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Quality Assurance in Welding of High Strength Steel in Penstock Construction †

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Abstract

A huge penstock has been constructed with heavy sectional high strength steel. On this construction, quality assurance through quality control was intended for not only welding in itself, but also preparation and other related works. However this report emphasizes on welding procedures.

KEY WORDS: (Quality Assurance) (Quality Control) (Site Welding) (Penstock) (Low Alloy Steel) (QT Steel)

1. Introduction

The penstock at the Okuyahagi No. 2 Hydro-electric Power Station is one of the largest penstocks in the world. It was 372 m vertical shaft between the upper horizontal water-way and the trifurcating branch which is located just up-stream of generators. Beside the vertical shaft, there are many technically interesting items such as trifurcating branch with heavy sectional forged rings 420 mm x 530 mm and very thick plates up to 91 mm, welding of high strength steel in tunnel, full mechanized MIG welding, and so on.

Quality assurance through quality control was intended for the welding of these heavy sectional high strength steel of 80 kg/mm^2 (784 N/mm^2) in tensile strength (hereinafter called HT 80).

The subjects of quality control are materials, cutting, bending, assembling, and welding. Following three items were considered the most impotant. The data were arranged in the order of date. The improvement and assurance of quality were confirmed.

– The number of notches: as an indicator of cutting performance.

– The differences of circumferencial lengths between connecting pipes: as an indicator of accuracy for final assembling.

– The results of radiographic inspections: as an indicator of overall quality of welding.

These quality control procedures were established on the basis of investigation of past projects (1).

This paper introduces the quality assurance through quality control of penstocks. Steel liners were also constructed using quality control procedures simillar to those used for the penstocks. However, the data are not included in this paper.

2. Outline of the construction

This construction consists of water-way tunnel steel liner, penstock with trifurcating branch and draft tunnel steel liner, as shown in **Fig. 1**. Total steel weight is about 5,630 ton. The construction work took about 2 years with average 60 men working, which required total 34,000 man-days.

Steel materials were manufactured by six steel manufacturers. After inspected by steel manufacturers, they were transported to fabricator's shop. The other materials such as welding consumables, paints, and so on, were transported to fabricator's shop or site shop after the required inspection by each manufacturer.

Individual members were fabricated at fabricator's shop shown in the flow chart of **Fig. 2**. They were transported to the site in accordance with the construction schedule. Straight pipes were transported to site shop after being fabricated into half-round sections. Others, such as branch, bent pipes, reduced pipes were transported to the site shop or the installation site in tunnel with fabrication accuracy checked by temporary shop assembly before delivery.

Individual members transported to the site shop were fabricated into pipes of a unit length of 6 m shown in the flow chart of **Fig. 3**. Then they were carried to the upper entrance of horizontal tunnel or the top of vertical tunnel by incline or cable crane. The unit pipes for horizontals were carried into the installation site by incline. While those for verticals were carried into the installation site by

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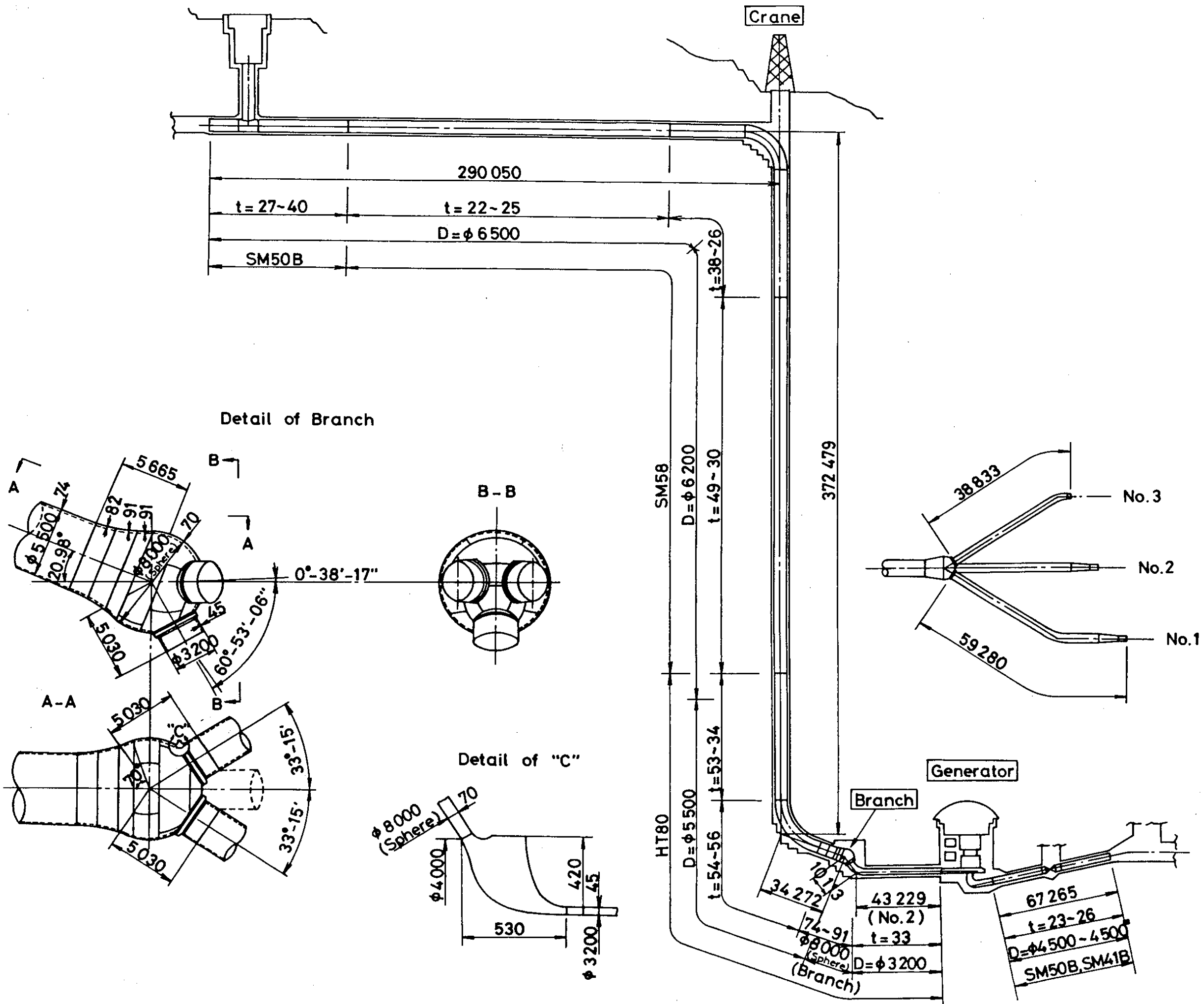


Fig. 1. General plan of the Project

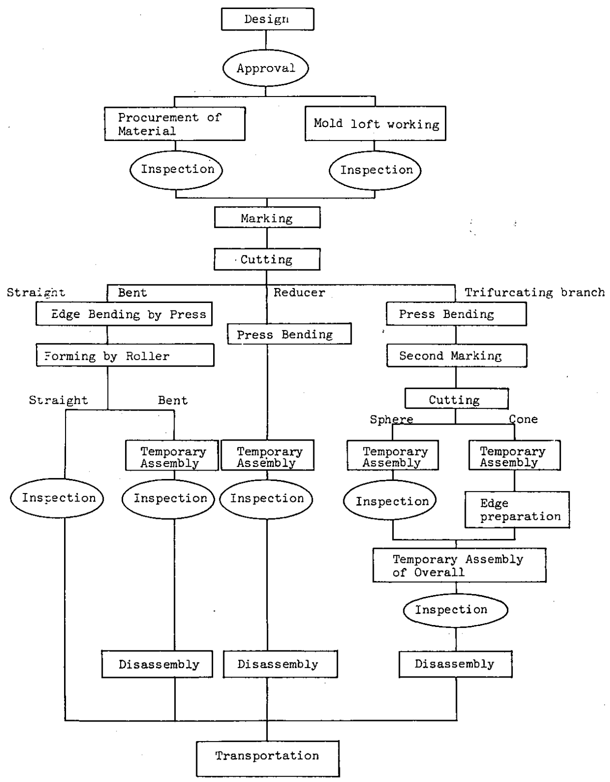


Fig. 2 Fabrication Flow Chart

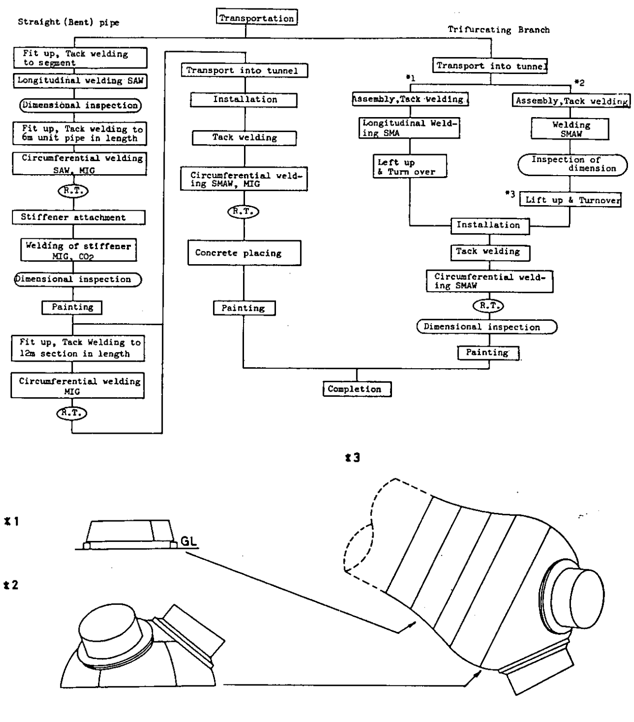


Fig. 3 Installation Flow Chart

80 ton portal crane after they had been fabricated into larger blocks of a length of 12 m from two units at the top of the vertical tunnel.

Full mechanized MIG welding was used for the circumferential joints of penstocks for the vertical shaft both in site shop at the top of the vertical tunnel and in the installation site in tunnel.

Installation was performed in accordance with the sequential processes shown in the flow chart of Fig. 3.

3. Policy of quality assurance

Quality requirements for this project were specified in "Construction Specification for Penstocks and Accessories of the Okuyahagi No.2 Hydro-electric Power Station" of the owner and "Standard Specification for Water Gates and Penstocks" issued by Water Gate and Penstock Association of Japan.

It is believed that controlled process at each step of construction makes quality. This means that high reliability for the service intended is achieved through established quality control system.

In the penstock construction, the key of quality assurance lies in the quality control of in-site fabrication and installation in the tunnel. In this project the most difficult process is the welding of HT 80.

As all site weldings were performed in the tunnel, there were no influences of rain and wind, but, on the other hand, there existed bad environmental conditions due to high humidity, narrow work space, insufficient ventilation, etc. Much difficulty exists in improving these bad environmental conditions, which makes the quality control of welding in the tunnel extremely difficult. Therefore, procedures were established to thoroughly implement pre-heating and post-heating for welds, to facilitate installation work by fabricating members and unit pipes with the required accuracy and to reduce factors such as miss-alignment, angular distortion, etc. which exercise bad effects on the quality of welds.

Quality level specified for the structures of this project was such a level that is considered severe for the structures of this type. In order to achieve this required quality level, quality control system using check sheets was adopted. The check sheets were used at every step during the entire process from the start of shop fabrication to the completion of site installation, statistical method of quality control was also used.

4. Operation of quality control

To attain the quality requirements, QC items and standards were specified as shown in Chapter 6. They were controlled using checksheets and inspection data sheets at each step of process.

Table 1 Names of check sheets and inspection records

Site	Procedure	All pipes except branch		Trifurcating branch	
Steel Manufacturer	Inspection	M	Mill sheet	M	Mill sheet
		M	IR on dimension	M	IR on dimension
				M	UT records
Fabricator's shop				L	IR on shop drawing
	Material check			BM	CS for material check
	Cutting	G	CS for gas cutting	BG	CS for gas cutting
	Bending	B	CS for bending		
	Dimension check	D	IR on shop fabrication	BD	CS for dimension
	Temporary assembly	A	IR on temporary assembly	BP	CS for eye piece
		J1	CS for fit up	BD	CS for dimension
				BJ	CS for fit up
				BA	IR on temporary assembly
Site shop and Installation site in tunnel	Assembling	J2	CS for unit pipe	BD	CS for dimension
		J1	CS for fit up	BJ	CS for fit up
	Welding	W1	QCS for consumables	W1	QCS for consumables
		W2	QCS for HT80 (SMA)	W3	QCS for HT80 (SMAW)
		W3	do. (SMAW)		
		W4	do. (MIG)		
		W5	QCS for repair welding	W5	QCS for repair welding
	RT	R	RT records	R	RT records
	Inspection of dimension	FD	IR on final dimension	BF	IR on final dimension
	Painting				
	Painting inspection	P	IR on painting	P	IR on painting

note) CS: Check sheet
QCS: Quality control sheet
IR; Inspection records
UT: Ultrasonic testing
RT: Radiographic testing

Table 2 Operation of check sheets and inspection records

Site	Sheet	Recorder	Confirmer	final confirmer
Fabricator's shop	Check sheets	Worker	Fabrication staff	QC staff
	Inspection records	Inspector	QC staff	QC manager
Site shop	Check sheets	Worker	Site shop staff	do.
	Inspection recorders	Inspector	-	do.
Installation site in tunnel	Check sheets	Worker	Installation staff	do.
	Inspection records	Inspector	-	do.

4.1 Operation of checksheets and inspection data sheets

Names of checksheets and inspection data sheets are shown in **Table 1**. Operating standards of these sheets is indicated in **Table 2**. From the basic concept that each procedure makes quality, workers self-check was intended, sampling check by foreman and/or staff was adopted in each procedure. QC group confirmed whether these systems were operated adequately or not. If necessary, recommendations on correction of QC system were to be made.

4.2 Repairing procedure of defects

Repairing procedure of defects was specified in **Table 3**

Table 3 Repairing procedure of defects

Class	Defects	Repairing procedure	Confirmation of repair
A (Sever)	1) Defect on chemical composition, mechanical properties, and dimension of steel. 2) Lamination 3) Defects to repair by welding: repairing procedure not specified 4) Crack of all kinds 5) Sever defects of dimension of products 6) Frequent occurence of class B defects	1) Stop of all the work related 2) Counsel meeting for repairing and prevention of the defect 3) Repair under counsel of QC manager 4) Report of repair 5) Improvement of work standards	Confirmation by QC mager and staff of the owner
B (Moderate)	1) Defects to repair by welding: reparing procedure specified 2) Defects of dimension of product 3) Frequent occurence of class C defects	1) Stop of the work concernd 2) Repair under counsel of QC staff 3) Report of repair 4) Improvement of work standards	Confirmation by QC staff
C (Slight)	Defect to repair only by grinding, no welding	Grinding by the judgement of the worker himself; if over grind, repair as class B defect	Confirmation by th worker himself

for the case of defects. However, actually class A and class B defects were nothing but several notches of class B defects occurred.

5. Education of workers

In this construction, several new installation procedures were used, such as full mechanized MIG welding in the tunnel, large block installation in the vertical shaft and spherical shell of trifurcating branch and so on.

It was important that not only fabrication plan and quality control system were complete, but workers engaged in this construction were required to have sufficient skill, knowledge and experience.

The foremen engaged in this construftion had much experience in penstock construction with high strength steel, and most workers had experience of this kind of construction. So, physical training was not needed except for full mechanized MIG welding. Explanation meetings on the following items were held so that all of the workers could understand the characteristic aspects and importance of this construction. Meetings were held each time when new workers were put in the work.

– Outline of the construction.

– Key points of construction and special requirements for high strength steel.

– Construction procedures and quality control procedures.

Welders were qualified for the applicable grades of JIS. Qualification tests of welders for high strength steel were witnessed by the owner. These tests were performed in accordance with the applicable requirements of JIS. The same consumables and pre-heating conditions as used in the actual work were used and the welding positions were vertical, horizontal and overhead. The tests were performed four times. A total of 54 welders were qualified in these tests.

6 operators of full mechanized MIG welding were selected from experienced operators of MIG welding on high strength steel of 58 kg/mm^2 (568 N/mm^2) in tensile

Table **Table 4** Chemical composition and mechanical properties of HT80 plates

Thickness (mm)		Chemical Composition (%)							Y.P. (kg/mm2)		T.S. (kg/mm2)		El. (%)		Charpy Absorbed Energy at 40°C (kg-m)	
		C	Si	Mn	P	S	Ni	Ceq	L	C	L	C	L	C	L	C
t ≦ 50	Spec.	≦0.13	≦0.55	≦1.50	≦0.015	≦0.015	0.90 -1.50	≦0.53	≧70		80-95		≧16		≧4.8	
	Max.	0.11	0.28	1.00	0.011	0.004	1.02	0.50	89	89	93	93	26	25	26.9	25.9
	Min.	0.08	0.24	0.81	0.006	0.002	0.97	0.48	77	78	82	83	21	20	18.5	8.9
	Ave.	0.104	0.253	0.921	0.0087	0.0026	0.994	0.493	84.0	84.4	87.7	88.5	23.4	22.9	23.1	18.4
	σ*	0.010	0.012	0.063	0.0015	0.0009	0.016	0.006	2.4	2.4	2.3	2.3	1.1	1.5	1.6	4.1
50 < t ≦91	Spec.	≦0.14	≦0.55	≦1.50	≦0.015	≦0.015	1.00 -1.60	≦0.57	≧68		78-93		≧16		≧4.8	
	Max.	0.12	0.37	0.94	0.015	0.005	1.40	0.53	82	83	86	88	28	26	26.3	20.3
	Min.	0.10	0.28	0.80	0.008	0.002	1.04	0.50	73	71	78	79	24	22	19.6	10.3
	Ave.	0.107	0.314	0.922	0.0113	0.0039	1.180	0.513	77.0	77.3	82.2	82.8	25.9	24.0	22.4	15.3
	σ*	0.007	0.023	0.046	0.0021	0.0009	0.129	0.012	2.5	2.5	2.1	2.1	0.9	1.1	1.3	4.2

note) * σ; Standard deviation
No. of samples: n=12 for chemical composition of t ≦50
n=10 for chemical composition of 50 < t≦ 91
n=97 for mechanical properties of t ≦ 50
n=74 for mechanical properties of 50 < t ≦ 91

strength and from semi-automatic MIG welding operators, after two weeks training on actural work at site.

Explanations on the following were made to all of the welders:

– Details of welding procedures.
– Use of checksheets and quality control system.

6. Quality control on each process

6.1 Materials

6.1.1 Plates

Chemical composition and mechanical properties of HT 80 plates are given in Table 4. There is little difference between longitudinal and transverse direction in mechanical properties.

It is clear that quality control in the manufacture of steel is sufficient and plates have good properties.

6.1.2 Forged rings

Forged steel for reinforcing rings were machined into the shape as shown in **Fig. 4**, followed by the required

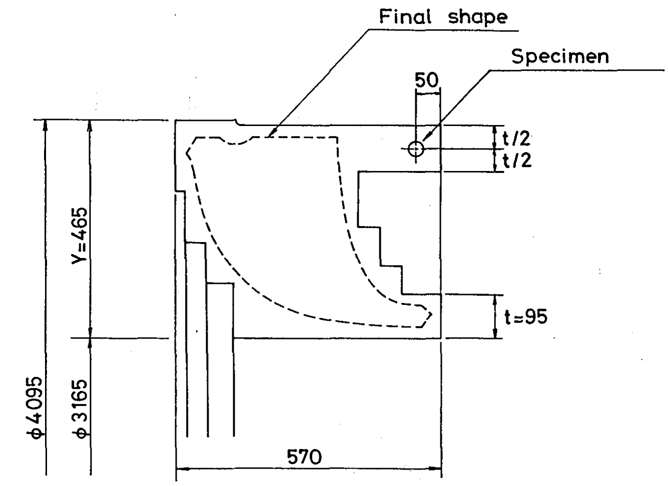


Fig. 4 Sampling of test specimen from forged ring

heat treatment. Ultrasonic tests were then performed and test specimens for mechanical testing were cut off. Forged rings were then finished to the final shape. As the mechanical properties of the center of the forged rings can not be tested on the products themselves, mechanical property tests were made on separate test coupons having a length of 600 mm which received the same heat treatments and had the same sectional dimensions (465 mm x 570 mm) as the products. The test coupons had the same history of manufacture as that of the products.

Ultrasonic tests were performed over the entire surfaces of the products in accordance with JIS. The results satisfied the specification. **Table 5** shows chemical

Table 5 Inspection results of forged rings

a) Chemical compostion

Heat No.	Chemical composition (%)									
	C	Si	Mn	P	S	Ni	Cr	Mo	V	Ceq
Spec.	≦0.14	-	-	≦0.015	≦0.015	-	-	-	-	≦0.60
78D302-1	0.13	0.11	0.83	0.008	0.004	1.94	0.86	0.37	0.06	0.58
78C128-1	0.13	0.10	0.80	0.008	0.006	1.90	0.85	0.36	0.06	0.57

note) Ceq = C + Mn/6 + Si/24 + Ni/40 + Cr/5 + Mo/4 + V/14

b) Mechanical properties

Products No.	Direction	Y.P. (kg/mm^2)	T.S. (kg/mm^2)	El. (%)	Chapy absorbed energy at -40°C (kg-m)
Spec.	L, C	≧68	78 ∿ 93	-	≧ 4.8
78D302-1-1	L	74.7 73.9	83.5 83.0	25.5 25.0	16.4 17.5 Av. 16.5 15.7
	C	74.0 72.4	82.9 81.9	23.1 22.5	13.2 5.2 Av. 7.9 5.2
78D302-1-2	L	73.3 74.7	82.3 83.3	25.0 24.0	16.3 16.5 Av. 16.8 17.5
	C	74.2 74.2	83.0 83.2	22.5 25.5	8.2 7.6 Av. 7.0 5.3
78C128-1-1	L	72.9 72.2	81.9 81.2	25.5 24.9	15.5 15.5 Av. 14.9 13.6
	C	72.5 74.2	81.9 82.9	23.5 23.7	6.0 6.2 Av. 5.7 4.9

composition and mechanical properties of the forged rings. All met quality requirements.

6.2 Shop fabrication

6.2.1 Cutting

Gas cutting was performed under the control standards shown in **Table 6.**

Fig. 5 is u-chart of gas notches. Although preheating burner and water cooled nozzle were used, gas notches occurred in the earlier stages of shop fabrication for plate thicknesses over 50 mm and large cutting size of V-vevel for MIG welding.

They were mainly caused by zincrich primer, painted on steel surfaces. So, a grinder to remove zincrich primer was attached to automatic gas cutting machine. Number of gas notches decreased and rough surfaces disappeared.

6.2.2 Bending

Bending was performed by press and/or bending roller. No defects occured.

Table 6 Control standards on gas cutting

Item	Standards	Method	Class of defect
Surface	Roughness ≦50S	Comparison with sample	C or B
	Notch ≦0.5mm	Visual	
Vevel	Vevel angle ±5°	Vevel gauge	C or B
	Root face ±2mm	do.	
	Root depth ±2mm	do.	
Dimension	Pipe length ±2mm	Tape	C or B
	Circumferential length ±2mm	do.	

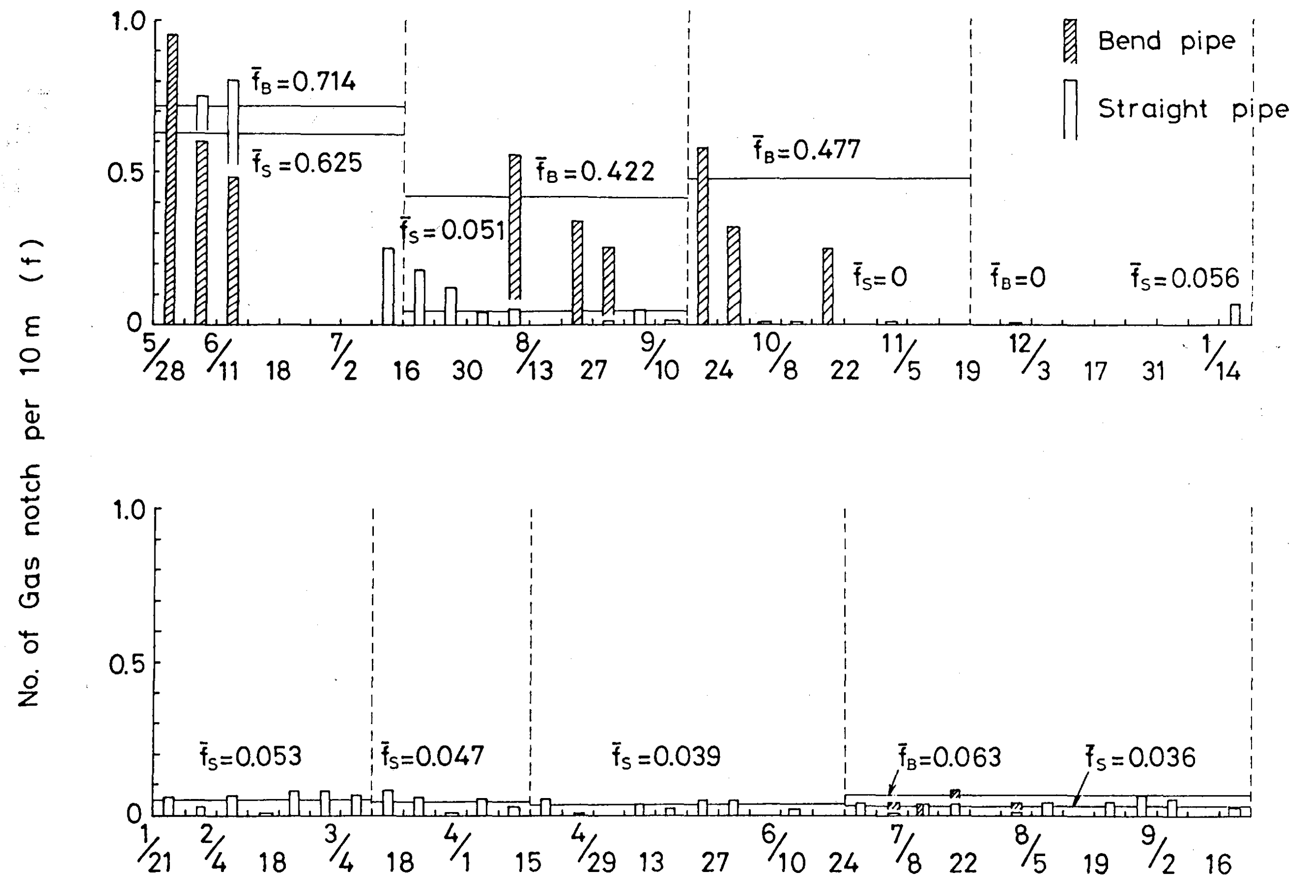


Fig. 5 U-chart of gas notches

6.2.3 Temporary assembly

Branch, bent pipes and reducer pipes were temporarily assembled in shop to confirm dimensions. The results of dimension measurement fully satisfied the requirements.

6.3 Assembling in site shop

6.3.1 Assembling of a pipe

In assembling a pipe, vevel accuracy, curvature, circumference and length were confirmed in accordance with acceptance standards shown in **Table 7**. Curvature and deformation were checked after welding of longitudinal joints. There were no defects.

6.3.2 Assembling of a pipe unit

After a pipe unit was assembled, vevel accuracy, circumference and length were checked in accordance with acceptance standards shown in Table 7. Then the pipe unit was welded, and inspected again on circumference and length. Their results satisfied QC standards.

Misalignment in circumferential joint is caused by the difference of circumference between connecting pipe units. So as to reduce misalignment in the joints welded at the installation site, efforts were made to reduce the difference of circumference to a possible minimum. **Fig. 6** shows the difference in the order of date.

Table 7 Acceptance standards of dimensional tolerance

Item	Standards	Method	Class of defects
Longitudinal joints	Misalignment $\leq$ 5% of plate thickness	Straight gauge	B
	Root gap $\leq$ 5mm for SMAW	Tapered gauge	B
	$\leq$ 0.8mm for SAW	do.	C
	Misalignment at pipe edge 2mm	Straight gauge	C
Curvature	gap to curvature gauge $\leq$ 3mm	Curved gauge (gauge length 1m)	B
Circumferential joints	Misalignment $\leq$ 10% of plate thickness	Straight gauge	B
	Root gap $\leq$ 5mm for SMAW	Tapered gauge	B
	$\leq$ 0.8mm for SAW	do.	C
Dimension of pipe unit	Circumferential length ±0.125%	Tape measure	B
	Longitudinal length +0.003L -0.0005L (L-length)	do.	B
	Roundness ±D/300 (D=diameter)	Bar gauge	B
Installation	off set of center axis of pipe $\leq$ 3mm	Plumb-bob and transit	B

note) * Sealing bead shall be made at the part of root gap over 0.8mm

6.4 Installation of a pipe unit

After installation of a pipe unit, accuracy of pipe's center axis and vevel accuracy were confirmed in accor-

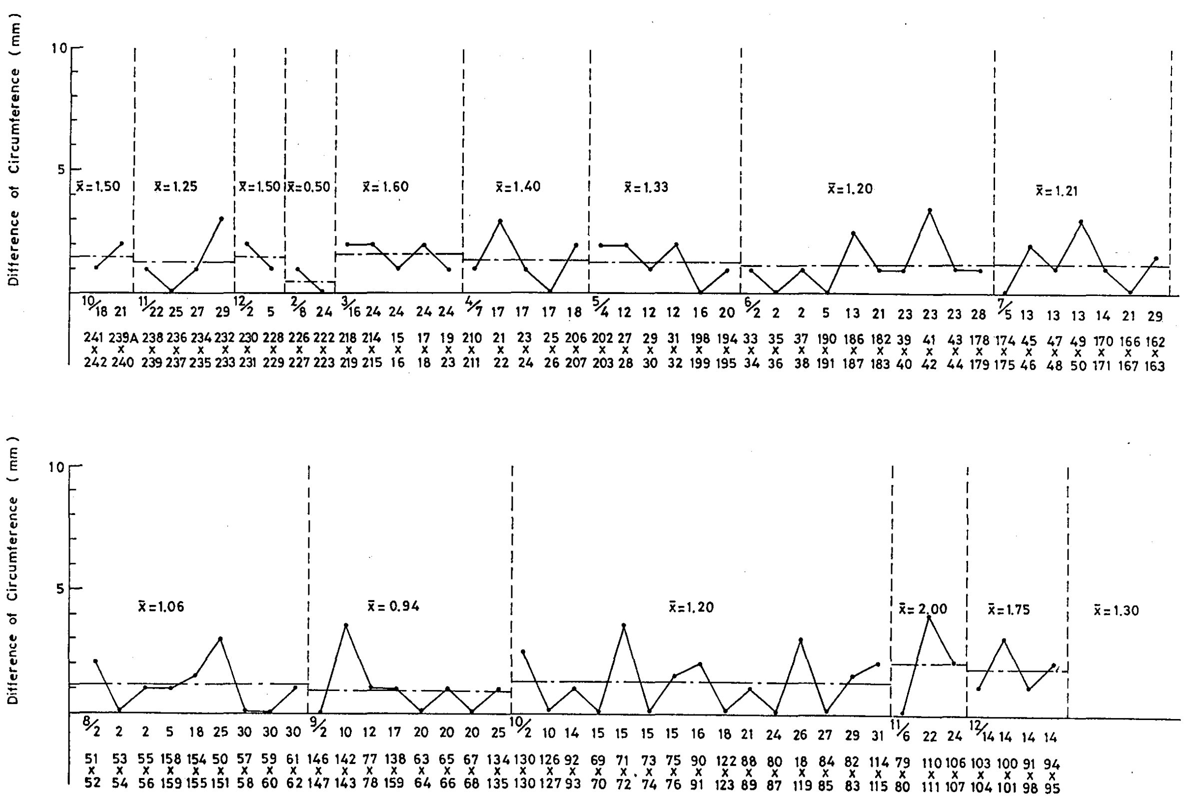


Fig. 6 Defference of Circumferential length

dance with acceptance standards shown in Table 7. There were no defects.

6.5 Welding

6.5.1 Welding methods

Shielded metal arc welding, submerged arc welding, CO_2 gas shielded arc welding and full mechanized MIG welding were used in this construction. The application is shown in **Table 8**.

Table 8 Application of welding procedure

Welding Process	Applied joint: Structure		Applied joint: Joint	Welding site: Fab's shop	Welding site: Site shop	Welding site: in tunnel
SAW	All pipes except branch		Longitudinal	*	*	
	Straight pipe Reducer pipe		Circumferential		*	
SMAW	Bent pipe, Reducer pipe		Circumferential		*	
	All pipes except trifurcating branch		Circumferential			*
	Trifurcating branch		All joints			*
	Stiffening plate for manhole		Fillet	*		
	Stiffener, Thrust collar		Fillet		*	
	Attachment pieces, Eye piece		Fillet	*	*	*
Full mechanized MIG	Straight pipe (Vertical)		Circumferential		*	*
	Bent pipe		Circumferential		*	
Semi automatic MIG	Stiffenner, Thrust collar	HT80	Fillet		*	
Semi automatic CO_2		SM58, SM50	Fillet		*	

6.5.2 Consumables

Consumables were used after they had passed the check with the specification intercharged with makers or JIS.

Electrodes and fluxes were dried according to the conditions as shown in **Table 9**, and stored in a drying oven or container.

When electrodes are left in the open air for a long period of time, coatings absorb moisture, which deteriorates the quality of welds. Therefore, to prevent the use of moisture-absorbed electrodes, it was specified that electrodes should be used within the periods of time after being removed from a drying oven or container as shown in **Table 10.**

Those electrodes, which had exceeded the limited time

Table 9 Drying and storing condition of consumables

Cunsumable	Type of flux	Brand Name	Drying condition: Temp.(°C)	Drying condition: Holding time (hr)	Storage temp.(°C)
Electrode	Low hydrogen	LB80UL, L80L LB62UL, L60L	350-400	1	125-175
		LB52	300-350	1	100-150
	Low hydrogen with iron	LB62-28 LB52-28	300-350	1	100-150
Flux	Fuse	MF38	250-300 for HT80	2	100-150
			150-200 for SM58 and SM50	1	

Table 10 Limited time for use and redrying

Steel grade	Time for use (hr.)			No. of redring
	Moisture pressure			
	Under and equal to 20mmHg		Over 20mmHg	
	Shop	in Tunnel	-	
HT80	1.5	1	0.5	1
SM58	3	2	1	2
SM50	4	4	2	2

for use, were returned for redrying. They were distinguished from the electrodes of first drying by brands and lot numbers.

The quantity of electrodes to be delivered to a welder at one time was also restricted to the limits as shown in **Table 11**, so that all electrodes delivered to welders can be used within the limited time. As the result, there were a few cases of redrying, and no cases of redrying twice.

Table 11 Maximum delivering number of electrode for each welder at one time

Brand name of electrode	Dia. (mm)	Tack welding	Welding
LB80UL, L80L LB62UL, L60L	4	15	25
	5	-	20
LB62-28 LB52-28, LB52	4	20	30
	5	-	25

6.5.3 Atmosphere

Temperature and humidity were measured at welding workshop in the site shop and tunnel. Temperature, humidity and moisture pressure, which was calculated from temperature and humidity, were reported at 8:00 a.m., 1:00 p.m. and 4:00 p.m. by QC staff. When moisture pressure was over 20 mmHg, the time limit of electrodes was made shorter. There were 5 days in July and 8 days in August of 1979 at the site shop when moisture pressure was over 20 mmHg.

Because of high preheating temperature (150° – 180°C), atmospheric temperature was sometimes over 50°C in the vicinity of welding work location for branch. However moisture pressure was not so high, since humidity decreased.

6.5.4 Preheating, postheating and interpass temperature

Minimum preheating temperatures for welding were as shown in **Table 12**. For tack welding, welding of small attachments, repair and so on, 30°C higher temperatures were specified.

Minimum interpass temperature was the same as preheating temperature. Maximum was 230°C for HT 80 and 250°C for SM 58. Though maximum temperature was not specified for SM 50, all the results of sampling check were not more than 250°C.

Table 12 Minimum preheating temperature for welding (°C)

Steel garde		Thickness (mm)	SMAW	SAW	GMAW
HT80	except branch	$t \leqq 25$	100	80	60
		$25 < t \leqq 50$	100	100	80
		$50 < t$	120	120	100
	Branch	$t \leqq 40$	120	--	--
		$40 < t$	150		
SM58		$t \leqq 25$	40	--	--
		$25 < t \leqq 50$	80	60	40
SM50		$t \leqq 38$	*	--	--
		$38 < t \leqq 50$	80	60	40

note) * Burning was performed only for drying in the tunnel

Post weld heat treatment (150°C, 2 hours) was performed after the completion of welding of HT 80 in the tunnel. In the case of interruption on the way of welding, the same postheat treatment was performed or joint was maintained in the specified preheating temperature till the resumption of welding.

Heating method and temperature control of pre- and postheating were as shown in **Table 13**. Gas flame heating was done by manual burner or burner heating equipment. In case of electric heater, required temperatures were controlled by automatic thermal regulators.

Table 13 Heating method and temperature control

Kind of joints		Heating method	Heated area	Confirming method	Measured point
Straight, Bent, Reducer pipes	Longitudinal joint	Gas burner	Both sides of weld line for 100mm	Thermo chalk Surface thermometer	50mm from weld line
	Circumferential joint	Electric heater Gas burner			
	Others	Gas burner			
Trifurcating branch	Longitudinal joint	Electric heater			
	Circumferential joint	Electric heater			
	Others	Gas burner			

6.5.5 Heat input

So as to insure toughness requirement on welded joints, the maximum heat input were specified. QC standards for heat input is shown in **Table 14**. In welding of HT 80 plates, heat input for each pass was controlled

Table 14 Maximum heat input

Steel grade		Heat input (kj/cm)	
		maximum	average
HT80	Plate	50	45
	Forged ring	40	-
SM58		90	-

so that the maximum heat input may be under 50 kj/cm and average under 45 kj/cm.

In submerged arc welding, standard welding conditions to meet QC standards for heat input were decided and checked strictly. Operators recorded current, voltage and travelling speed for each pass on 'welding control sheet.' QC staff calculated heat input and confirmed. **Fig. 7** shows the records of heat input for HT 80. These satisfied QC standards.

Heat input of full mechanized MIG welding is lower than that of SAW, however it was controlled by the same control sheets as used for submerged arc welding. **Fig. 8** shows heat inputs of MIG welding for HT 80.

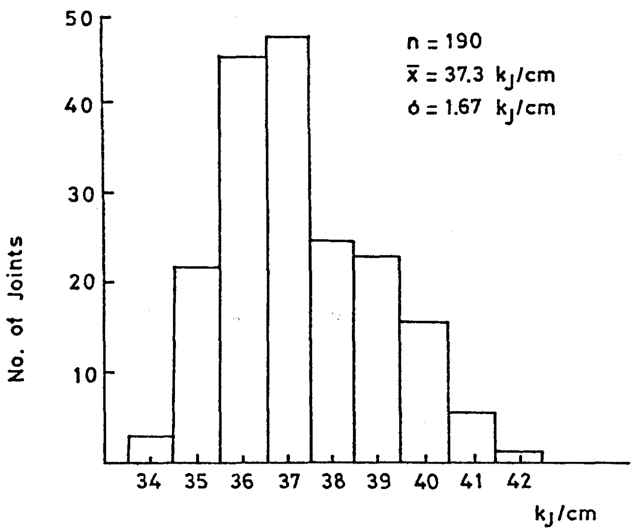


Fig. 7 Heat Input of SAW

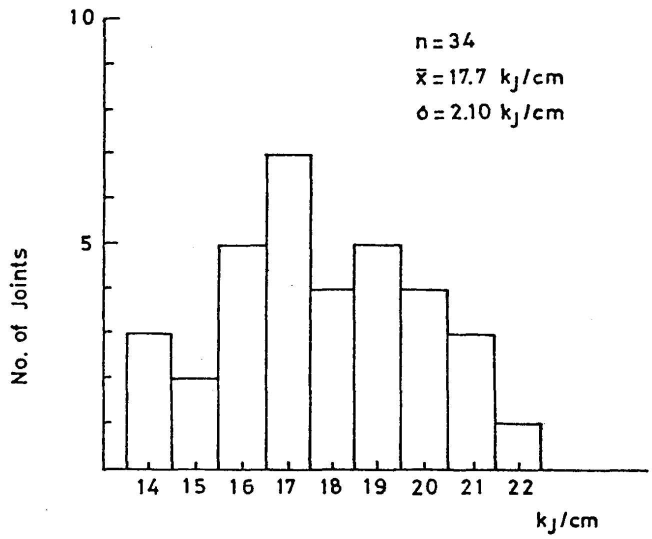


Fig. 8 Heat Input of MIG

In shielded metal arc welding, measurement of welding speed is difficult. Bead length from one electrode with critical heat input was measured before welding. Heat input for the work was controlled by measuring the bead length. **Table 15** gives the bead length for one electrode.

Table 15 Minimum bead length per one electrode (cm)

Dia. (mm)	Amp. (A)	Heat input (kj/cm)		
		40	45	50
4	120	8.6	7.6	6.9
	130	8.9	7.8	7.1
	140	9.1	8.2	7.3
	150	9.4	8.3	7.5
	160	9.5	8.6	7.7
	170	9.8	8.7	7.8
	180	10.1	8.9	8.1
5	160	12.4	11.0	9.9
	170	12.6	11.3	10.1
	180	13.3	11.7	10.6
	190	13.6	11.9	10.9
	200	14.0	12.4	11.2
	210	14.3	12.6	11.4
	220	14.5	12.9	11.6
	230	14.8	13.1	11.8
	240	15.1	13.5	12.1

note) Consumable length of electrode was found 350mm per one electrode

6.5.6 Welding of branch

Welding of spherical shell was performed by the sequence as shown in **Fig. 9**.

In welding of spherical shell and of joints between shell and reinforcing ring, three groups of welders worked all at once at symmetrical location.

Each layer (inside and outside of pipe) was devided into two layers and welding was performed alternately.

Cooling suit was put on, when temperature exceeded

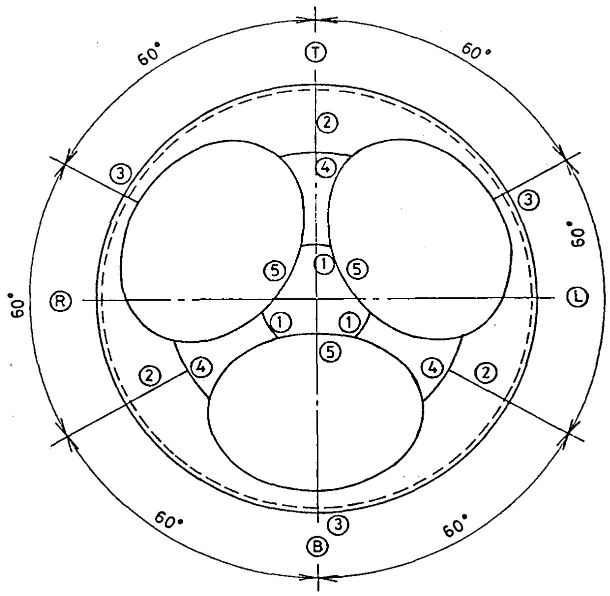


Fig. 9 Welding Sequence of Spherical Shell

50°C in the vicinity of weld by high preheating temperature.

All of welds were inspected by radiographic examination. Radiographic examination for circumferential joints was performed at once, by setting a source (^{60}Co) at the center of pipe.

As it is difficult to repair defects occured at the center of thick plates, radiographic inspection was carried out when half of welding was made. However ho defects were found.

6.5.7 Counterplan for unusual situation

The following counterplan for unusual situations such as worse environment and electric power shutt off were prepared.

Temperature under 0°C

Number of days under 0°C was 28 at 8:00 a.m., once at 1:00 p.m. and nothing at 4:00 p.m. at the site shop. In these case preheating of 15°C to 50°C was given even for steels which would not be preheated at usual conditions, and preheating time was increased for steels for which preheating was required.

Moisture pressure over 20 mmHg

There were no days in the tunnel, and 36 days at the site shop when moisture pressure exceeded 20 mmHg. In these cases the limit hours for using of electrodes were shortened as mentioned above.

Electric power shutt off

Though the counterplan for electric power shutt off had been prepared, there was no electric power shutt off during welding work.

6.5.8 Inspection of welds

Inspection of appearnace of welds and radiographic examinations were performed each time when welds had been completed.

Inspection of appearance of welds was performed, first, by welders themselves and then by a QC staff and a staff of the owner. If necessary, repair was made according to QC standards shown in **Table 16**.

Radiographic examinations of HT 80 welds were performed 48 hours after completion of welding at the site shop, and 24 hours after post weld heat treatment for diffusion of hydrogen at site in the tunnel. Though the specification was not given for SM 58 or under, it was performed 12 hours after welding.

All of the cross joints of longitudinals and circumferentials and 5% of welds in length were inspected on pipes except branch. Sampling rate was 15.4% for HT 80, 13.6% for SM 58, and 13.2% for SM 50. All the welds in branch were inspected.

The films better than **Table 17** is specified to be accepted, where classification is based on JIS.

Table 16 Acceptance standards of appearance of welds

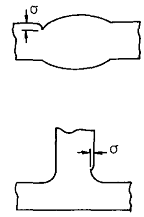
Item	Standards
Under cut	$\sigma \leqq 0.8$mm for groove joint and fillet joint 90% of welds σ shall not be more than 0.5mm 
Hight of reinforcement	under 2.5mm for t ≦ 25mm 3.0mm for t > 25mm
Fillet welds size	minus size: under 1mm
Others	Overlap, pinhole, crack and others shall not be permitted

Table 17 Acceptance standard of radiographic test

Type of defects	Plate thickness	
	t ≦ 50mm	t > 50mm
Porosity	2nd class	1st class
Slag inclusion	do.	do.
Crack	not acceptable	
Mixed (porosity and slag inclusion)	2nd class	2nd class

note) Classified by JIS

Test results were analysed at the end of every months on the type and grade of defects with regard to welding site, welding method, and steel grade.

Results were as shown in **Table 18**. All welds passed and no repairs were made.

7. Conclusion

In this construction, the basic policy 'each procedure makes quality' was recognized by all of staffs and workers concerned. Quality assurance was intended through quality control. Quality control was performed systematically.

Such efforts were made as to establish fabrication and inspection procedures, to constitute QC standards, and to educate workers, in order to satisfy the quality requirements.

Very good quality was attained, for example total of 4111 radiographic inspection passed the standards and no repairs were made.

Table 18 Results of radiographic testing

Welding site	Welding Process	Steel grade	No. of film	1st class				2nd class		
				no defect	porosity	slag inclusion	mixed	porosity	slag inclusion	mixed
Site shop	SAW	HT80	394	393 (99.7%)				1 (0.3%)		
				369	18	6	0	1	0	0
		SM58	1,304	1,289 (99.0%)				13 (1.0%)		
				1,137	118	30	4	10	1	1
		SM50	67	66 (98.5%)				1 (1.5%)		
				53	10	3	0	0	0	0
	Full mechanized MIG	HT80	84	80 (95.2%)				4 (4.8%)		
				25	39	2	14	2	0	2
		SM58	220	203 (92.3%)				17 (7.7%)		
				9	129	14	51	10	2	5
	SMAW	HT80	228	227 (99.6%)				1 (0.4%)		
				182	24	14	7	1	0	0
		SM58	157	157 (99.4%)				1 (0.6%)		
				102	30	22	3	0	0	1
Installation site in tunnel	Full mechanized MIG	HT80	24	23 (95.8%)				1 (4.2%)		
				2	17	0	4	1	0	0
		SM58	220	197 (89.5%)				23 (10.5%)		
				11	129	6	51	16	0	7
	SMAW	HT80	328	323 (98.5%)				5 (1.5%)		
				237	41	26	19	4	0	1
		SM58	410	409 (99.8%)				1 (0.2%)		
				271	69	59	10	0	0	1
		SM50	40	39 (97.5%)				1 (0.5%)		
				30	4	4	1	1	0	0
		HT80 (Branch)	636	636 (100%)				0 (-)		
				627	8	0	1	0	0	0
Total			4,111	4.042 (98.3%)				69 (1.7%)		
				3,055	636	186	165	47	3	19

This paper is a sample of quality assurance in welding of a penstock with high strength steel. The autors wish that many structures will be constructed under the appreciation of quality assurance through quality control.

Acknowledgements

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Reference

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