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SUPERFLUID He TESTING OF TITANIUM–STAINLESS STEEL TRANSITIONS FABRICATED BY EXPLOSIVE WELDING

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Исследование в сверхтекучем гелии переходных соединений (титан – нержавеющая сталь), изготовленных методом сварки взрывом

Создана экспериментальная установка для исследований в жидком гелии биметаллических трубчатых соединений (титан – нержавеющая сталь), изготовленных методом сварки взрывом. Измеренные во ФНАЛ (Батавия, США) после термоциклирования уровни течи исследуемых образцов ($7{,}5 \cdot 10^{-10}$ торр · л/с — при температуре окружающей среды и $7{,}5 \cdot 10^{-9}$ торр · л/с — при температуре жидкого азота) совпали с данными для тех же образцов, полученными ранее в ОИЯИ (Дубна, Россия) и ИНФН (Пиза, Италия).

Для испытаний с жидким гелием биметаллические трубки были сварены попарно своими титановыми концами. При комнатной температуре уровень течи во всех трех исследованных парах составил $4{,}9 \cdot 10^{-10}$ торр · л/с. На первом этапе испытаний (4–6 K) в одной из пар появилась течь. Испытания будут продолжены, поскольку методика сварки взрывом представляется весьма перспективной как технология нового поколения.

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Сообщение Объединенного института ядерных исследований. Дубна, 2009

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Superfluid He Testing of Titanium–Stainless Steel Transitions Fabricated by Explosive Welding

An experimental setup was constructed to test in liquid He bimetallic (titanium–stainless steel) tube joints which were manufactured by an explosive welding method.

The leak levels of the samples tested at room temperature $7.5 \cdot 10^{-10}$ and $7.5 \cdot 10^{-9}$ Torr · l / s at 77 K, correspondingly, measured at FNAL (Batavia, USA) after the thermocycling have coincided with the earlier results obtained at JINR (Dubna, Russia) and INFN (Pisa, Italy) data for the same samples. For the liquid helium test the tubes were welded in pairs by their titanium ends. At the room temperature the leak level of the three tested samples was $4.9 \cdot 10^{-10}$ Torr · l/s.

At the first cryogenic tests (4–6 K) one of the samples manifested a leak. The investigation will be continued since the explosive welding seems to be a very perspective new generation technology.

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna, 2009

INTRODUCTION

Our research centers participate in the development of a unique project of the 21st century which is known as the International Linear Collider (ILC). This study was undertaken as an execution of the preliminary R&D plan (PR&DP) formulated for discussions by F. Bedeschi, J. Budagov, B. Kephart, D. Mitchel, S. Nagaitsev, and R. Roser at FNAL (Batavia) in April 2006. This R&D, which is currently expressed in the corresponding agreements, is approved and supported in general by the FNAL (Batavia), JINR (Dubna), and INFN (Pisa) directors. The RFNC (Sarov, Russia) is a key participant in some essential stages of these studies.

The ILC will allow electron–positron collisions at energies 500–1000 GeV. It is the next step after the Large Hadron Collider (LHC), the world's largest particle accelerator which is put into operation at CERN (Geneva). Construction of the new accelerator will contribute to development of promising directions in the field of nuclear power engineering and technology and, as a result, to the research on new power sources, new materials, etc. Apart from the leading accelerator centers of the United States, Japan, Germany, and Russia, which are seeking to accommodate the ILC on their territory, a lot of research centers from many other countries participate in the project.

Electrons and positrons are accelerated over $\cong$ 40 km length by means of superconducting cavities of highly pure niobium (Nb). Some 20 000 cavities are required in total. The cavities should be kept at the temperature 1–2 K. For this purpose, they are placed in titanium (Ti) vessels filled with liquid helium. Helium is continuously supplied to the vessels through a Ti tube running along the entire length of the accelerator. The choice of Ti is due to the welding features of niobium and titanium. The ILC leading body has considered and JINR is examining an option of making the helium supply tube from stainless steel (SS), which allows a substantial decrease in the cost of the project. The key problem of this structure is a *joint between the stainless steel tube and the titanium vessel* [7].

Stainless steel-to-titanium bimetallic transitions have been made with an explosively bonded joint. This novel joining technique was developed by the Russian Federal Nuclear Center (Sarov), working under contract for the transition piece manufacturers at the Joint Institute for Nuclear Research, Dubna, Russia [1–3]. These transitions are being considered for use in future Superconducting Radio-Frequency (SRF) cavities. These transition joints will be tested in superfluid helium conditions at Fermilab's A0 Vertical Test Dewar (VTD) (Figs.1 and 2).

Fig. 1. SS-to-Ti transition joints

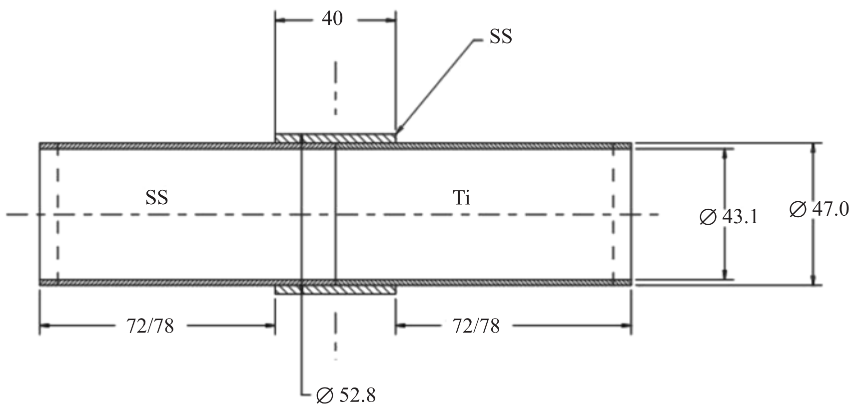

Fig. 2. The transition joint design

CONCEPT VERIFICATION AND PREVIOUS TESTING

Prior to shipment to Fermilab (Batavia), seven SS-to-Ti joints were tested under various conditions at INFN (Pisa) and JINR (Dubna) [4–6]. These bimetallic joints were pressurized to 6 atm and successfully leak-checked. Furthermore, these pieces were successfully leak-checked after 5 thermal cycles to 77 K to leak rate $< 5 \cdot 10^{-10}$ Torr · l/s.

The thermal cycle tests to 77 K were repeated at Fermilab (Fig. 3), and the results were unchanged. Again, the leak rate of $< 5 \cdot 10^{-10}$ Torr · l/s was observed. Six thermal cycles were performed. The leak check setup at Fermilab is shown in Fig. 3.The acceptance criteria for the maximum integral leak rate have been established. It should not exceed:

- at room temperature — $1 \cdot 10^{-10}$ Pa · m^3 / s = = $< 7.5 \cdot 10^{-10}$ Torr · l/s,
- at cryogenic temperature — $1 \cdot 10^{-9}$ Pa · m^3 / s = = $< 7.5 \cdot 10^{-9}$ Torr · l/s.

Fig. 3. Initial leak checking at the transition joint at Fermilab

Two versions of the transition joint are available: non-annealed or annealed (after the explosion-bonding procedure). Six tubes will be available for cryogenic testing, denoted as 3N, 7N, 5A, 6A, 8A, and 9A.

WELDING AT FERMILAB

For superfluid testing purposes, three transition joint test articles were assembled. They consist of two SS-to-Ti transition joints welded together at their Ti ends, and SS blank welded at one end, and a 3.3/8" SS Conflat flange with a through-hole welded at the other end (Fig. 4).

To complete the transition joint test article assembly, one Ti weld and two SS welds were required. A chamfer was machined on the Ti tubes by the Fermilab machine shop to facilitate the Ti welding. The titanium welds were made within a «glove box» inerted with an argon atmosphere. This welding facility is shown in Fig. 5.

Tooling was provided to support this welding job. A threaded rod with holding flanges at either end was used to hold the two transition joints together during the welding. Also, water-cooled copper heat sinks were made to keep the explosive-bonded joint cool during the welding process. These pieces are shown separately in Fig. 6 and installed for welding in Fig. 7. Dan Watkins of Fermilab performed the welds, as shown in Figs. 8 and 9.

Fig. 4. The transition joint test articles

Fig. 5. Fermilab's titanium welding «glove box»

Fig. 6. Water-cooled copper heat sinks

Fig. 7. The heat sinks installed for welding

Fig. 8. Welding of the titanium ends of the transition joint test article

WELDING PROCEDURE AND RESULTS

Initial testing was done with stainless steel welds to test the concept of the water-cooled heat sinks (Fig. 6). Two stainless steel tubes were welded to imitate the welding of the bimetallic tubes. In one case, the temperature rises from 68 °F to 104 °F. In the second case, the temperature rise was from 67 °F to 86 °F. This shows that the heat sinks are very effective at keeping temperature low during the welding process.

The final production of welding procedure for the transition joint test article assembly was carried out inside the LABCONCO glove box in the argon atmosphere. The following was observed:

1) The first pair to be welded were tubes 5A+6A. Both tube pieces were cooled during welding by domestic cold water through the copper ring heat sinks fixed close to the SS collars (Figs. 7, 8). The temperature during the welding was measured by thermocouples on both SS collars of the pair. The elapsed time for the entire welding procedure was ~ 5 min. The temperature in °C was recorded ~ every 1 min:

Left side (5A)	Right side (6A)
20.0	20.6
20.2	20.9
21.1	22.1
21.7	22.9
36.3	40.3
41.0	47.6

Around the welded line, colored spots were observed. It means that gas has admixtures.

2) The second pair consisted of bimetallic tubes 3N and 7N. They were not annealed after explosion-bonding. The gas was replaced. Cooling water was flowing. Temperature measurements were taken more often:

Left side (3N)	Right side (7N)
23.3	24.1
23.6	24.2
24.9	26.3
28.4	30.6
31.4	33.9
34.7	37.0
38.4	40.2
41.7	43.9
46.4	48.1

Around the welding line, the coloration was still present, but less in comparison with the first pair.

3) The third pair included bimetallic tubes 8A and 9A, annealed after explosion welding. This pair was welded without water cooling:

Left side (8A)	Right side (9A)
23.6	24.0
28.1	26.6
33.6	32.7
36.7	36.1
40.1	38.8
44.2	43.4
47.7	46.9
49.6	49.9
59.9	68.2

The temperature increase was not that much greater than the temperature rise for those welded with water-cooling. This suggests that these bimetallic tubes can be safely welded in real condition (cryomodule) without any special cooling.

THE SUPERFLUID HELIUM TEST FACILITY

The original plans implied the use of Fermilab's Meson Detector Building Horizontal Test System (HTS) for superfluid helium testing of the SS-to-Ti transition joints. The benefit of this installation is that the transition joints would be tested in actual service conditions with superfluid He on the interior and insulating vacuum around. But a big negative factor would be the inability to get sensitive leak-rate measurement. The HTS insulating vacuum of a relatively large volume has a relatively high He background and much more cold connections which could be potential leak indications. These factors would make it difficult to make a straight forward leak-rate assessment of the bimetallic bond. Therefore, we altered our plans and agreed to test these SS–Ti transition joints in Fermilab's A0 Vertical Test Dewar (A0 VTD) (Fig. 9). The major benefit of this is that the interior of the transition joint can be connected to a high vacuum Residual Gas Analyzer (RGA) for direct leak-rate measurements while the exterior is bathed in superfluid helium (Fig. 10). The RGA measurements will be recorded during cooldown as well. It should be noted that in this configuration, superfluid helium is on the exterior side of the transition joint, opposite to the actual service conditions.

Fig. 9. The A0 vertical test dewar

Fig. 10. Transition joint test article mounted on top insert, prior to installation in the A0 VTD

A piping system assembly for installation into the HTS is still being worked on. The benefit will be to test the joints in their actual service conditions with superfluid in the interior, surrounded by insulating vacuum.

The top plate for the VTD is a new component, which has not been used before. We have some concerns that it needs a backout to get high sensitivity/low background for initial room temperature checking. With this setup, we were never able to get sensitivity better than $\sim 10^{-9}$ Torr · l/s.

GENERAL SUPERFLUID HELIUM TEST PLANS

The transition joint test assembly will be mounted on the top plate insert of the vertical test dewar. It will be leak-checked at room temperature to confirm that it is initially free of leaks. During cooldown, the RGA signal will be monitored. The system will be initially filled with 4.2 K LHe. Then, vacuum pumps will be used to complete the cooldown to 1.8 K superfluid He. Under these conditions, the leak rate test will be conducted.

Then, we will initiate warmup to room temperature, approximately a 24 h process. Then, we will recool after thermal cycling, as the schedule permits.

FIRST ASSEMBLY (8A/9A) COOLDOWN PREPARATION (UNSUCCESSFUL)

Our colleague Brad Tennis is directing the assembly and conducting the cold testing. For the first cooldown, we selected the third pair tubes 8A and 9A. This is of great interest because it was welded without water cooling. Since the transition joint test article will be installed in the vacuum system that is normally used for SRF cavity beam tubes, it had to be particulate free. It received ultrasonic water cleaning.

Prior to cooldown, the test assembly (see Fig. 11) was leak-checked. During the very first assembly, it was measured at the background of $\sim 2 \cdot 10^{-8}$ Torr · l/s, which we thought gave us no indication of a leak at any of the welded or explosion-bond joints. Unfortunately, after installation into the VTD, the assembly was only leak-checked to around 10^{-6} Torr · l/s. Originally, it was suspected that during the lifting and mounting process, one of the vacuum flanges or bellows began leaking (but this proved to be false). The insert assembly had to be removed to identify and possibly repair the leak.

Fig. 11 Test setup that identified leak on tube 8A, at location with tubing running to it

LEAK IDENTIFIED ON FIRST ASSEMBLY (8A/9A): DUE TO ULTRASONIC CLEANING

After the assembly was removed from the VTD, we first looked at the flanges and bellows at the very top. These were the areas we worried about during the rigging procedure. Those areas were checked OK, and the work was continued. Helium identified a $\sim 10^{-6}$ Torr · l/s leak on the Ti end of the explosion joint on the upper bimetallic transition tube 8A (see Figs. 12 and 13). We missed this in the original leak check, probably because it took a bit of time for the spraying to register a signal. This leak was reconfirmed by Wilson Cross in the test of the test assembly at the AD/Cryo shop. It is underneath the SS sleeve on tube 8A.

It is not plausible that all the earlier leak checks (both at INFN and at Fermilab) missed this. This bimetallic tube was tested many times at various conditions (before/after LN2 shock, at internal pressure 6 atm). Did the welding create a problem? This leaky transition joint test article was the only one welded without water cooling. Or was it the ultrasonic cleaning? The designers and industry experts now tell us we should not clean these by ultrasonic methods. The concern is about the explosion joint, one can destroy the structure of the diffusion layer, which is only 50–100 μm thick. Therefore, the hypothesis is that the bimetallic joint was damaged during the ultrasonic cleaning.

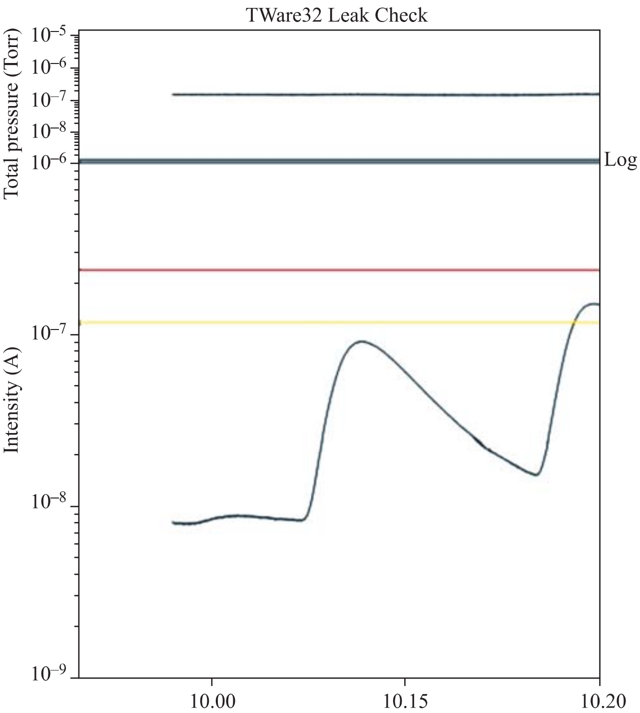

Fig. 12. Leak identified at the explosion-welded joint at room temperature for tube 8A. Note: units are amperes, conversion is required to give Torr · l/s (approximate conversion is to multiply by 10)

INITIAL RESULTS OF SUPERFLUID He TEST OF USING SECOND ASSEMBLY (5A/6A)

This stage of work was mainly performed by our colleague Brad Tennis whom we refer to as «BT» further on in this section. BT will proceed by installing another transition joint test assembly. BT was indeed able to get a good leak check. This assembly comprised tube pairs 5A/6A. Also, he made some changes in the top plate rigging, added thermal insulation baffles and the warmup heater. On June 20, 2008 BT cooled down the bimetallic tube assembly (with tubes 5A/6A) in VTD. He continuously monitored leaks with the RGA. Then BT filled VTD with liquid helium and pumped to superfluid. No leaks were observed when cold! (See Fig. 14). In envi-

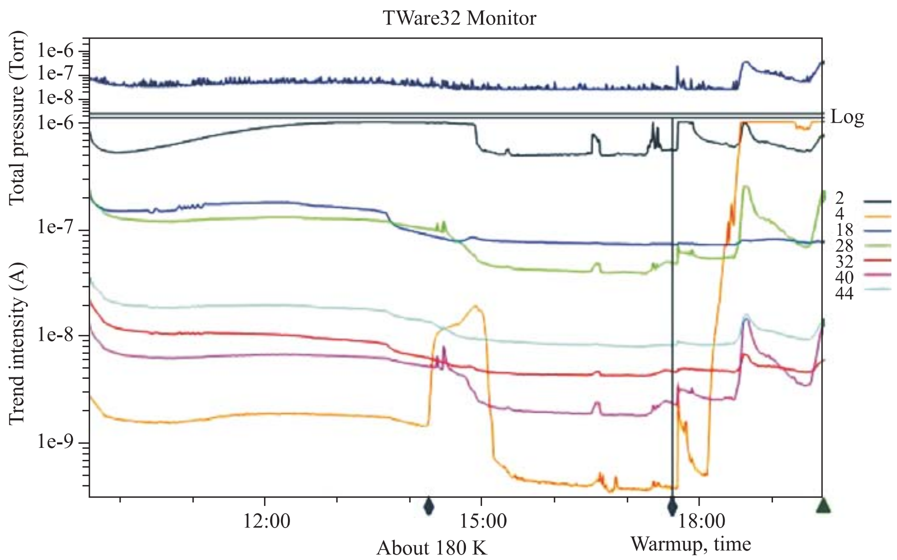

Fig. 13. Cooldown leak check results for tubes 5A/6A. Normal liquid helium present at ~16:00. Superfluid He present from 17:30 to 17:40. Note: units are amperes, conversion is required to give Torr · l/s (approximate conversion is to multiply by 10)

ronment with liquid helium and superfluid state the RGA showed no leak of the $\sim 4 \cdot 10^{-9}$ Torr · l/s.

Some unusual behavior was observed by BT. During cooldown, there was a transient spike when gas temperature was ~ 180 K (but actual local temperature was not known). Later, when BT initiated warmup by boiling off normal LHe with resistance heater coil, he did briefly saw a signal for He with the RGA. However, this proved to be transient. We do not fully understand this response yet. BT does not interpret this as a leak, which would most likely be continuous. We will see if the behavior persists for the next cooldown.

After warmup to room temperature, the test assembly was removed from the vertical dewar, and we make another detailed leak check, with the article bagged in He gas. No leaks were observed (see Fig. 15). Both before and after the cooldown, this setup gave us an RT sensitivity of $\sim 2 \cdot 10^{-8}$ Torr · l/s with no rise in the signal when it was externally exposed to He. Thus, the conclusion is that the test assembly, including explosion-welded bonds, did hold and remain leak tight with superfluid.

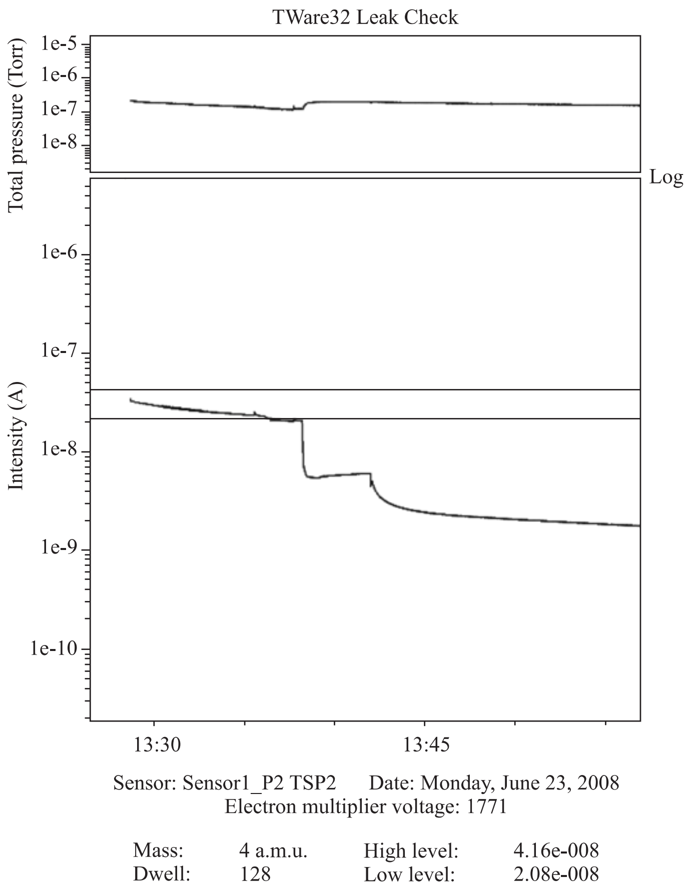

Fig. 14. Room temperature leak check results of the assembly 5A/6A after cooldown with superfluid He

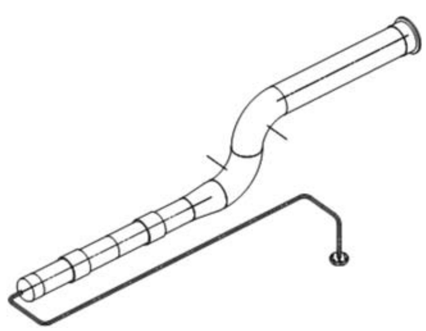

Fig. 15. SS–Ti transition test assembly for horizontal test system (draft)

THIRD ASSEMBLY (3N/7N) COOLDOWN PREPARATION

Plans are being made for the final test assembly (with tubes 3N/7N) to be cooled down in VTD. It was initially checked OK at room temperature, so it is eligible for a cold test. BT has it at the scale of 10^{-10} A, or $\sim 10^{-9}$ Torr · l/s with no leak observed. It will be interesting to compare its behavior to the first one we cooled down.

After repeating the RT leak check with the test article assembled on the top of the plate insert, one sees high background, possibly caused by moisture in the upper top plate portion or possibly a leaking connection on the top plate (maybe not the bimetallic tube). Current plans are to bake out the top plate to remove moisture. One of us will *individually* check the leak of the bimetallic tube and the top plate separately. To speed up the work on schedule for fitting into the available VTD test window, we unfortunately did not do this previously.

FUTURE WORK

Thermal cycling of 5A/6A and 3N/7N tube joints. Up to 5 thermal cycles.

Pressure test of one transition joint test article at 8 bar. This will certify them for pressure piping operation in the HTS which has the maximum allowable working pressure.

Accomplishment of the piping assembly for installation and test within HTS (see Fig. 13).

The last agreed version of the drawing of bimetallic tubes has been created:

- Dubna will send the finished pipe assembly with a final length of 170 mm.
- Other dimensions should be fixed as follows :
  internal diameter — 54.6 ± 0.2 mm,
  external diameter — 60.2 ± 0.2 mm,
  wall thickness — 2.8 mm.
- SS sleeve ring :
  external diameter — 66 ± 1 mm,
  length — 30.0 mm.

The outer surfaces will be machined to remove any scale and marring. The maximum amount of material to be removed is 0.5 mm of the diameter. The inner surfaces must be clean and free of rust or any other foreign materia.

POSSIBLE FUTURE WORK

Pressure test of one transition joint test article at 16 bar. This will certify them for pressure piping operation in the future ILC cryomodule (which has the planned maximum allowable working pressure of 4 bar).

The Table presents the preliminary results of the tests made at Fermilab. In the subsequent development we should repeat tests for all assemblies leak tests at RT prior to VTD He cooldown and as well leak rate at 1.8 K in VTD.

Bimetallic transition assembly leak rate summary (July 8, 2008). Preliminary results

Welded assembly	Consists of assembly	Water cooling while welding	Ultrasonic cleaning after welding	Leak rate before/after LN2 thermal cycles (Torr · l / s)	Leak rate At RT prior to VTD He cooldown (Torr · l / s)	Leak rate at 1.8 K in VTD (Torr · l / s)
I	Tubes 5A/6A	Yes	Yes	$< 4.9 \cdot 10^{(-10)}$	$< 2 \cdot 10^{(-8)}$	$< 4 \cdot 10^{(-9)}$*
II	Tubes 3N/7N	Yes	Yes	$< 4.9 \cdot 10^{(-10)}$	To be determined	To be determined
III	Tubes 8A/9A	No	Yes	$< 4.9 \cdot 10^{(-10)}$	Leaks at $1 \cdot 10^{(-6)}$	Not tested

*Initial leak cheks during June 2008 in the new VTD top plate assembly had relatively high He background readings. We are working to achieve better sensitivity for future testing.

Fig. 16. Some of the personnel involved in the Fermilab tests. Bill Soyars, Basar Sabirov, Elvin Harms, and Jay Theilacker planning the cryogenic tests

CONCLUSION

From JINR, Dubna a set of bimetallic Ti–SS tubes manufactured in Sarov (Russia) was delivered to FNAL (Batavia) within the framework of the FERMILAB–JINR MOU and Addendum #1 to this MOU. The set consists of 7 tubes: 3 tubes underwent to the thermo-annealing procedure after explosion welding, 4 tubes did not. To verify the prior tests made at JINR (Dubna) and INFN (Pisa), the thermal cycle tests to 77 K were repeated at Fermilab, and the results were unchanged: leak rate $7.5 \cdot 10^{-10}$ Torr $\cdot$ l/s at room temperature and $7.5 \cdot 10^{-9}$ Torr $\cdot$ l/s at cryogenic temperature. For the installation and test of the tubes in Horizontal Test System (HTS) the tubes were welded in pairs: (I) 5A + 6A (annealed), (II) 3N + 7N (non-annealed) and (III) 8A + + 9A (annealed). The titanium ends were welded together, SS blank welded at one end, and SS Conflat flange with a through-hole at the other end. The welding procedure was carried out within the «glove box» in the argon atmosphere. During the welding both tubes were cooled by water using copper heat sinks for the first and second assemblies, and the temperature of both collars was continuously measured. Heating of collars did not exceed 50 °C. The third assembly was not cooled, and temperature of the collar was about 80–90 °C. To test the assemblies at 1.8 K, it was decided to connect these Ti+SS transition tubes to a high vacuum Residual Gas Analyzer (RGA) with further purpose to test them at Fermilab's A0 Vertical Test Dewar (VTD). The initial tests were only as preliminary check of the system. In the nearest time all tests with RGA and in VTD should be done.

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