around the inner tube, (3) welding, (4) prestressing, (5) bakeout, (6) K-Factor testing, and (7) the threaded connection. This paper discusses each except the threaded connection being a subject of its own.

Manufacturing Processes – Cleanliness:

In vacuum technology cleaning is both the removal of the visible dirt and removal of all the contaminants physically stuck on the surfaces (oil, grease, oxides, etc.). Mill scale, oxides and similar surface layers can be removed by mechanical and/or chemical methods such as abrasive blasting or pickling. After proper cleaning, the most efficient method of reducing the outgassing rates of the materials of the vacuum systems is by long term bakeout at temperatures from 100°-200°C (200°-400°F) as previously written, followed by high temperature getter activation at 350°-370°C (650-700°F).

What to look for:

- General cleanliness of the manufacturing operation.
- Surface cleaning of the outer tube ID and the inner tube OD prior to assembly operations.
- Procedures and processes used to insure persons involved in the assembly process do not contaminate the insulation system (oils for hands and perspiration).

Manufacturing Processes – Welding:

Two types of welds are typical for VIT joint:

(1) The two welds connecting each end of the upset inner tube to the outer tube.
(2) The seal weld of the vacuum port plug typically at one end of the outer tube and used in the bakeout connecting the annulus of the joint to a mechanical vacuum pump.

The manufacture will have quality documentation on both these welds consisting of a Welding Procedure Specification (WPS) and Procedure Qualification Record (PQR).

The WPS document describes how welding is carried out in production and include sufficient details to enable any competent person to apply the information and produce a weld of acceptable quality. The WPS will include but is not limited to:

- Procedure number
- Process type
- Consumable size and type
- Thickness range
- Tubing diameter range
- Welding Position
- Joint fit up, preparation, and cleaning
- Pre-Heat
- Post Weld Heat Treatment (Time and Temperature)
- Welding Technique
- Specifics and limits to the welding process (current, speed, voltage, wire configuration, shielding, etc)
- A sketch of the joint configuration including basic dimensions of the weld preparation

The Procedure Qualification Record (PQR) document contains details of the welding test conducted on a periodic basis to confirm the WPS.

What to look for:

- Review WPS and PQR documents.

Manufacturing Processes – Prestressing

With VIT a high-temperature differential exists between the inner and outer tubes and it is common practice for joints of VIT to be prestressed in order to compensate for differential expansion of the hot inner tube relative to the cold outer tube.

The prestressing operation is a controlled elongation of the inner tube relative to the outer tube. There are several processes to accomplish this elongation, one is mechanical by installing the insulated inner tube[4] into the outer tube, welding and heat treating one end of the inner tube to the corresponding end of the outer tube, then installing this tube assembly into a fixture that rigidly holds both the inner and outer tubes while the inner tube is mechanically elongated relative to the outer tube. Then, while the inner tube is mechanically held in the elongated position, the second weld of inner to corresponding outer tubes is made and properly heat treated. Another process could be to use a thermal process to elongate the inner tube.

The prestressed inner tube will have internal supports/centralizers at intervals within the annular space between the inner and outer tubes maintaining the spaced relationship between the two tubes preventing buckling, bowing, and deformation. The number of centralizers is calculated from standard columnar buckling formulas.

Once the joint is put into service and steam temperatures causes growth of the inner tube, this growth will first releases the elongation placed into the inner tube and only then will the inner tube expand putting the outer tube into compression. This compression / tension relationship results in lower overall string thermal expansion of VIT compared to bare non-insulated tubing strings.

[4] Inner tube is wrapped with multiple layers of Aluminum foil separated by corresponding layers of insulating paper, and having getter installed in close proximity to the inner tube.

What to look for:

- o Manufacturer's ability to control the process so that each joint is the same, including welds and post weld heat treating.
- o Method of centralizing the inner tube within the outer tube and checking the placement of these centralizers so they minimize the chance for thermal shorts and becoming a path for conductive heat losses.

Manufacturing Processes – K-Factor Inspection

Each joint of VIT) should be tested for its thermal conductivity value (K-Factor) after manufacturing. Manufacturers using a bakeout cycle can easily perform this test after removal from the oven and while the completed VIT joint is cooling. Completed joints can be removed from the bakeout oven and the open ends of each joint temporarily plugged keeping the inner tube hot. Thermocouples can be attached to the OD of the outer tube and installed into the inner tube. With the outer tube exposed to atmospheric temperature it will cool quickly relative to the inner tube and the temperature changes between outer and inner tube taken over time can be used to calculate a conductivity value (K-Factor) for each individual joint.

What to look for:

- o A conductivity value (K-Factor) report for each joint of tubing shipped should be provided to Buyer.

Q***uality Control and Non-destructive Testing***

Proof of Weld Integrity: The integrity of welds connection inner and outer tubes is a question commonly asked by buyers.

The weld connecting the inner to outer tube is located in an area that is impossible to inspect with NDE equipment including x-ray. Manufacturers using a Bakeout process gain a NDE weld inspection advantage. Once the insulated joints are removed from the bakeout oven both outer and inner tubes are hot being near the getter activation temperature somewhere in the range of +340°C (+650°F). Once removed from the oven they are subjected to ambient temperatures causing the outer tube to cool faster than the inner tube (See K-Factor testing).

During the conductivity value (K-Factor) test described above, the temperature differential between the inner and outer tubes is approximately 290°C (550°F) wherein the outer tube is cooling quickly in the ambient environment (assume <38°C (100°F) and the inner tube remains approximately +340°C (+650ºF). At this point thermal loads on the inner/outer tube welds are high and these loads can be calculated according to the following analysis.

The coefficient of thermal expansion is 8.64 x 10-6 inch/inch-°F[5], and the Young modulus of elasticity of material is 32,000,000 psi. The calculated combined thermal stress for the inner and outer tubes is:

(8.64 x 10-6)(550ºF)(32,000,000) = 152,000 psi

This stress is distributed inversely proportional to the area of the weight of each tube. Based on a 4-1/2" - 11.35 pounds/foot outer tube and a 3-1/2" - 8.81 pounds/foot inner tube, the combined weight is 20.16 pounds/foot. The 4-1/2" OD x 4" ID outer tube has a cross sectional area of 3.34 in^2, and the 3-1/2" OD x 2.992" ID inner tube has a cross sectional area of 2.59 in^2, for a total area of 5.93 in^2.

Outer tube stress = (152,000) (2.59/5.93) = 63,389 psi – 23,620 psi = 39,769 psi (tension)

Inner tube stress = (152,000) (3.34/5.93) = 85,612 psi – 30,000 psi = 55,612 psi (compression)

The above calculated thermal stress values are the extreme case and based on the high oven temperature of getter activation approximately 370°C (700ºF).

These calculations show stress on the inner and outer tube connection welds during bakeout, after bakeout, and during the cool down cycle are higher than any thermal stress the tubulars will see when used downhole. The calculated stresses are as follows:

Weld area of a 4-1/2" x 3-1/2" VIT joint (based on fillet weld at face of the inner tube being 0.25" high) has an OD of 3.75" and ID of 3.35" being 2.75 in^2.

Force on Welds = Cross sectional area of the Inner Tube x Compressive Stress on the Inner Tube (psi)

Force on Welds = (2.59 in2) (55,612 psi) = 144,035 pounds

Weld Stress = 144,035 pounds / 2.75 in^2 = 52,376 psi

The 144,035 pound force on the welds and the 52,376 psi thermally induced weld stress into each weld during the bake-out and cooling process is a significant event: If any weld failed or suffered from welding process problems it would cause a weld leak resulting in vacuum failure and be immediately detected during the K-Factor. Therefore the bakeout and the K-Factor test becomes a comprehensive test of both thermal performance and structural weld integrity.

[5] JFE Steel Corporation literature

<u>What to look for:</u>

- Post manufacturing inspection procedures.

Conclusion: Purchase of Vacuum Insulated Tubing represents a substantial investment and a logical and technical approach for evaluating various manufacturers is important. The author has encountered a general lack of understanding of high vacuum multilayered insulation (MLI) systems, and the purpose of this paper is to review MLI fundamentals and general manufacturing practices for high vacuum insulation systems specifically Vacuum Insulated Tubing (VIT) giving future buyers a guide to make informed decisions. In so doing, it is hoped VIT understanding is improved, mis-information dispelled, and buyer's use this information as a tool to make better purchasing decisions.

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