THE USE OF TITANIUM TUBES IN FRENCH SEA-WATER COOLED NUCLEAR PLANT CONDENSERS

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Magnitude of the French Nuclear Plant Construction Programme

Electricité de France has started the construction of 34 x 900 MW nuclear units and 16 x 1300 MW units, and commissioning, that started in 1977 with the two FESSENHEIM units, is taking place at the rate of 5 to 6 units per year (appendix one gives the list, location and commissioning dates of the French nuclear plants).

Sea-Water Cooling

Some of those nuclear plants will be sea-water cooled : GRAVELINES (6 x 900 MW units) and LE BLAYAIS (4 x 900 MW), PALUEL, FLAMANVILLE (each 4 x 1300 MW) and others are now planned (PLOGOFF, PENLY).

Specific Problems Attached to the Use of Sea-Water ; Selection of Condenser Tube Material

The safeguard of steam generator integrity implies high cycling water purity and, therefore, a virtually absolute tightness of the condenser tube barrier between the sea-water and the water-steam thermodynamic system. The overall surface of this barrier is about 5 x 10^4 m2 (5 ha) per 900 MW unit, and 7 x 10^4 m2 (7 ha) per 1300 MW unit. Any leak in this barrier, allowing an admission of sea-water of about 1 litre per hour, makes it necessary to stop the unit ; it would, indeed, be possible to process the so polluted condenser extraction water, but a new condition would then be added to the operation, and a risk of sodium hydroxide release, liable to favor caustic corrosion, or other chemicals, would be added.

Further to a serious technical and economic investigation, EdF directed its efforts, since 1974, to the construction of "zero leak" condensers with the use of titanium tube bundles, a material that adds to interesting physical properties an excellent resistance to :

a) corrosion by chemical agents, and in particular by sea-water at the usual temperatures and by non-condensable gas cooler ammoniated steam ;

b) erosion-corrosion, both by sea-water up to a 3 m/s flow-rate and by high velocity (200 m/s) wet steam.

Taking into account the experience gained from laboratory and plant tests, the tubes are rolled-welded, with a thickness set at 0.5 mm, and 0.6 mm for impact tubes (6 % of the total number).

Further more, to avoid any leak due to tube expansion in the tube plates, the latter are made of twin plates with an intermediate space filled with de-mineralized water under slight overpressure, acting as a hydraulic barrier. Another solution used for FLAMANVILLE consists in providing, in the middle of single tube-plate borings, intercommunicating recesses, also filled with overpressurized de-mineralized water.

EdF Experience in the Use of Titanium for Plant Condensers

Electricité de France kept itself well informed of industrial tests and experiments made in the World regarding the use of titanium for sea-water cooled condenser tube bundles.

To that knowledge, EdF added, from about 1970, its own investigations, mostly made in its laboratories, such as SAINT-DENIS and LES RENARDIERES, but also in cooperation with the CEA (Commissariat à l'Energie Atomique). In TOULON station, these investigations being complemented by behaviour tests run on models and in some thermal plant condensers.

Those investigations were made in close collaboration with tube manufacturers, in particular with Société VALLOUREC on the one hand, and with condenser manufacturers : DELAS-WEIR, PECQUET-TESSON and MUNCH.

1. Laboratory research and testing

- Determination of the chemical, metallurgical and mechanical characteristics of the tubes and of the tube sheet metal.

- Tests of tubes
  . Check their strain capacity (flaring and flattening tests).
  . Check the possible effect of coloured oxides at tube surface.
  . Fatigue characteristics by rotating beam tests on 330 mm tube sections with a length of 100 mm submitted to a constant torque.

The fatigue-limit curve up to 2.10^7 cycles was set for the various tested tubes. It showed that the fatigue cracks on welded non-annealed tubes initiated most of the time in the welded area, but that the $\frac{\sigma D \text{(endurance limit)}}{Rm \text{(tensile strength)}}$ value was not significantly affected and was about 0.4 for most of the tested tubes.

The fatigue characteristics were not at all affected by the presence of sea water or ammonia, contrary to the results obtained with copper alloys tubes submitted to the same fatigue corrosion tests for the sake of comparison.

- Determination of the optimum rolling expansion parameters : type of tool, expansion torque, cleanness of the contact surfaces, lubrication and checking of the leak tightness to a 2 bar water overpressure or 1 bar helium pressure.

Since tightness problems were faced when assembling the first twin-plate condensers, a systematic investigation was started and is still going on. It covers the study of the following factors, regarding tightness measured with a device that provides the pressure level of pressurized air leaks between the tubes and the plates : tube and plate nature and mechanical characteristics, tube thickness and tube and plate hole geometric tolerances, expansion torque, circumferential and longitudinal roughness, presence of a twin plate and order in which expansion occurs.

- Determination of conditions of tubes welding on tube sheet plated with titanium.

- Pull strength and alternated bending tests ; Checking of the permanent strain of the holes.

- Examination of models made by the manufacturers to qualify the fabrication processes.

- Investigation of the condensation process on titanium tubes, the heat transfer characteristics, the fouling of the tubes, the effect of chlorination, and of the resistance to abrasion in sea-water containing injected sand (0.7 g/l) as a function of the flow-rate (up to 3 m/s).

- Corrosion tests during periods up to 20 000 hrs in natural sea-water (North and Mediterranean Sea).

Inspection of the Cu Al 9Ni 5Fe 3Mn and Cu Al 9Ni 2Fe 1Mn alloy tube plates showed some light damage near the tubes, mainly due to aluminium loss. This damage does not seem to be increased by a continuous chlorine injection (1 g/m3).

Cathodic protection was imposed on some assemblies, up to 0.900 V/SCE and the potential was determined in terms of the distance from the tube input and of the time. The current required to provide the plate imposed potential was followed. The high potential caused a serious tube hydriding, with some local crumbling. On the other hand, any plate corrosion near the tubes disappeared, as expected.

An electro-chemical laboratory study allowed a better knowledge of the coupling risk of various plate materials in relation with water inlet turbulence, chlorine addition and cathodic protection. The conclusions are similar to those of Japanese research workers who recommend a cathodic protection of the plate at a potential of 0.450 to 0.700 V/SCE to avoid plate corrosion by coupling, while avoiding titanium hydriding.

2. Industrial manufacturing and tube behaviour tests on models

2.1. A model was put into service on unit 2 of DUNKERQUE sea-water cooled thermal plant at the beginning of 1976. This model, designed by DELAS-WEIR and built by MUNCH comprises 660 rolled-welded tubes made by TIMET and VALLOUREC. These tubes, with a diameter of 19 mm, 0.5 mm thickness, 1 m length, are expanded in twin tube plates 80 mm apart from each other on the inlet side, and 4 mm on the outlet side. The condenser is steam fed by bleeding off from the turbine. This model, that represents the GRAVELINES condenser, was successfully and many times "thermal shock" tested with steam at 30°C and 100°C alternatively, and it allowed validation of the design and development of the construction and assembling of the tubes and tube plates.

The model was kept working to follow its endurance strength and to make cathodic protection tests and tube plate resistance checks under the influence of electric coupling between the tube plate titanium and copper-aluminium.

2.2. Semi-industrial model comprising a full cluster of the 1300 MW condenser of PALUEL plant (that has 24 clusters).

This model, built at the end of 1977 by PECQUET-TESSON, comprises 3461 x 19 mm Ø, 0.5 mm thick tubes, expanded, on one end in a twin tube plate made of an assembly of one copper-aluminium plate with 5 % nickel and one plain steel plate with a 60 mm spacing ; on the other end, the tubes are expanded and welded on a steel plate, plated with a titanium sheet (composite plate, height 4035 mm, width 1360 mm, thickness : steel 28 mm, titanium 5 mm, manufactured by "Nobel-Explosifs").

This model, fitted up in GENNEVILLIERS thermal plant, successfully passed resistance under 40 to 105°C thermal cycles.

After some weeks of operation of this model, that was then used as an auxiliary turbine condenser, some impact tube breaks were noticed, due to vibrations under wind excitation. After repair, anti-vibration slats were fitted.

2.3. "Conti" model to study the tube behaviour in the high speed wet steam flow.

The examination of titanium mechanical features, and in particular the low modulus of elasticity, the technico-economic selection of a small diameter (19 mm Ø) thin (0.5 mm) tube for GRAVELINES plant, and finally the titanium test tube breakage that occurred in CHOOZ plant, on the one hand, and copper alloy breakage in TIHANGE (BELGIUM) on the other hand, led EdF to starting an important programme for the study of condenser tube wind excitation.

While the phenomena of aero-hydro-elastic excitation of a tubular bundle by single-base fluids are getting better known, the position is different as regards very wet, high velocity and low specific weight steam, as is found in condensers. That is why the decision was taken, at the beginning of 1976, to build a model to study the behaviour of bundle tubes subject to a high speed wet steam flow (up to 300 m/s). The tube bundle is represented, in its most exposed part, by some hundred tubes of actual length (up to 15 m) supported by intermediate plates the spacing and number of which are adjustable.

This model allowed testing of the GRAVELINES, PALUEL and BUGEY condenser bundles. The tests showed that these tubes would have vibrated, in winter time, with the condenser operating at low pressure (below 40 mbar). Seeing these results, it was decided to either alter the intermediate plate distribution or to put anti-vibration bars.

3. On-site behaviour tests in plant condensers

The titanium tubes were distributed over brass bundles when tubing or re-tubing the condensers. These tests are still going on :

a) Since July 1971, at DUNKERQUE plant, unit n° 2, 44 tubes external diameter 18 mm, 0.5 mm thick, 34 of which are seamless and 10 welded. These tubes are expanded in copper-aluminium tube plates with 2 % nickel. No incident was reported at the end of 1979, after 123 000 hours of use.

b) Since May 1973, at MARTIGUES plant, unit n° 3, 500 rolled-welded tubes, external diameter 20 mm, 0.5 mm thick, expanded in copper-aluminium tube plates with 2 % nickel. No incident reported at the end of 1979, after 40 000 hours of use.

c) Since June 1974 and March 1975, at BOUCHAIN plant, units n° 1 and 2, respectively (atmospheric cooling towers). Twice 2000 rolled-welded tubes expanded in steel plates. No incident reported after 63 000 and 59 000 hours of use.

Finally, let us mention the unfortunate test, but rich in information, made at CHOOZ plant : 350 titanium rolled-welded tubes, fitted as impact tubes to replace brass tubes eroded by high flow-rate wet steam, had to be removed soon after they were fitted, as a result of contact between tubes and breaks due to vibrations resulting from wind excitation.

Selection of Materials - Manufacturing Experience

1. Tube

The tube manufacturing specification is based on the U.S. ASTM B 338 standard, complemented by the following data :

- . the titanium used corresponds to grade 2 ;
- . after welding, the tubes are annealed at a minimum temperature of 600°C in an inner and outer argon atmosphere ;
- . any tube showing a flaw equal to, or greather than 0.1 mm is discarded. To comply with this specification, the non-destructive checking comprises an Eddy currents test and, since the end of manufacture of GRAVELINES, unit 1, tubes, an ultrasonic check, since it was noticed that the Eddy currents test might not "see" a slow drift in weld quality.

2. Tubular plate and tube expansion

The selected material, on sea-water side, is a copper-aluminium alloy with 5 % nickel, to get high mechanical features, better adapted to thin titanium expansion.

When expanding the tubes of GRAVELINES plant, unit 1, and in order to facilitate compliance with the strict expansion water and air tightness criteria, the tube/plate bonding was improved by machining, in the bore, some circular groves of a few tenths of mm, in which the titanium is inlaid when expanded.

Another type of tube plate is now under test on a model. This is a single plate in which each bore is recessed at mid-thickness. All recesses are intercommunicating and filled with de-mineralized water under slight overpressure, as a sealing barrier.

On the other hand, on unit 2 of PALUEL plant, one of the copper-aluminium plates will be replaced by a steel plate (4.1 m x 5.2 m, 28 mm thick), plated with a sheet (5 mm thick) of titanium. After expansion, the titanium tubes will be welded to the titanium sheet.

Conclusions

The present operational results and various analyses confirm the good behaviour of titanium tubes and copper-aluminium plates in sea-water, whatever the latter quality and degree of pollution.

The manufacturing and control problems of titanium tubes, their fitting inside condensers and mechanical strength during operation, seem to be overcome despite the thickness of such tubes : 5 mm.

The success in using titanium tubes for sea-water cooled nuclear plant condensers is a serious contribution to the proper availability of these plants and to the success of the French electro-nuclear programme.

THE FRENCH ELECTRO-NUCLEAR PROGRAMME

Name of plant and unit n°	Type of reactor	Net electric power in MW	Condenser cooling	Year of Commissioning
MARCOULE G2	U.N.G.G[(1)]	38	River	1959
MARCOULE G3	"	38	"	1960
CHINON 2	"	200	"	1965
CHINON 3	"	480	"	1967
SAINT-LAURENT 1	"	480	"	1969
SAINT-LAURENT 2	"	515	"	1971
BUGEY 1	"	540	"	1972
MONTS d'ARREE (EL4)	HWGGR[(2)]	70	Lake	1967
CHOOZ	PWR	310	River	1970
FESSENHEIM 1	"	880	"	1977
FESSENHIEM 2	"	880	"	1978
BUGEY 2	"	920	"	1979
BUGEY 3	"	920	"	1979
BUGEY 4	"	900	Cooling tower	1979
BUGEY 5	"	900	" "	1979
TRICASTIN 1	"	920	River	1980
GRAVELINES B1	"	920	Sea-water	1980
DAMPIERRE 1	"	900	Cooling tower	1980
TRICASTIN 2	"	920	River	1980
GRAVELINES B2	"	.920	Sea-water	1980
DAMPIERRE 2	"	900	Cooling otwer	1980
TRICASTIN 3	"	920	River	1980
GRAVELINES B3	"	920	Sea-water	1981
DAMPIERRE3	"	900	Cooling tower	1981
TRICASTIN 4	"	920	River	1981
SAINT-LAURENT B1	"	880	Cooling tower	1981
LE BLAYAIS 1	"	920	Sea-water	1981
GRAVELINES B4	"	920	Sea-water	1981
DAMPIERRE 4	"	900	Cooling tower	1981
SAINT-LAURENT B2	"	880	" "	1981
LE BLAYAIS 2	"	920	Sea-water	1982
CHINON B1	"	880	Cooling tower	1982
CHINON B2	"	880	" "	1982
LE BLAYAIS 3	"	920	Sea-water	1982
PALUEL 1	"	1285	" "	1983
LE BLAYAIS 4	"	920	" "	1983
PALUEL 2	"	1285	" "	1983
CRUAS 1	"	880	Cooling tower	1983
CRUAS 2	"	880	" "	1983
CRUAS 3	"	880	" "	1984
PALUEL 3	"	1285	Sea-water	1984
SAINT-ALBAN 1	"	1295	River	1984
CRUAS 4	"	880	Cooling tower	1984
GRAVELINES C5	"	920	Sea-water	1984
FLAMANVILLE 1	"	1285	" "	1985
CATTENOM 1	"	1280	Cooling tower	1985
GRAVELINES C6	"	920	Sea-water	1985

Name of plant and unit N°	Type of reactor	Net electric power in MW	Condenser cooling	Year of Commissioning
PALUEL 4	PWR	1285	Sea-water	1985
FLAMANVILLE 2	"	1285	" "	1985
CATTENOM 2	"	1280	Cooling tower	1986
CHINON B3	"	880	" "	1986
SAINT-ALBAN 2	"	1295	River	1986
BELLEVILLE 1	"	1280	Cooling tower	1986
CHINON B4	"	880	" "	1986
NOGENT 1	"	1280	" "	1987
GOLFECH 1	"	1280	" "	1987
BELLEVILLE 2	"	1280	" "	1987
GOLFECH 2	"	1280	" "	1988
PHENIX	FAST.(4)	233	River	1974
CREYS-MALVILLE (Super-phenix)	"	1200	River	1983

(1) UNGG : Natural uranium reactor, graphite moderated and carbon dioxide cooled.

(2) HWGGR : Carbon dioxide cooled heavy water reactor.

(3) PWR : Pressurized water reactor

(4) Fast : sodium cooled fast neutron reactor.

FRANCE
NUCLEAR POWER STATION