METHODOLOGY EVOLVED FOR REPAIR WORK ON HELIUM LINES OF A RESEARCH REACTOR IN INDIA

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ABSTRACT

In India, the research reactor CIRUS was operational since 1960. In this reactor, helium gas is utilized as the cover gas. The helium lines are connected with the tube sheet at the top of the calandria. There are eight such helium lines at the top of the calandria, which have tongue and groove joints for connecting the stainless steel piping with the aluminum piping. With the prolonged operation of the plant, leakage was observed at these joints. As a part of reactor refurbishing work, these joints were required to be repaired. Due to inaccessibility in joints area, the entire job was to be carried out remotely and therefore, a fail-safe scheme was to be evolved. This paper highlights how analytical simulation of actual site scenario was carried out based on site feedbacks at various stages of operations vis-à-vis the strategies formulated to overcome various challenges at the site. This paper also highlights the methodology evolved to arrive at optimum sequence of tightening at various stages, implementation of which resulted into achievement in the form of a substantial helium leakage reduction by around 80-85% at the site. This success attributed in significant achievements in terms of savings in man-rem consumption, overall cost and time.

INTRODUCTION

The CIRUS reactor uses light water as coolant and heavy water as moderator. In this reactor, helium gas is utilized as the cover gas. The helium gas lines total eight in numbers, are having tongue and groove joints for connecting the stainless steel piping with the aluminum piping. These joints use a gasket, which is made of Buna-N material and is having a thickness of 1.6 mm. With the continued operation of the plant, leakage was observed at these joints. Since these joints are situated in an inaccessible area, the repair work on these lines was required to be carried out remotely. It was decided to carry out analysis of the system to find out the exact sequence of tightening as well as to find out the permissible amount of tightening so that the load on the aluminum pipe and the other connected piping systems is minimum and also within the permissible limits. This paper deals with the methodology adopted to arrive at the sequence of tightening and the maximum permitted gasket compression value. Subsequently, this paper describes the step-by-step sequence of procedures suggested for the tightening of flange joints with due consideration given to the feedback obtained from the site regarding the condition of flange joints at various locations. Based on these recommendations, the tightening work was undertaken at the site, which has resulted in a substantial amount of reduction (by around 80-85%) in the helium leakage.

SYSTEM DESCRIPTION

The helium (He) lines of CIRUS reactor are of 2” NB size. They are made of half hard ALCAN 6056 material, whose composition is close to Aluminum-1S (Al-1S). These lines from the top of the reactor vessel are connected with Al-2S pipe through a socket. The welds at the socket as well as at the reactor tube sheet location are of 3/16” size. This pipe then runs up for around 45” height before it is rolled into Stainless Steel (SS) flange. This flange is bolted to another SS flange, which is connected to the He system SS piping (SS 304). This flange joint is a tongue and groove joint, which uses a 1.6 mm thick ring type gasket made of Buna-N material. This 2” pipe takes a 90^0 turn and joins to a ring header, which is also made of SS 304. The piping starting from the other side of header is subsequently embedded in heavy density concrete wall.

The flange joint described above is located below the top biological shield, which is about 9 ft. below the accessible area (the upper header room). This flange joint connection was then about 38 years old. The fluid inside the piping is He at a pressure of 12” of water column. The maximum temperature is around 45^0 C during reactor operation, which reduces to below 30^0C during reactor shut down.

There are 8 such vertical pipes starting from the reactor vessel, 4 of which join a ring header, 3 others join another header and the remaining one directly gets connected with the stainless steel piping (Fig.1). The system in which 4 of the vertical pipes are joining a particular ring header sees the maximum stress conditions since it has the least flexibility due to minimum pipe length available from the fixed end (at the wall) to the header. Subsequently similar exercises have been extended for other systems, i.e. header with three He-lines and on single He-line.

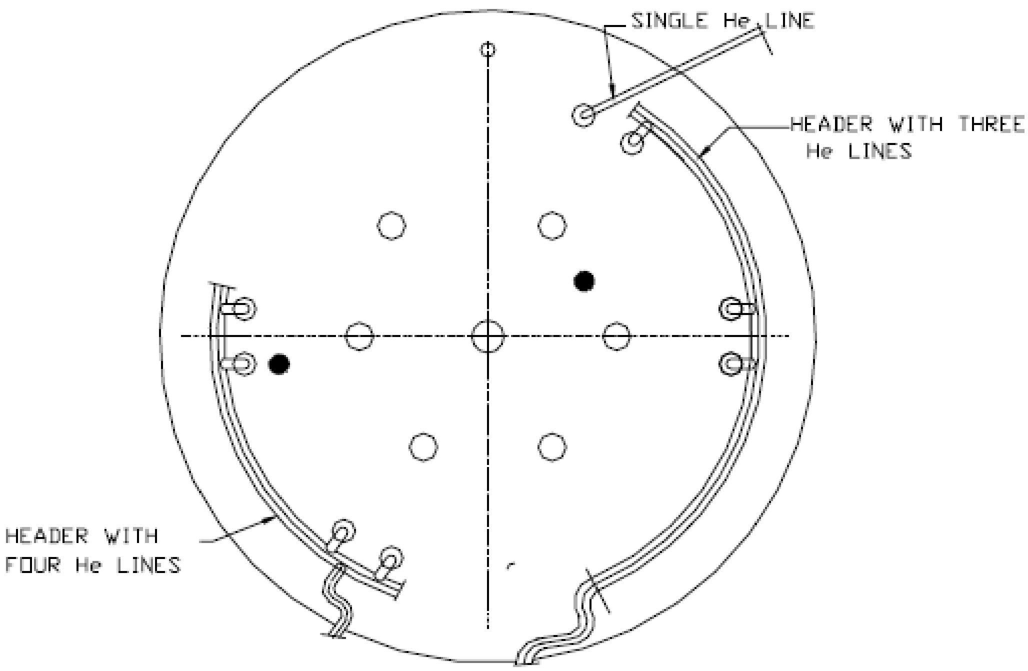

Fig.1: Schematic Arrangement Showing Arrangement of He-line System (All 8 lines)

MATHEMATICAL MODELLING OF THE LOOP

The piping loop has been modeled using the piping analysis software CAESAR-II [1]. Entire piping including the calandria vessel, ring header, branches with flange joints and the stainless steel piping up to wall has been modeled. Calandria bottom is free to move up, but all other translation directions are restricted. Piping models have been prepared using elements of straight pipes, bends and by incorporating various directional restraints present in the piping system. Modeling has been carried out with the following considerations:

(i) Calandria has been modeled to take care of its interaction effect with the connected piping system.

(ii) Actual gaps measured at the site have been modeled where initial gaps were observed at the flange joints as per the design drawing details.

(iii) No credit has been taken for the increase in yield strength and ultimate tensile strength of the Al-material because of irradiation effect.

(iv) To account for the loss in ductility of aluminum material due to irradiation, allowable stress has been reduced by 25% of that of the virgin material.

(v) Stiffness properties derived from the test results on the irradiated gaskets have been utilized in the analysis.

Based on the above considerations and with the help of the various information received from the site including feedbacks on the gasket compressions and the problems faced at various stages in the tightening process, mathematical models of the system have been prepared and upgraded for the various stages of analyses. The major challenges in modeling include simulation of gaps (if present), gap closure effects and the curvature effect of header resulting in opening/closing of adjacent flange joints during the tightening process (Fig.2).

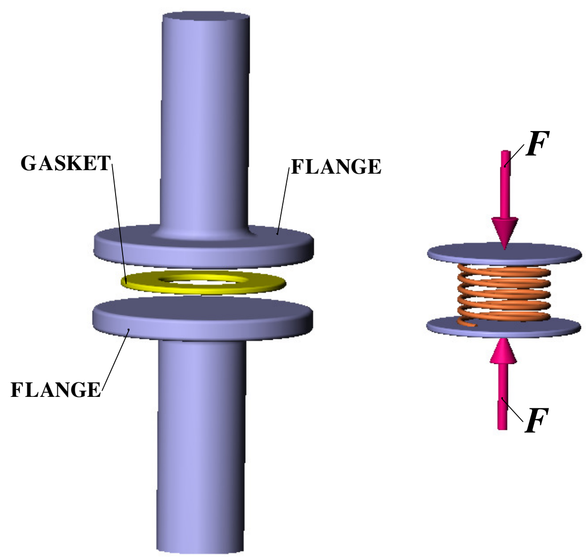

Fig. 2: Simulation of Load Application by Split Sealing Clamp for Tightening at Flange Joint

METHOD OF ANALYSIS

The piping is subjected to internal pressure, temperature and weight loading under normal operating conditions. During the tightening operation, external forces required to compress the gasket, will also be required to be sustained by the system. This system has been designed as per the Power Piping Code ANSI B31.1 [2]. The loadings have been categorized into the following three groups:

(i) Sustained loading: Dead weight, internal pressure,
(ii) Expansion loading: Temperature, thermal anchor movement, and
(iii) Tightening load: external force required to compress the gasket.

The stresses due to the various loadings are limited within the allowable limits as per the design code. The equations used for the stress checks are as follows:

For sustained loading,

$$(PDo / 4t_n) + (0.75i\ M_a/Z) \leq 1.0\ S_h \quad (1)$$

For thermal expansion loads,

$$S_e = (i\ M_c / Z) \leq S_a \quad (2)$$

Where P is internal design pressure, D_o is outside diameter of pipe, Z is section modulus, t_n is nominal wall thickness of the component, M_a is resultant moment loading on the cross section due to sustained loads, i is stress intensification factor (the product of 0.75i shall not be taken less than 1.0), M_c is range of resultant moments due to thermal expansion and S_a is the allowable stress range for expansion stresses which is nothing but S_a = f (1.25 S_c

+ 0.25 S_h) in which S_c is basic material allowable stress at minimum (cold) temperature, S_h is basic material allowable stress at maximum (hot) temperature and f is stress range reduction factor for cyclic conditions for total N number of full temperature cycles over total no. of years during which the system is expected to be in operation.

Static analysis has been carried out to evaluate the response of the piping due to weight, internal pressure, thermal loading and the loading coming due to flange tightening. Analysis has been carried out using the piping analysis software CAESAR-II for both sustained and expansion loadings.

EVOLUTION OF TIGHTENING CRITERIA

In order that the various components in the system get stressed to a minimum possible level during the course of tightening of these joints, it is desirable to work out a proper sequence of tightening and the maximum permissible gasket compression at these joints.

Sequence of Tightening

A proper sequence of tightening of the joints to achieve the above objective has been worked out based on following two important considerations:

(i) Load imposed on the Al-pipe, and
(ii) The opening / closing of adjacent flange joints during the tightening process.

Amongst the above two criteria, the first criterion is more crucial from the point of view of the safety of the weld joints between the Al pipe and the calandria vessel. To start with, it was assumed that there is no compression in any of the gaskets. To make a decision regarding as to what should be the starting location for the tightening process; four separate exercises were performed with tightening of individual gaskets by 0.1 mm one-by-one. During each of these exercises, one of the four joints is tightened by 0.1 mm and the other three are left untightened. For example, when the joint at line no. 2 is tightened by 0.1 mm, the joints at line nos. 1, 3 and 4 are not touched. The force required to achieve the compression of 0.1 mm is around 105-110 Kgf in each case. It has been observed that tightening of either of the line no. 4 or 1 is imposing minimum load on the Al pipe and since with tightening of line no 4, the opening of gasket at any location is minimum as compared to other cases, it is suggested to start the tightening with line no. 4. With the subsequent exercises, it has been concluded that the sequence 4-1-3-2 (Fig.3) should be followed while carrying out the tightening in steps of 0.1-0.2 mm. Similar exercises carried out on 3-branch header revealed 2-1-3 as the optimum sequence of tightening.

Maximum permitted gasket compression

Having established the sequence of tightening, it is essential to determine the maximum compression that can be permitted on any gasket. The limiting value for this parameter depends on the following factors:
(i) The stresses induced in the weld joints on the Al piping between the vertical branch lines and the calandria tubesheet, (ii) The integrity of gaskets, and (iii) The stresses induced in the connected piping.

There were challenges associated with the job which emphasized requirement of a fault-proof scheme:
(i) The entire job was to be carried out remotely.
(ii) Due to irradiation effects, both the Al-piping and the gasket material had lost their ductility and so utmost care was required while imposing any additional loadings on these materials.
(iii) The initial state of gaskets at the various flange joints in terms of compression or gap present was unknown. Hence, the gaps between the top and bottom flanges at each location were decided based on filler gauge measurements and study of the design drawings. The reason of uncertainties in exact gap measurement can be attributed to several probable site factors including tolerances on groove depth, tolerance in flange dimensions, probable variation in the gasket thickness etc.
(iv) A proper calibration for each split sealing clamp was essential on the mock-up station to generate the information in terms of the number of turns required for tightening it versus the movement of top flange.

Prior to this exercise, on a mock up system it was established and confirmed that it requires around 0.4 mm of gasket compression for the joint to attain a no-leak condition from its fully loose condition. Therefore, the exercises related to maximum permitted gasket compression have been carried out on 4-branch header system assuming leak-tight condition with initial gasket compression of 0.4 mm at all four locations (Fig. 3). Presuming that repair work is being carried out and gaskets are subjected to additional compression, it was observed that the force required to compress all the gaskets by 0.4 mm is 380 Kgf on each joint. The results with further tightening by 0.4 mm (i.e. for a total gasket compression of 0.8 mm) at the gasket location for line no.2 (which is the worst case observed, while carrying out exercises with various options) show that the maximum load on Al pipe, due to sustained loading condition, is 148 Kgf. The maximum stress observed on Al pipe, for sustained loading condition are 79.40% of the allowable value in tension and 84.13% of the allowable value in shear. Thus, with additional tightening upto 0.4 mm, still a 15% margin remains with the allowable value. The force required for gasket compression increases from 380 Kgf to 870 Kgf on line no. 2 to finally achieve 0.8 mm total gasket compression on this line. Therefore, it is evident from these exercises that the total maximum permitted compression on any gasket is 0.8 mm. Further same exercises have been repeated on the other two systems i.e. the one with three He lines connected to a ring header and the other one with a single He line connected with 1” SS piping. Results showed that the finding regarding the maximum permitted amount of tightening is valid for the other two systems also.

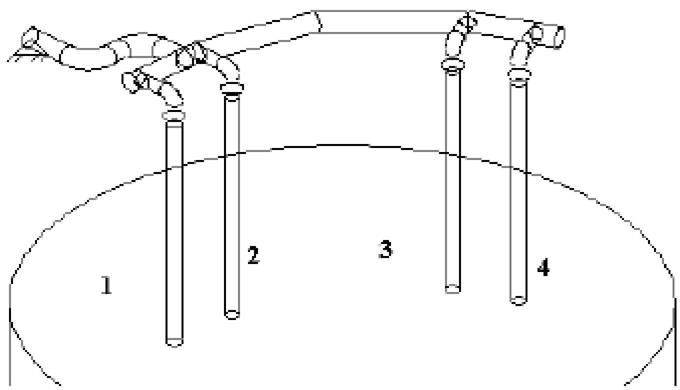

Fig.3: Modeling of 4 He Lines System alongwith Header and Calendria (1,2,3 and 4 marked on Fig above are showing He-line numbers)

ANALYTICAL EXERCISES TO DECIDE STEPS DURING THE COURSE OF TIGHTENING

The analytical exercises were performed under various steps, with the following aims:
(i) To simulate the exact site scenario in the mathematical model and also the tightening phenomena to arrive at the sequential steps to be suggested for tightening exercise.
(ii) To simulate the updated scenario regarding the condition of flange joints as being reported by the site with the implementation of the above-suggested steps.
(iii) To suggest the various possible alternative tightening schemes to overcome the problems if any observed/reported by the site during the course of tightening process.
(iv) To suggest the additional possible tightening steps based on the available stress margins, which can be undertaken to reduce the leakage further subsequent to the implementation of the various suggested steps at the site.

Step-1 (Revised tightening scheme for the 4-branch header)

Site measurements indicated that gaps exist at the gasket locations at all the flange locations of the four He-lines. The measured gaps reported by the site at respective flange locations have been incorporated in the model. Exercises have been carried out to confirm validity of the evolved sequence of tightening (4-1-3-2) and to find out the maximum amount of compression permitted in the present state. Two possible scenarios have been simulated:
(i) First Scenario: The measured gaps exist as reported by the site.
(ii) Second Scenario: The measured gaps do not exist and the flanges are just touching the gasket.

First Scenario

Exercises were carried out with the first scenario where it has been assumed that the measured gaps as reported by the site exist. Initial gaps reported by the site were 0.4 mm, 0.12 mm, 0.12 mm and 0.4 mm at line nos. 1, 2, 3 and 4 respectively (Fig. 3). Results of the exercises carried out in the step-by-step sequence, in terms of the loads on Al-pipe and gasket compression observed are as shown in the Table 1. Based on the results of above exercises, following inferences have been drawn:

(i) To start with, the measured gaps should be closed at locations 4 and 1 by 0.4 mm each. It was observed that the gaps at the inner lines (i.e., 2 and 3) get closed by tightening of the outer ones (i.e., 4 and 1).

(ii)Further tightening can be carried out in steps of 0.2 mm in the same sequence till minimum 0.4 mm is achieved at all places. Total tightening up to this stage is 0.8 mm, 0.4 mm, 0.4 mm and 0.8 mm at locations 1-2-3-4 respectively.

(iii) Since loads on the aluminum piping gets balanced out by tightening of all the four lines as suggested in (ii) above, further tightening by 0.2 mm with the same sequence 4-1-3-2 can be carried out if required. Stresses in the piping as well as in the weld joints remain within limits.

Table 1: Loads on Al-Pipe with gasket compression for various steps under Step-1 with gap simulation

	Loads on Al pipes (Kgf) {+ve compression, -ve tension}				Gasket compression (mm)			
	Line-1	Line-2	Line-3	Line-4	Line-1	Line-2	Line-3	Line-4
Closing the gaps at Line no. 4 and then 1 by 0.4 mm	-34	28	38	-26	0.000	0.027	0.038	0.007
Further 0.4 mm at line-4	-25	19	109	-84	0.010	0.016	0.116	0.403
Next 0.4 mm at line-1	-83	74	90	-75	0.404	0.077	0.096	0.414
Next 0.4 mm at line-3	-100	105	6	-13	0.385	0.112	0.403	0.482
Next 0.4 mm at line-2	-52	6	38	-21	0.439	0.404	0.439	0.473
Additional 0.2 mm at line-4	-49	3	62	-41	0.442	0.400	0.466	0.607
Next 0.2 mm at line-1	-72	25	55	-37	0.600	0.425	0.457	0.611
Next 0.2 mm at line-3	-80	40	15	-8	0.591	0.442	0.603	0.643
Next 0.2 mm at line-2	-53	-15	33	-13	0.621	0.603	0.623	0.639

Second Scenario

The second scenario is with presumption that measured gaps do not really exist at the reported locations and flanges are just touching the gaskets. This may lead to worst possible scenario in which case if tightening is carried out at lines 4 and 1 by 0.4 mm each, as a step to close the reported gaps, it will give rise to a gasket compression of 0.4 mm, 0.1 mm, 0.1 mm and 0.4 mm at locations 1-2-3-4 respectively. Further tightening at this stage will give rise to scenario as shown in Table 2. Based on the results, following inferences can be drawn:

(i) Further tightening should be in the same sequence, i.e., line nos. 4-1-3-2 by 0.2 mm at all the locations. At this stage, gasket compressions at the locations 1-2-3-4 are 0.6 mm, 0.3 mm, 0.3 mm and 0.6 mm respectively.

(ii) Further, additional tightening by 0.2 mm in the same sequence can be carried out. Thus, at this stage, total tightening on the outer lines (i.e., 4 and 1) is 0.8 mm each and on the inner ones (3 and 2), it is 0.5 mm each.

Recommendations for Step-1

Based on the results of the above two scenarios, following sequence of operations have been finalized and suggested to the site. Step-by-step sequence of operations and the observations to be recorded are as follows:
(i) Firstly, the tightening should be carried out on the 4th and subsequently on the 1st line by 0.4 mm each.
(ii) Subsequently, tightening should be carried out in steps of 0.2 mm with the same sequence, i.e. 4-1-3-2. It is expected that after completion of this step, leakage should reduce appreciably or should get stopped. If stopped, no further tightening should be done.
(iii) If the leakage reduces or still remains the same, tightening by further 0.2 mm can be carried out with the same sequence (4-1-3-2) of tightening and observations regarding feel of tightening and also regarding leakage reduction should be recorded at various stages elaborately. At the end of this stage, the leakage must stop or reduce by significant amount. If there is no change in leakage at this stage, further tightening should not be carried without a detailed review of the scenario.
(iv) The tools / tackles used for tightening the flange joints shall be re-calibrated for the wider range of tightening. This should be done for both the scenarios, i.e. with and without the presumption of the measured gaps.

Table 2: Loads on Al-Pipe with gasket compression for various steps under Step-1 presuming no initial gap

	Loads on Al pipes (Kgf) {+ve compression, -ve tension}				Gasket compression (mm)			
	Line-1	Line-2	Line-3	Line-4	Line-1	Line-2	Line-3	Line-4
Further 0.2 mm at line-4	79	69	124	-103	0.408	0.072	0.133	0.605
Next 0.2 mm at line-1	-107	96	115	-99	0.600	0.102	0.123	0.610
Next 0.2 mm at line-3	-117	114	66	-63	0.59	0.122	0.303	0.650
Next 0.2 mm at line-2	-87	52	86	-68	0.623	0.304	0.325	0.644
Additional 0.2 mm at line-4	-83	49	115	-91	0.627	0.300	0.358	0.807
Next 0.2 mm at line-1	-109	73	107	-88	0.805	0.327	0.348	0.812
Next 0.2 mm at line-3	-117	89	65	-57	0.795	0.345	0.502	0.846
Next 0.2 mm at line-2	-92	35	82	-61	0.824	0.503	0.522	0.841

Step-2 (Further tightening at location 3 for the 4-branch header)

Based on the exercises carried out in the Step-1, it was recommended that tightening at locations 1-2-3-4 (K-28, H28, B-22 and A-19) should be carried out with the suggested sequence 4-1-3-2 with the maximum tightening of 0.8 mm, 0.5 mm, 0.5 mm and 0.8 mm respectively at these locations. It was reported by the site that the total achieved gasket compression at location 1 is 0.63 mm; at location 2 is 0.35 mm; at location 3, it is 0.5 mm and at location 4, it is 0.4 mm. It was also reported that further tightening could not be carried out at locations 1,2 and 4 since the flanges got stuck at these locations possibly because further load could not be applied through the existing tightening tool. However, the site reported that possibility of further tightening exists at location 3 where the recommended amount of tightening has been already achieved. It was, thus felt that if location 3 can be tightened further, it may help in reducing the He-leakage further. This required further analyses by simulating the as achieved condition at the four locations. Based on the subsequent analyses, it was suggested that further tightening at location 3 can be carried out in steps of 0.1-0.15 mm upto a total gasket compression of 0.8 mm. It was also observed that with this process, i.e. by tightening location 3 by 0.3 mm further, the gasket at location 4 would also get compressed further by 0.1 mm, which is a desirable phenomenon (Table 3).

Table 3: Further compression at line no. 3 till 0.8 mm gasket compression (Step-2)

	Loads on Al pipes (Kgf) {+ve compression, -ve tension}				Gasket compression (mm)			
	Line-1	Line-2	Line-3	Line-4	Line-1	Line-2	Line-3	Line-4
As suggested case	-92	35	82	-61	0.824	0.503	0.522	0.842
Compression at line-3 upto 0.7 mm	-101	54	33	-25	0.813	0.524	0.701	0.881
Further compression at line-3 till 0.8 mm	-107	64	6	-5	0.807	0.535	0.804	0.904

Step-3 (Tightening scheme for the 3-branch header and single He-line system)

After achieving the tightening on the four He-lines connected to the header following the above suggested two steps, exercises were planned on the other two systems i.e. 3-branch header system and single He-line system. Analysis for the 3-branch header was carried out by simulating the measured gaps at the respective locations. Based on the exercises carried out for this header, following recommendations were made:

(i) Tightening should be carried out in the sequence of line nos. 2-1-3.
(ii) To start with, no further tightening should be carried out at location 3.
(iii) Tightening should be carried out at location 2 by 0.1 mm and subsequently at location 1 in two steps by 0.2 mm and then by 0.15 mm. At this stage, gaskets at location 2 and 1 are tight by 0.65 mm each.
(iv) Next step should be tightening by 0.15 mm at location 2 and then at location 1. At this stage gaskets at all the locations are tight by 0.8 mm or more. Hence, this should be the limiting stage.

Analyses on single He-line system revealed that tightening can be carried out in steps of 0.15-0.2 mm in a single step till a total gasket compression of 0.8 mm. Results for this stage of total 0.8 mm gasket compression showed that load transmitting on Al-pipe is very less and well within the allowable limits.

Site reported that the above suggested tightening scheme could be successfully implemented at the respective locations. At this juncture, it was decided that since there is no scope for further tightening at any of the locations, the total He-leakage reduction achieved should be assessed. Subsequent He leak rate test performed by the site at the full operating pressure of 12" of WG indicated that the He addition rate in the system has come down from 200 cfm to around 35-40 cfm. This meant that a reduction of around 80-85% in the He leak rate has been achieved with the above tightening exercises. Site expressed complete satisfaction with the achievement as the He leak rate is assessed for reactor shut down condition which may further reduce when reactor will go operational.

CONCLUSIONS

The remote repair work on the tongue and groove joints of the He lines has been carried out by the site as per the suggested sequences of tightening at the various flange locations. Due to many challenging aspects, utmost care was emphasized while deciding steps for various stages of operation. He leak rate test performed by the site indicated that the tightening performed resulted in a significant reduction in the Helium leakage to the tune of 80-85% in reactor shut down condition which may further improve when reactor will go operational. The remote repair work performed on these He lines has resulted in a lot of savings in the man-rem consumption which would have been otherwise very high, if the entire job would have to be performed by removing the biological shields, associated piping, components, etc. Moreover, later option would have been costlier and time consuming.

REFERENCES

(1) Piping Analysis software CAESAR-II ver. 3.23, COADE Inc., Houston, Texas, USA
(2) Power Piping Code ANSI B31.1