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STRAIN MEASUREMENT ON A COMPACT NUCLEAR REACTOR PRESSURIZER

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ABSTRACT

This work presents the strain measurement procedures applied to a compact nuclear reactor pressurizer, during a hydrostatic test, using strain gage technology.

The temperature of the pressurizer wall was kept at 25 ºC during the measurement and the pressurizer loading was performed using the following pressure steps:

Step 1: 140 Kgf/mm^2
Step 2: 170 Kgf/mm^2
Step 3: 210 Kgf/mm^2

The measurement points on both internal and external pressurizer walls were established from pre-calculated stress distribution by means of numerical calculation (finite elements modeling).

Strain values were obtained using a quarter Wheatstone bridge circuit.

Stress values were determined from experimental strains and were compared to numerical calculation results.

Keywords: Strain gages, hydrostatic test, compact nuclear reactor, pressurizer.

1. INTRODUCTION

The Pressurizer (PZ) is one of the equipments that belong to the CS-1 nuclear safety class of the primary circuit of the Nucleoeletric Generation Laboratory Reactor (LABGENE) that will be built in the facilities of the Navy Technological Center in São Paulo (CTMSP-ARAMAR), in Iperó, a city 80km from São Paulo city- Brazil.

Jaraguá Industrial Equipments Ltda was the company contracted by CTMSP for production the equipment.

UNITÉCNICA is the engineering company contracted by CTMSP for making of the memorial of equipment calculation.

The hydrostatic test of the Pressurizer aims at evaluating the stress developed in the equipment during the pressurization and possible leaks through you weld surfaces, connections and gaskets. In order to evaluate the stresses in the equipment during the hydrostatic test, rectangular strain gage rosettes were installed in both internal and external surfaces of the PZ.

The whole test was accompanied by an independent inspector of the Brazilian Institute of the Nuclear Quality (IBQN).

2. METHODOLOGY

2.1 Materials, Equipments and Methods Used

Strain Gage:

Rectangular Rosette, mark Kyowa, model KFG-5-120-D17-11;

- Nominal Resistance: 120,04 ± 0,4 Ω;
- Sensor Length: 5 mm;
- Gage Factor K: 2,11 ± 1%;
- Thermal Coefficient Expansion: 11,7 ppm/°C;
- Temperature compensation: Steel.

Rectangular Rosette, mark Kyowa, model KFG-5-120-D17-16;

- Nominal Resistance: 120,04 ± 0,4 Ω;
- Sensor Length: 5 mm;
- Gage Factor K: 2,18 ± 1%;
- Thermal Coefficient Expansion: 16,2 ppm/°C;
- Temperature compensation: Stainless Steel.

Adhesive:

Resin cyanoacrylate, mark Kyowa, model CC33A;

- Operation temperature: -196°C a 120°C.

Protection:

For treating a test submerged (the strain gage is immersed in water) and under pressure it was necessary to use a protection on the internal strain gages. A protection was also used on the due to external strain gages by virtue of the risk to wet during the test. For protecting the internal strain gages, the protection AK22 was selected due to be efficient in cases of immersion in water under pressure up to 400 bar. For the protection of the external strain gages, the protection ABM75 was selected due to be efficient for situations where immersion can occur on the strain gages.

The internal points were protected with two varnish layers, mark EMEME (Vishay), model MCoat A; a thick layer of mass, mark HBM, model AK-22; an aluminum foil leaf and adhesive tape mark 3M, model silver tape.

The external points were protected with two varnish layers, mark EMEME (Vishay), model MCoat A; a mass layer with leaf of aluminum, mark HBM, model ABM75 and adhesive tape mark 3M, model silver tape.

Connection:

Each gage (the rectangular rosette possesses 3 gages) was connected through a cable with 3 armored threads to the Wheatstone bridge as presented in Figure 1. The Wheatstone bridge was set up, being strain gages of type rectangular rosette model CEA-06-250-UR-120 manufactured by Measurements Group bounded in bars of steel rigid not submitted to mechanical efforts. The Wheatstone bridge was installed close to the rosettes to minimize the size of the threads of the strain gage connection.

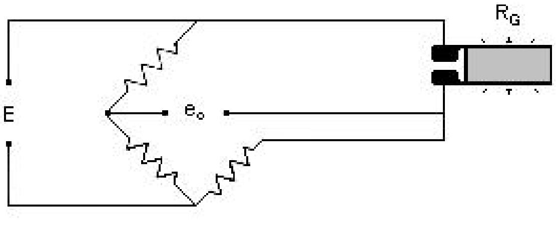


Figure 1 – Connection of the strain gage to the Wheatstone bridge.

A cable with 4 armored threads was used to connect the bridge of Wheatstone to the data acquisition system and the feeding source. To the data acquisition system were connected the terminals suitable e_0 in Figure 1 and the terminals E were connected to the power supply.

The Wheatstone bridge was fed with 2 volts and this value was monitored by the data acquisition during the measurements.

The connection of the internal points was done through the use of feedthrough, mark CONAX, model HD37-450(60Cu)PG4AL-70/24.

Acquisition and Data Treatment System:

The acquisition and data treatment system was composed by:

- 01 system with 48 channels, mark Agilent, model 34970A, with 03 modules of switch, model 34902A.
- 01 system with 60 channels, mark Agilent, model 34970A, with 03 modules of switch, model 34901A.
- 01 microcomputer type notebook, mark Texas Instruments, Extensa model 610CD, pentium 133 Mhz.

PZ Internal Pressure Measurements:

Internal pressure measurement was not accomplished by the data acquisition system. The PZ internal pressure was accomplished through manual reading in two manometers with calibration and certification both valid and updated. These manometers were installed by the Jaraguá team. The reading was done every ten minutes.

Pressurization System:

The equipments for pressure application and for the pressurization rate control were supplied by Jaraguá.

The hydrostatic test was led by the Jaraguá team.

Strain Gages Calibration:

- Effect of the pressure in the strain gage.

Analysing the stress of pressure vases, the bounded strain gages in the internal surface are exposed to the flowed or pressurized gas, which acts directly in the strain gage element. Under such conditions, the resistance of the strain gages suffers a small increase due to the pressure that acts perpendicular to its grade and it should be taken into account for the strain gage readings analyzis. For the strain gages used in this test, the correction is given by:

$$\frac{\Delta R}{R} = 0{,}016x10^{-6} \text{ por MPA} \quad (1)$$

- Compensation due to the strain gage factor K.

The compensation of the values of K was accomplished = 2,11 for the strain gages used for the Steel SAE 508 class 3 and of K = 2,18 for the strain gages used for the Stain Steel 347. This compensation is made by using in the Equation (2) the K values described above.

$$\varepsilon = \frac{4\Delta V}{KV} \quad (2)$$

- Factor of correspondence of the strain values.

The readings were corrected through the technique of external shunt, using standard resistors of precision, mark Vishay, model S-59880-01, tolerance 0,01%, whose equivalent strain is of 1000 µm/m for a nominal resistance of 120 ohms and factor K=2 of the strain gages. For this correction, were made readings of the points with and without the standard resistor inserted in parallel with the strain gages. The result of these readings was compared with calculated values being considered the resistance values and the factor K of the used strain gages.

Uncertainty of the Measurements:

The whole measurement system was previously gauged. The global uncertainty of the measured values was evaluated in 4% of the read values.

Measurement procedure:

For the reading of the 22 installed rectangular rosettes, 66 reading channels were used, being 30 channels read in the system 34970A with 48 channels and the other 36 channels read in the system 34970A with 60 channels. The two systems were controlled by the program developed by CDTN (Center of Development of the Nuclear Technology), which presents the following data in real time:

- Strain of the three rectangular rosette gages.
- Principal strains, maximal, minimal and angular.
- Principal stresses, maximal, minimal and shear.
- Angle and direction of the principal strains.

It is presented in Figure 2, a typical screen of the program results.

Figure 2 – Screen of results typical of the acquisition program and data treatment.

With the Pressurizer full of water and before being submitted to pressure, it was made a series of readings of the points scored for the determination of the zero reading system.

2.2 Location of Strain Gages Rosettes in the Pressurizer

The strain gages of the rectangular rosettes are numbered from 1 to 3 in the counterclockwise sense as presented in Figure 3. The final orientation of the strain gages 1, 2 and 3 of the rectangular rosettes are suitable in Table 1.

The location of the 22 (twenty two) rectangular rosettes installed in the CTMSP Pressurizer followed the indications of the document NEQ184 Rev05 of the Quality Program of Warranty of Jaraguá Industrial Equipments Ltda approved by CTMSP. The final position of the rectangular rosettes installation is indicated in the Figure 4 and Figure 5. The identification of the rectangular rosettes positions was accomplished by the Jaraguá team through references traced with relation to the principal axes of the equipment.

The rectangular rosettes identification followed the suitable nomenclature in the document NEQ184 Rev05.

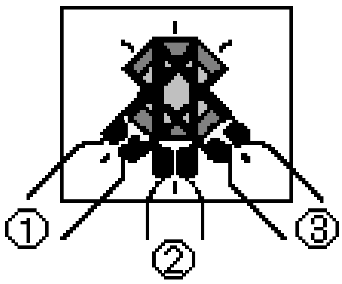


Figure 3 – Numbering and orientation of the rectangular rosette gages.

Table 1 – Gages orientation of the rectangular rosettes.

POINT	***GAGES***		
	1	**2**	**3**
SG1	Circunferencial	45	Longitudinal
SG2	Longitudinal	45	Circunferencial
SG3	Circunferencial	45	Longitudinal
SG4	Longitudinal	45	Circunferencial
SG5	Circunferencial	45	Longitudinal
SG6	Circunfer'encial	45	Longitudinal
SG7	Longitudinal	45	Circunferencial
SG8	Circunferencial	45	Longitudinal
SG9	Longitudinal	45	Circunferencial
SG10	Circunferencial	45	Longitudinal
SG11	Circunferencial	45	Longitudinal
SG12	Longitudinal	45	Circunferencial
SG13	Longitudinal	45	Circunferencial
SG14	Circunferencial	45	Longitudinal
SG15	Longitudinal	45	Circunferencial
SG16	Circunferencial	45	Longitudinal
SG17	Longitudinal	45	Circunferencial
SG18	Longitudinal	45	Circunferencial
SG19	Circunferencial	45	Longitudinal
SG20	Longitudinal	45	Circunferencial
SG21	Circunferencial	45	Longitudinal
SG22	Longitudinal	45	Circunferencial

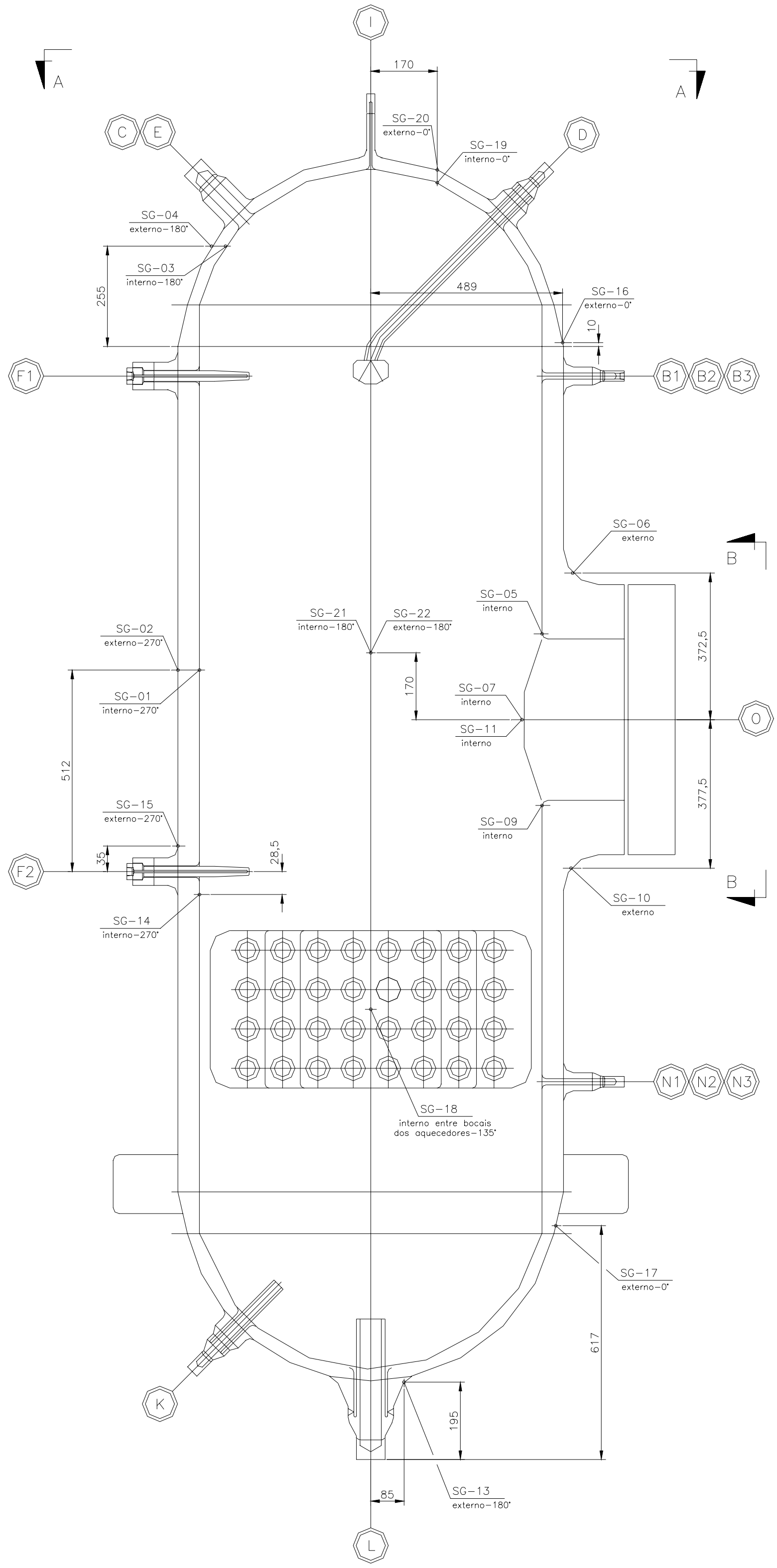
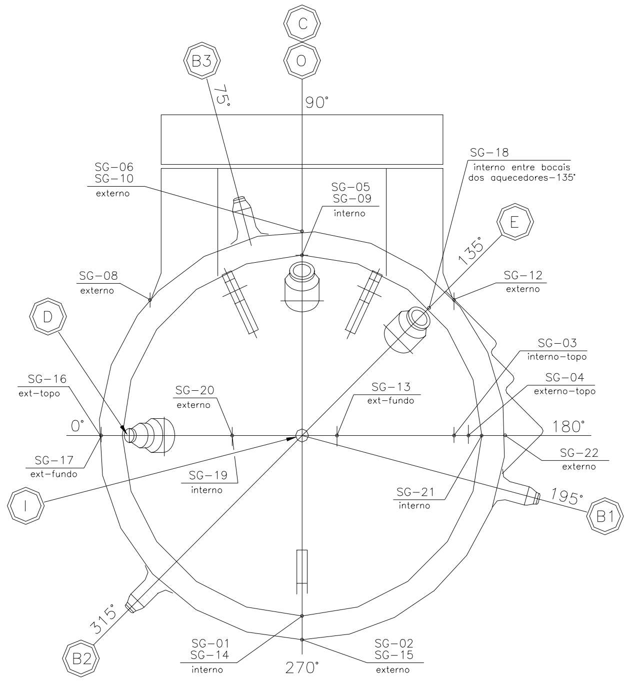
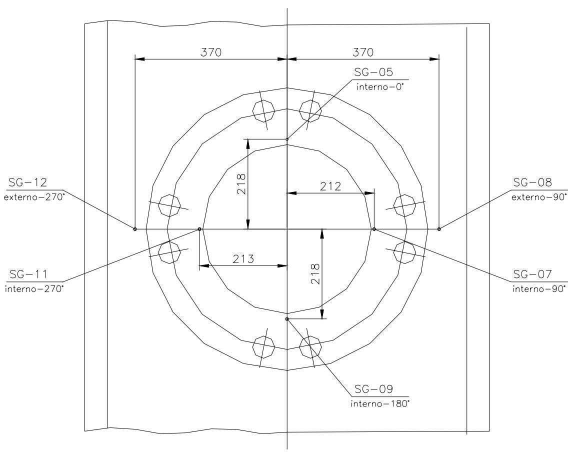


Figure 4 – Location of the rectangular rosettes in PZ of INAP.



VISTA "A – A"



VISTA "B – B"

Figure 5 – Location of the rosettes rectangular views A-A and B-B.

2.3 Pressurization and Depressurization of PZ

The pressurization and depressurization of PZ were commanded and operated by the Jaraguá team and done according to the document NEQ184 Rev.. 05 of the Quality Program of Warranty of Jaraguá Industrial

Equipments Ltda.

The pressure values, to which the PZ was submitted, didn't exceed the established limits.

Minimal Pressure Test:

210 kgf/cm2 - according to the text of the document NEQ 184 Rev. 05 copied as follow:

"As recommended in the Paragraph NB-6221 of ASME Section III - Div. 1 Subsection NB Edition 1986 + A86, the minimal pressure of the hydrostatic test to which the equipment should be submitted, cannot be smaller than 1,25 times the smallest project pressure, that is, 210,7 kgf/cm2 abs, added to the pressure difference (column of water) regarding accomplishment of the test in the horizontal position, instead of the vertical one, therefore, we will adopt as minimal pressure of: 210 kgf/cm2 man."

Maximal Pressure Test:

The maximum pressure cannot introduce a membrane stress superior to 280 MPa, according to the text of the document NEQ 184 Rev. 05 copied as follow:

"As recommended in the Paragraph NB-6222 of ASME Section III - Div. 1 Subsection NB Edition 1986 + A86, the maxim pressure of the hydrostatic test which the equipment should be submitted to, cannot implicate that the stress limit specified in the Paragraph NB-3226 surpasses the acceptable value of the general membrane stress, that is, the strain gage located in the internal walls of the equipment (SG-01), distant from any discontinuity (that measures the general membrane stress) cannot accuse a stress larger than 0,9 Sy = 0,9 x 318 = 286 MPa. For safety, we will adopt as a maximal, the stress of: 280 MPa."

The PZ pressurization was made in a slow and gradual way to an approximate rate of 2,5 kgf/cm^2, and was performed in four stages, as described bellow:

1st Stage (operation pressure):

The hydrostatic pressure was elevated until the operation pressure (140 kgf/cm^2 man) and kept at this level for 30 minutes.

Intermediate Stage (project pressure):

The hydrostatic pressure was elevated until the project pressure (170 kgf/cm^2 man) and kept at this level for 30 minutes.

2nd Stage (test pressure):

The hydrostatic pressure was elevated until the test pressure (210 kgf/cm^2 man) and kept at this level for 2 hours.

3rd Stage (project pressure):

The hydrostatic pressure was reduced until the project pressure (170 kgf/cm^2 man) and kept at this level for 30 minutes.

After the 3rd Stage, the PZ was completely depressurized and drained at water in its interior.

RESULTS

In Diagram 1, are presented the internal values pressure which were read from the manometers and the medium internal value pressure of the Pressurizer. Diagram 2 shows the temperature values of the Pressurizer external wall which values represent the average taken from the temperature reading in five points of the external wall.

In the diagram 1, the following nomenclature is used for the legends:

Pressure 1 = PZ internal pressure read in manometer 1,

Pressure 2 = PZ internal pressure read in manometer 2,

Pressão_média = the average of the pressure works read in manometers 1 and 2.

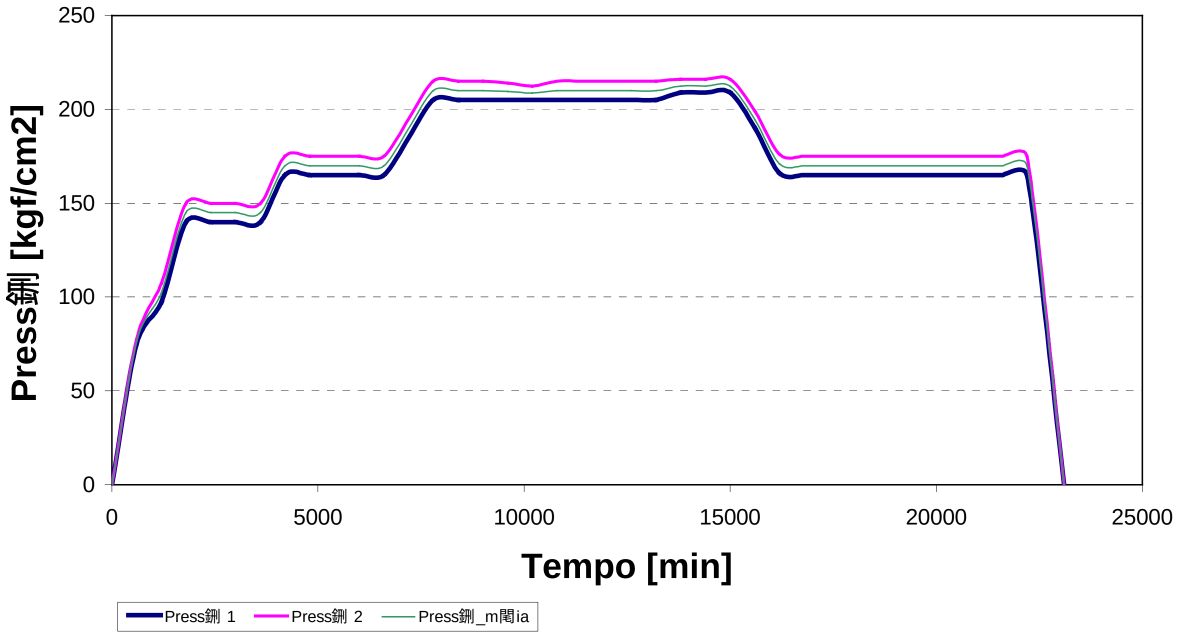


Diagram 1 – PZ internal pressure.

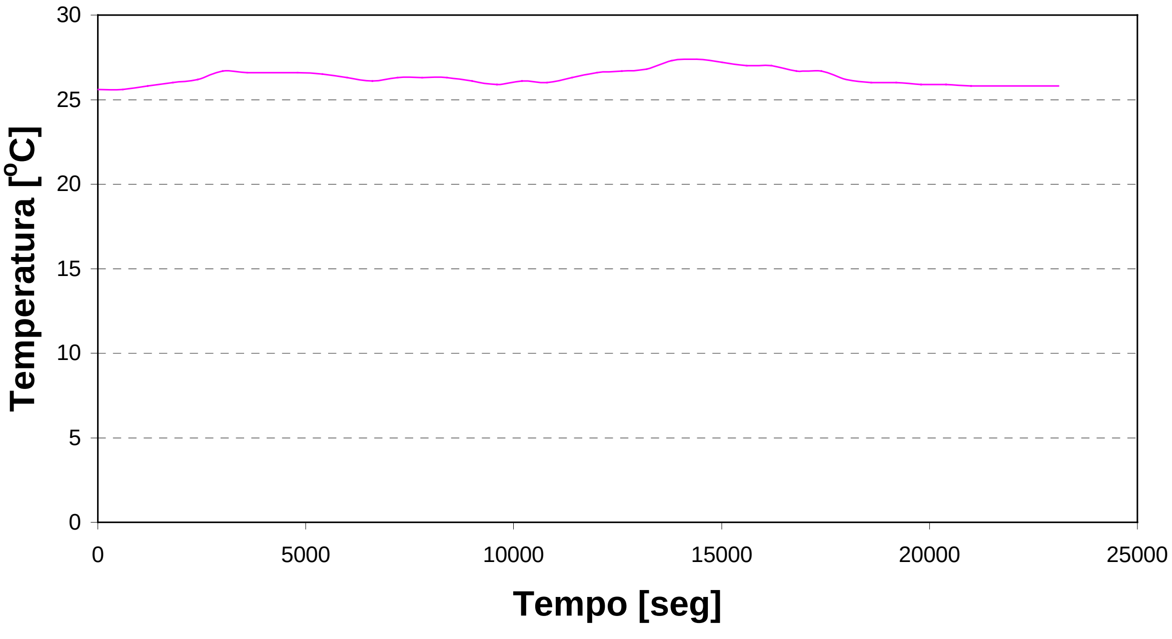


Diagram 2 – PZ external wall temperature.

In the following tables, the medium values read at the levels of the each stage during the PZ hydrostatic test. For the stress calculation, the following module of elasticity values and the coefficient of Poisson were used:
Stain Steel AISI 347 (Pressurizer internal coating):
Elasticity Module in the 20°C = 195,100 MPa.
Steel SA-508 cl3 (body of the Pressurizer):
Elasticity Module in the 20°C = 191,700 MPa.
Coefficient of Poisson = 0.3 for the two materials.

Table 2 - Strain and stress values for each point scored in the operation pressure.

Pressure of Operation - 140 Kgf/cm2				1st Stage			Average of the values during the landing				
Point	ε_1	ε_2 (45)	ε_3	ε_{max}	ε_{min}	γ_{max}	σ_{max}	σ_{min}	σ_{os}	Angle	Direction
	(μm/m)	(μm/m)	(μm/m)	(μm/m)	(μm/m)	(μm/m)	(MPa)	(MPa)	(MPa)		
SG1	581	357	89	563	87	238	126	55	36	4	ε_{max}
SG2	88	264	411	412	88	162	92	44	24	-3	ε_{min}
SG3	363	332	308	362	308	27	98	89	4	-2	ε_{max}
SG4	348	345	335	349	334	7	95	92	1	12	ε_{max}
SG5	1903	382	-607	1931	-635	1283	373	-12	193	-6	ε_{max}
SG6	141	12	-104	141	-105	123	23	-13	18	-1	ε_{max}
SG7	38	8	-29	39	-29	34	7	-4	5	2	ε_{max}
SG8	571	436	313	571	313	129	140	102	19	-2	ε_{max}
SG9	-479	371	1823	1861	-518	1190	286	9	179	7	ε_{min}
SG10	166	50	-50	166	-50	108	32	6	16	-2	ε_{max}
SG11	-38	1	31	31	-38	35	4	-6	5	-4	ε_{min}
SG12	325	472	623	623	325	149	152	108	22	0	ε_{min}
SG13	17	137	282	283	17	133	61	21	20	2	ε_{min}
SG14	1144	353	-293	1148	-297	723	227	10	108	-3	ε_{max}
SG15	1	63	146	146	0	73	31	9	11	4	ε_{min}
SG16	352	221	102	352	102	125	81	44	18	-1	ε_{max}
SG17	30	180	325	325	30	148	70	27	22	0	ε_{min}
SG18	70	101	185	190	64	63	45	26	9	12	ε_{min}
SG19	431	363	373	458	345	57	120	103	9	-29	ε_{max}
SG20	369	356	377	391	355	18	105	99	3	39	ε_{min}
SG21	409	301	153	411	152	129	98	59	19	4	ε_{max}
SG22	162	288	438	438	162	138	103	62	20	2	ε_{min}

(Pink highlight) The stress values are merely informative since the material is not in the elastic region

Table 3 - Strain and stress values for each point scored in the project pressure.

Pressure of Project - 170 Kgf/cm2				Stage Intermediate			Average of the values during the landing				
Point	ε_1	ε_2 (45)	ε_3	ε_{max}	ε_{min}	γ_{max}	σ_{max}	σ_{min}	σ_{os}	Angle	Direction
	(μm/m)	(μm/m)	(μm/m)	(μm/m)	(μm/m)	(μm/m)	(MPa)	(MPa)	(MPa)		
SG1	660	430	112	664	109	278	149	66	42	4	ε_{max}
SG2	101	319	492	493	100	197	110	52	29	-3	ε_{min}
SG3	438	400	361	438	361	38	117	106	6	0	ε_{max}
SG4	421	412	400	421	400	11	114	111	2	5	ε_{max}
SG5	2302	454	-761	2334	-794	1564	449	-20	235	-6	ε_{max}
SG6	169	18	-121	169	-121	145	28	-15	21	-1	ε_{max}
SG7	50	11	-32	50	-32	41	9	-4	6	1	ε_{max}
SG8	682	518	372	683	372	155	167	122	23	-2	ε_{max}
SG9	-581	445	2197	2243	-628	1435	441	10	215	7	ε_{min}
SG10	198	61	-58	199	-58	128	38	0	19	-2	ε_{max}
SG11	-42	2	36	36	-43	39	5	-7	6	-4	ε_{min}
SG12	386	561	732	732	386	173	179	128	26	0	ε_{min}
SG13	17	164	341	341	16	163	73	25	24	2	ε_{min}
SG14	1432	443	-350	1438	-356	897	205	16	135	-3	ε_{max}
SG15	-4	70	165	166	-4	85	35	10	13	4	ε_{min}
SG16	430	253	117	431	115	158	98	52	23	-4	ε_{max}
SG17	37	214	388	388	37	176	84	32	26	0	ε_{min}
SG18	82	114	209	217	75	71	51	30	11	13	ε_{min}
SG19	513	433	440	534	420	57	141	124	9	-25	ε_{max}
SG20	443	423	455	476	422	27	127	119	4	38	ε_{min}
SG21	475	354	186	477	184	146	114	70	22	5	ε_{max}
SG22	192	342	521	521	192	165	122	73	24	2	ε_{min}

(Pink highlight) The stress values are merely informative since the material is not in the elastic region

Table 4 - Strain and stress values for each point scored in the test pressure.

Pressure of Test - 210 Kgf/cm2				2nd Stage			Average of the values during the landing				
Point	ε_1 (μm/m)	ε_2 (45) (μm/m)	ε_3 (μm/m)	ε_{max} (μm/m)	ε_{min} (μm/m)	γ_{max} (μm/m)	σ_{max} (MPa)	σ_{min} (MPa)	σ_{cis} (MPa)	Angle	Direction
SG1	822	648	157	827	152	338	187	86	51	5	ε_{max}
SG2	149	406	629	629	148	240	142	71	35	-2	ε_{min}
SG3	590	526	455	591	455	68	156	138	10	0	ε_{max}
SG4	539	530	513	540	512	14	146	142	2	7	ε_{max}
SG5	3078	578	-1140	3114	-1176	2145	592	-52	322	-5	ε_{max}
SG6	212	22	-153	212	-153	183	35	-19	27	-1	ε_{max}
SG7	64	14	-36	64	-36	50	11	-4	8	0	ε_{max}
SG8	875	663	476	875	476	200	214	156	29	-2	ε_{max}
SG9	-824	574	2915	2973	-882	1928	581	2	289	7	ε_{min}
SG10	252	79	-73	252	-74	163	48	0	24	-2	ε_{max}
SG11	-50	0	44	44	-50	47	6	-8	7	-1	ε_{min}
SG12	499	717	936	936	499	216	228	164	32	0	ε_{min}
SG13	16	218	441	442	15	213	94	31	31	2	ε_{min}
SG14	1941	614	-417	1950	-427	1189	391	34	178	-4	ε_{max}
SG15	-29	67	193	193	-30	112	39	6	16	4	ε_{min}
SG16	545	328	148	546	147	199	124	65	29	-4	ε_{max}
SG17	44	272	495	495	44	225	107	41	33	0	ε_{min}
SG18	100	135	255	266	89	88	53	36	13	14	ε_{min}
SG19	654	591	569	658	555	51	177	161	8	-11	ε_{max}
SG20	570	539	593	626	537	44	166	153	7	37	ε_{min}
SG21	587	443	243	590	241	174	142	80	26	5	ε_{max}
SG22	246	437	663	664	245	209	155	94	31	2	ε_{min}

(pink) The stress values are merely informative once the material is not in the elastic region

Table 5 - Strain and stress values for each point scored in the project pressure.

Pressure of Project - 170 Kgf/cm2				3rd Stage			Average of the values during the landing				
Point	ε_1 (μm/m)	ε_2 (45) (μm/m)	ε_3 (μm/m)	ε_{max} (μm/m)	ε_{min} (μm/m)	γ_{max} (μm/m)	σ_{max} (MPa)	σ_{min} (MPa)	σ_{cis} (MPa)	Angle	Direction
SG1	656	466	145	665	137	264	151	72	40	7	ε_{max}
SG2	125	328	503	503	124	190	114	58	28	-2	ε_{min}
SG3	498	423	360	499	360	74	129	107	11	0	ε_{max}
SG4	444	437	422	445	421	12	120	117	2	10	ε_{max}
SG5	2562	455	-1005	2591	-1034	1812	489	-55	272	-5	ε_{max}
SG6	164	12	-131	164	-131	147	26	-17	22	-1	ε_{max}
SG7	37	9	-20	37	-20	28	7	-2	4	0	ε_{max}
SG8	696	526	375	697	375	161	170	123	24	-2	ε_{max}
SG9	-729	448	2435	2486	-780	1633	483	-7	245	7	ε_{min}
SG10	197	59	-67	197	-67	132	37	-2	20	-1	ε_{max}
SG11	-32	-4	14	15	-32	23	1	-6	4	-7	ε_{min}
SG12	397	564	728	729	397	166	178	130	24	0	ε_{min}
SG13	1	168	364	364	0	182	77	23	27	3	ε_{min}
SG14	1740	531	-418	1748	-426	1087	347	21	163	-3	ε_{max}
SG15	-41	36	134	135	-41	88	26	0	13	4	ε_{min}
SG16	443	263	92	444	91	176	99	47	26	-4	ε_{max}
SG17	35	216	397	397	35	181	86	32	27	0	ε_{min}
SG18	78	93	181	193	66	63	46	27	9	17	ε_{min}
SG19	524	517	447	535	435	50	147	128	7	21	ε_{max}
SG20	465	436	485	516	434	41	136	124	6	37	ε_{min}
SG21	416	337	208	418	206	105	103	71	16	7	ε_{max}
SG22	196	351	532	533	196	169	125	75	25	2	ε_{min}

(pink) The stress values are merely informative once the material is not in the elastic region

CONCLUSIONS

The theoretical analyses were executed by UNITÉCNICA using manual methods and the finite elements method (programs ANSYS, [4]); the strain gage test was executed by CDTN and with the participation of JARAGUÁ, CTMSP and IBQN (see [2]). The hydrostatic equipment final test was performed at JARAGUÁ, equipment manufacturer, and as followed [1].

The comparison was made for the case of the project pressure that has great interest and whose values always have acceptable values in the project code; for the test condition, the code doesn't present acceptable for the secondary stresses and, for the operation condition, the equipment internal pressure is smaller than the project pressure.

The values presented in Table 6 are the calculated value (S1) obtained according to [1] and the measured value (S2) was obtained according to [2].

It was considered acceptable a variation of ±15% among the values of measured and calculated stresses.

Table 6 – Stress obtained by analysis and measurement.

Point	S1	S2	(S2/S1)
SG1	161	149	0,92
SG2	124	110	0,89
SG3	118	117	0,99
SG4	106	114	1,08
SG5	459	449	0,98
SG6	32	28	0,88
SG7	12	9	0,75
SG8	198	167	0,84
SG9	459	441	0,96
SG10	37	38	1,03
SG11	12	5	0,41
SG12	198	179	0,90
SG13	77	73	0,95
SG14	269	285	1,06
SG15	47	35	0,75
SG16	118	98	0,98
SG17	97	84	0,87
SG18	122	51	0,42
SG19	169	141	1,14
SG20	132	127	0,96
SG21	117	114	0,97
SG22	134	122	0,98

The calculated value for SG7 and SG11 is 12 MPa. The obtained results were of 9 and 5 MPa in the studied areas. These values are a little below those expected; however, the differences are small in relation to the stresses that act in the component (about 10 MPa in relation to the other values, in general, above 100 MPa).

The stress value measured for the region of SG18 was of 56 MPa, and is below the expected value (122 MPa). Analyzing the test results for the several logged pressures (45 MPa for 140 kgf/cm^2, 51 MPa for 170 kgf/cm^2 and 63 MPa for 210 kgf/cm^2). One can observe that the values are quite consistent what indicates that there was not any problem with the strain gage fastened in the region.

In the finite elements analysis, the heaters region was modeled being adopted an equivalent value for the elasticity module region aiming at simulating the existent holes for the mouthpieces heaters. Besides, in the analyzed model, the holes for the heaters assembly were not considered and it can alter the stress values calculated in the region.

Therefore, it is possible to affirm that such procedure is more conservative, resulting in much higher stresses than the real existing ones.

One can conclude, that the measured and calculated values are much more adjusted.

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