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LIFE CYCLE COST EVALUATION OF CARBON STEELS, AUSTENITIC AND DUPLEX STAINLESS STEELS FOR STORAGE TANKS

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ABSTRACT

Due to its availability and low cost, carbon steel has been used for decades to build storage tanks. The main applications were petrochemical industry, food industry, water treatment units and parachemical industry.

Nevertheless, as this material is readily oxydable even in the atmosphere, painting and coating are often to be applied to protect it. For the time being, the use of coated carbon steel remains a routine practice, but detailed analysis of capital investment cost as well as life cycle cost demonstrate that stainless steels are cost competitive. Among these materials, duplex grades, thanks to their higher mechanical properties, appear to be less expensive than coated carbon steel.

The paper presents an extensive and detailed analysis of the manufacturing and maintenance costs for storage tanks made of various materials including several carbon steel grades and stainless steels either austenitics and super-austenitics or duplexes and super-duplexes.

A friendly software has been developped which permits to calculate and compare automatically investment and life cycle costs of tanks made of different materials. The simulation is based upon API (USA) and CODRES (France) calculation codes ; moreover, taylor made simulations may also be achieved.

INTRODUCTION

Due to its availability, low cost and easy fabricability even in non developped countries, carbon steel (CS) has been used for decades to build storage tanks. The main applications were petrochemical industry, food industry, water treatment units and parachemical industry.

Unfortunately, this material is readily oxydable even in the atmosphere and in weak environments, so that its lifetime is often limited to short periods unless it is protected or its initial thickness is very important.The bad corrosion resistance of CS is due to the fact that iron is able to form a stable and protecting oxide film onto its surface only when pH is situated between 9.5 and 12 and temperature near ambient ; such conditions are rarely encountered in practice. In addition, depending on the actual pH value, oxygen coming from air may play various effects. Indeed, as soon as pH is lower than about 10, oxygen induces a passivation of aerated zones while dearated areas become active (they dissolve) due to a strong galvanic coupling ; such a process often occurs in storage tanks at the interfacial area between the liquid and the atmosphere. Moreover, in caustic environments, if iron is able to passivate when pH is higher than 12, it corrodes rapidly at pH higher than 13 either due to uniform corrosion or to caustic cracking, depending on temperature and residual stresses.

In conclusion, CS is generally not corrosion resistant enough so that it has to be protected either by means of electrochemical techniques (cathodic protection by sacrificial anodes or applied current) or by means of coatings. The both techniques are more or less efficient and necessitate a close control and regular maintenance, without having always a sufficient safety margin. This justifies the growth of stainless steels use for storage tanks now.

STEPS OF THE COST ANALYSIS STUDY

Calculation of the minimum thickness value

- Mechanical properties :

Study and fabrication of low internal pressure storage tanks are governed by rules and standards which take into account provisions considered as minimal towards safety. These rules concern notably design and dimensioning of constitutive elements of the storage tanks like shell, bottom, roof, accesoories (piping, flanges, nozzles, openings, ladder ...).

Originally, these standards have been developped for the storage of oil and oil based products but they may be adopted with equal safety and economy by other industries and for the storage of other products. The main concerned applications are food industry, chemical industry and water treatment units.

The most well known and most widely used standards for designing cylindrical storage tanks are the followings :

- CODRES standard (French)
- API 650 standard (American)
- BS 2654 standard (British)
- DIN 4119 standard (German)

Concerning the wall plates dimensioning, the standards specify a minimal thickness which depends on the tank part considered and on the tank dimensions, the characteristics and the height of the fluid stored, and the mechanical properties of the material used (yield strength, tensile strength, Young modulus).

The rules which specify the minimum shell plate thickness for the CODRES and API 650 standards are the followings :

• CODRES :

$$e_v(i) = \frac{[\rho \cdot G\,(H(i) - 0{,}3) + P] \cdot 10E\text{-}6 \cdot D}{2 \cdot f} + c$$

where

$e_v(i)$ is the minimum thickness for the course under consideration (in mm)
ρ is the maximum density of the fluid stored (in kg/cu.m)
G is the gravitational acceleration (in m/sq.s)
H(i) is the distance from the bottom of the course under consideration to the maximum liquid height (in m)

P is the design pressure (in Pa)
D is the tank diameter (in mm)
f is the allowable design stress (in Mpa)
c is the corrosion allowance (in mm)

- API :

$$Td = \frac{2.6D(H-1)G}{Sd} + CA \qquad Tt = \frac{2.6D(H-1)}{St}$$

where

Td and Tt are respectively the design shell thickness and the hydrostatic test shell thickness (in inches)
D is the nominal tank diameter (in feet)
G is the design specific gravity of the liquid to be stored
Sd is the allowable stress for the design conditions (in lb/sq.in)
St is the allowable stress for the hydrostatic test condition (in lb/sq.in)
CA is the corrosion allowance (in inches)

The stress allowance specified in the above mentioned formulas take into account the mechanical properties of the material used for the tank manufacture. According to the different standards, it is defined according to the following rules:

- CODRES : f = the lesser of 260 or 2/3 of the yield strength

- API :

- for carbon steels : Sd = the lesser of 2/3 of the yield strength or 2/5 of the tensile strength
St = the lesser of 3/4 of the yield strength or 3/7 of the tensile strength

- for austenitic stainless steels:
Sd = the lesser of 0.3 of the yield strength or 0.9 of the tensile strength

CODRES and API allowable stress values for various CS and ASS are listed in table 1.

Tab.1 : Allowable stress values for various carbon steels and austenitic stainless steels

Material	CODRES	API 650	
	f (psi)	Sd (psi)	St (psi)
A516 gr 60	21,300	21,300	24,000
A516 gr 70	25,200	25,300	28,500
304L	19,300	21,000	22,500
316L	21,800	21,000	22,500
317LNM	28,100	24,000 (*)	27,000 (*)
UNS N08904	23,700	21,300 (*)	27,900 (*)
UNS 31 266 (**)	37,700	28,500 (*)	50,400 (*)

** extrapolated values*

*** UR B66 : USINOR INDUSTEEL tradename : 24Cr – 22Ni – 6 Mo- 2W – 1.5 Cu – 3 Mn - 0.4N*

Up to now, the API 650 standard does not take into account DSS. This standard covers only the austenitic stainless steels 304, 304L, 316, 316L, 317 and 317L since the 1995 edition.

For the DSS allowable stress determination, following the API 650, the costs comparison programme which has been developped calculates an extrapolated value following the two modes, on the one hand with the formulas used for CS, on the other hand with the formulas used for ASS, and let the user the possibility to select either the CS rules or the ASS rules.

The extrapolated allowable stress values for various DSS are listed in table 2.

Tab.2 : Allowable stress values for various duplex stainless steels.

Material	CODRES	API 650 (*)			
		Allowable stresses calculated from carbon steel formulas		Allowable stresses calculated from austenitic stainless steel formulas	
	f (psi)	Sd (psi)	St (psi)	Sd (psi)	St (psi)
UNS S32 304	37,700	34,800	37,300	26,100	52,200
UNS S31 803	37,700	36,000	38,600	27,000	58,500
UNS S32 520 (**)	37,700	44,000	47,100	33,000	72,000

** extrapolated values*

*** UR 52N+ (USINOR INDUSTEEL tradename) : 25 Cr – 7 Ni – 3.5 Mo – 1.5 Cu – 0.25N)*

For the manufacturing of storage tanks, the use of materials with high mechanical properties as DSS allows in many cases to reduce the wall thickness, notably for the shell plates. The thickness reduction generates savings at various levels. The more important cost reducings are in relation with material cost, welding cost and forming cost but the biggest savings are definitely due to an important reduction of welding time. The weight saving induces also a decrease of certain indirect costs, as plates transport cost or crane renting cost.

- Corrosion Resistance

The calculation rules which define a minimum wall thickness include a corrosion allowance which depends both on the general corrosion resistance properties of the material and on the predicted life time of the tank. The corrosion allowance thickness will be variable depending on whether an internal coating will be applied or not, and according to the steel grade used to build the tank.

Due to its low corrosion resistance in most media, even in weakly corrosive environments, carbon steel needs an internal coating to protect it. Several parameters such as chemical aggressivity of the stored products (components concentration, impurities, pH…) and storage temperature have to be considered for choosing the type of coating, which can be simply an epoxy painting or more resistant and expensive coating systems such as butyl rubber lining or resin bonded glass coating. Moreover, the fact that carbon steel is readily oxydable makes it unsuitable for atmospheric exposure and implies that a protection painting should be applied on the external surfaces.

Nevertheless, internal coating usage does not exclude the necessity of a corrosion allowance for carbon steels. In effect, lining permeability, presence of porosities or defects developping along service may induce locally a rapid corrosion of the CS. As a result, for safety reasons, it is necessary to apply an additional thickness on CS, notably on the shell top where the degradation risk of the lining is often the most important due to either condensation of agressive species or differential aeration processes. Indeed, coating damage appears on the interfacial zone between the stored liquid and the atmosphere. This leads to frequent repairs of coatings and implies to include a corrosion allowance for the base material made of carbon steel.

Because of their high corrosion resistance in a lot of media due to the formation of a passive film at their outer surface, ASS and DSS do not need any internal coating to protect them from the agressiveness of the stored product. Besides, for specific applications as water treatment or food industry, stainless steels provide a clean and hygienic surface.

The storage conditions and the medium aggressivity must be properly assessed in order to select the better grade of stainless steel. The designer must consider the corrosion type that might be encountered. If only general corrosion may occur, a corrosion allowance depending on the corrosion rate of the material and the required life time must be added to the minimum calculated plate thickness. When the chemical environment can lead to a risk of localised corrosion such as crevice, pitting or stress corrosion, the designer will choose a stainless steel grade completely resistant to corrosion in the considered environment. In case of crevice corrosion risk, an extra thickness may be applied to the minimum calculated thickness.

Another interest of the stainless steel use for storage tank construction is their very high resistance to atmospheric corrosion when appearance of the exterior surfaces constitute an important factor. ASS and DSS can retain their bright appearance under atmospheric exposure for many years and do not need any external painting. In addition, it is quite easy to decorate the tanks by drawing art pictures directly onto the external surface using grinding techniques ; when properly conducted then passivated by diluted nitric acid solution, such pictures may last for decades without any maintenance which is never the case for painted decorations.

- Cost Analysis for Fabrication

The configuration holded for the cost comparison programme corresponds to a vertical, cylindrical tank, with flat bottom and self-supporting roof . The roof designed without supporting structure can be conical or spheroidal and the bottom have a ring of annular plates.

The total investment cost is calculated in adding the costs for materials, fabrication and installation . In a first time, in order to simplify the calculation, only the manufacture of the main components (shell, bottom, roof) corresponding to the tank structure have been taken into account. All the accessories such as piping, flanges, openings, ladder are not integrated into the investment cost. The capital cost are decomposed as follow :

• **material cost** : it corresponds to the plate costs, depending on the total calculated weight. The plate thickness is determined using the selected code (CODRES or API) and the basic parameters like tank dimensions, fluid density and corrosion allowance. For CS, the nominal shell plate thickness may be increased of 25% in order to prevent cracking of brittle coatings as a consequence of lack of rigidity of the base material. Moreover, the plate dimensions are optimized in accordance with the maximum dimensions of the plates which can be produced in USINOR INDUSTEEL works.

• **cutting and forming costs** : these fabrication costs include shell plates and roof plates forming. Roof forming costs include plate cutting, spherical cap welding, spherical cap and segments pressing, assembling, edge preparation and final cutting, dimensional control and packing.

Compared to CS, stainless steels forming leads to an extra cost due to slightly higher welding costs and higher cutting costs, and for duplex grades higher pressing costs in relation with their high mechanical properties.

• **welding cost**: the welding process used is coating electrode, which correspond to a typical welding process for field construction. The welding operations include edges preparation, dye-penetrant control, installation, welding (including labor time and filler metal cost), grinding, backing pass and control operations. A multipying factor 1,15 is applied to welding time for duplex stainless steels.

Due to their high mechanical properties, duplex grades can provide economic benefits through welding operations. Indeed, the wall thickness reduction permits to use less filler metal and to reduce labor time. Besides, handle and installation of the plates are easier due to the use of lighter components.

• **coating costs**: internal and external protective coatings can be used to protect the tank surfaces, depending on the steel grade selected, the stored product and the external environment.

For internal coating, a choice between several types of linings such as for example vinylester epoxy resin or rubber butyl is offered to the user. For CS, an extra thickness of about 25% can be applied to increase rigidity. The coating cost depending on the total coated area includes surface preparation, material cost, labour cost and control (of thickness, porosity, hardness, welds …).

The protection of external surfaces of CS tanks must be ensured by painting. The successive operations in order to obtain high-quality coating able to protect durably the tank surfaces consist in surface preparation (grinding, zincing), and applying of primer, reinforcing and finishing coats.

According to the environment, external painting may be applied on stainless steel tank. Generally, stainless steel grades do not need any external protection. Nevertheless, painting may be used when severe conditions are encountered (marine atmosphere for seaside buildings made of low alloyed stainless steels). In fact, most often, the selection of a higher corrosion resistant grade is not more expensive than using a basic stainless steel with painting. Whatever, painting costs are less important for stainless than for CS because they require more simple surface preparation (only wall sanding and applying of primer and finish coats).

Coating cost constitutes an important part of the total investment cost (from 40% to 65% depending on the kind of lining) so that selecting stainless steels which do not need to be coated lead to very important economical benefits. The biggest capacity tank, the highest savings.

• **pickling cost** : this operation concerns only stainless steel tanks which should be decontaminated after all the manufacturing and erecting operations. For the internal surfaces, pickling cost includes cleaning, pickling, passivation, rinsing and effluents treatment. Concerning the external surfaces, only welded joints have to be pickled.

Pickling operation constitutes an extra cost for stainless steel tanks, but in fact this cost is much lower than cost induced by the coating operations on CS.

It is important to stress that all considered costs were obtained after extensive and deep discussions with specialists of each operation. Coating costs are estimated by surface unit and labor costs can be easily adapted according to the country where the tanks will be made.

- Life Cycle Cost (LCC)

For a pertinent comparison between alternative materials of construction, the LCC should be considered. This approach implies to assessing the investment costs and the maintenance costs over the whole life of the tank.

Maintenance costs are mainly related to CS tanks and more precisely to internal and external coatings since these organic based components are sensitive to ageing in atmosphere and chemicals. Stainless steels are virtually immune if they have been correctly selected.

Maintenance costs should be evaluated in terms of :

- *inspection frequency*

- *repair or replacement of coatings* : industrial experiences showed that external painting must be completly replaced at regular periods with a maximum periodicity of 10 years. On the other hand, maintenance operations on internal coatings correspond often to local repairs but this induces extra costs compared to the initial coating cost. Indeed, operations to be conducted before repair include full cleaning of the tank, scaffolding erection, installation of lighting and so on, like if a whole replacement of the coating had to be done.The periodicity depends on the actual local agressiveness of the stored product

- *production loss* : when tanks are completely integrated in the production line, maintenance cost operations are increased due to the loss of production. Such a loss can be very high depending of the type of production. Very often, some tanks have to be duplicate in order to avoid production loss, but in this case, this increases investment costs. So, it it obvious that selecting a suitable stainless steel instead of a CS tank is a better solution.

LCC analysis of several industrial plants showed that maintenance cost of coated CS tank over its whole life represents considerable expenses which can be, for a long life time, much higher than initial capital cost. On the other hand, stainless steel use generally leads to suppress maintenance cost and needs only regular inspections.

LIFE CYCLE COST ANALYSIS SOFTWARE

An Excel® based software has been developped in order to calculate and to compare the LCC of tanks for different materials.

As soon as he has defined the basic tank data corresponding to its needs, the user has to enter the following parameters in any order :

- tank dimensions (capacity, tank diameter, roof slope for conical roof, cap diameter and R/D ratio for spheroidal roof)
- fluid density
- life cycle
- country, currency rate
- materials (grades, corrosion rate, material price, welding material price)
- calculation mode for duplex allowable stress
- plates dimensions (for each part of the tank)
- pressure : design pressure, loading (external tempory loading, snow effect)
- internal coating characteristics (tank parts coated, choice of extra thickness for rigidity, kind of liner, liner price)

- external painting characteristics
- maintenance (frequency, repared surface %, production shortage, extra cost)
- labour costs
- indirect costs like transportation, erection (scaffolding erection, crane renting)

As soon as these parameters have been validated, total investment cost, LCC and detailed cost data concerning all manufacturing operations and maintenance appear on the screen in a few seconds. Tabulated form or graph form may be selected.

Easy accessibility to parameters change makes this software very effective to conduct optimization of the tank dimensions. An example of simulation showing LCC for four materials is presented here-under ; the first screen picture of the software including the main parameters is presented in Fig. 1.

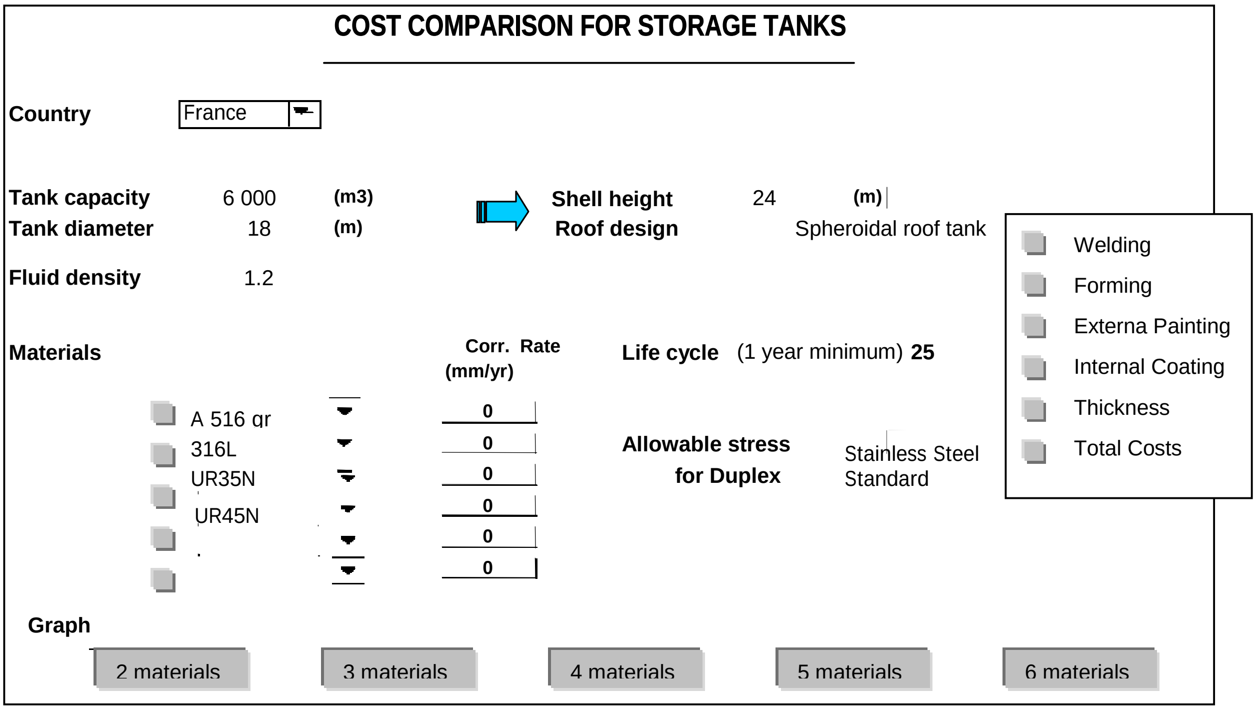

Fig. 1 : Main screen of the « CALRES » software

A516 gr 60 CS coated with vinylester epoxy resin inside and painted outside is compared with non coated 316L austenitic stainless steel, UR 35N (UNS S32304) and UR 45N (UNS S31803) duplex stainless steels. The tank of 6 000 m3 capacity (18 m diameter, 24 m height) is designed for 25 years service life. Maintenance and repair are planned with 5 years frequency (20% repared surface for each maintenance period) for the internal coating and 10 years frequency for external painting.

Table 3 and Fig.2 show the results of various costs including investment and LCCs for each of the four materials : the calculation was done using the following costs for plates (FF/kg) : 3,8 for CS, 14 for 316L, 13,5 for UNS 32 304 and 18 for UNS 31 803. These costs can be easily modified by the user. No extra thickness was taken into account for CS to prevent brittleness of the internal coating ; this option is very beneficial for the cost of the CS tank. The cost for internal coating was 900 FF /m2. The considered labor costs were 220 FF for construction, 245 FF for welding and 230 FF for control.

Table 3 : Sum-up of the main costs for 4 different materials.

UNIT : 1000 FF	A 516 gr 60	316L	UR35N	UR45N
Material cost	513	1885	1566	2086
Forming cost	188	221	227	227
Welding cost	1566	1638	1579	1560
Pickling cost	0	292	370	370
Coating + Painting cost	2164	0	0	0
Total investment cost	**4431**	**4036**	**3742**	**4243**
Maintenance cost	2925	0	0	0
Life cycle cost	**7356**	**4036**	**3742**	**4243**

These results demonstrate that the use of stainless steels for building stainless storage tanks does not induce investment costs higher than those for CS. More particularly, the use of basic duplex grade UNS 32 304 / UR 35N leads to about 15% savings.

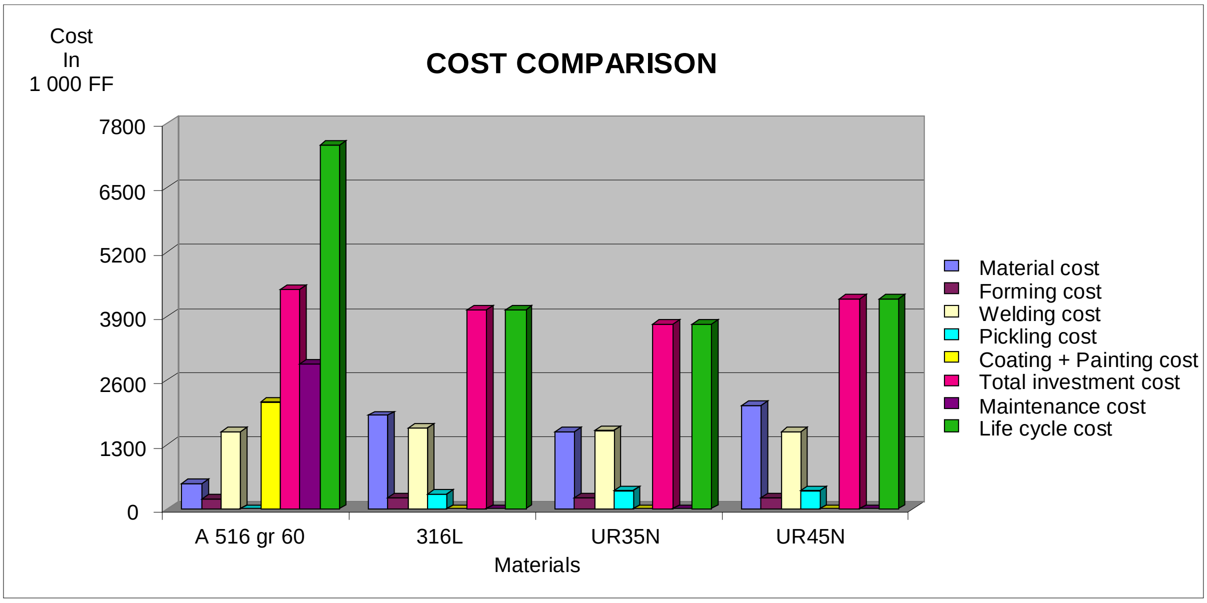

Fig.2 – Screen of the costs calculation.

Considering LCC , it appears that stainless steels are much more competitive than coated CS even when considering the very corrosion resistant UNS 31 803/UR45N duplex grade.

CONCLUSION

Due to a lack of corrosion resistance in many environments, CS tanks need to be protected by painting on their external surface and coatings on their internal surface. This implies heavy additionnal costs, especially in modern developped countries where labor costs are important. Moreover, coatings often need regular maintenance operations which, added to production shortage lead to a further cost increase.

Stainless steels in general are much more corrosion resistant than CS so that painting and coating are not necessary. Besides, selecting nitrogen containing stainless steels and more precisely duplex stainless steels allow , thanks to their high mechnical properties , to reduce the wall thickness of the tanks even though some calculation codes do not permit to take full advantage of these properties.

Fig. 3- UNS 32 304 and 31 803 Kraft Liquor Tanks (by courtesy of SUNDS DEFIBRATOR, Finland).

Nevertheless, cost analysis showed that not only the wall thickness reduction but much more savings related to welding operations (less weld material and reduced labor time) induced by the lower thickness account for important reduction of investment costs. Indirect costs like transportation and erection are also saved thanks to weight reduction.

A software taking into account the methodology of calculation described in the present paper has been designed for the French « CODRES » and the US « API » codes. Other codes will be introduced in the near future. As soon as the main parameters have been introduced in the main screens, investment and LCC comparison for up to 6 materials appear at the user’s fingertip in secondes together with detailed cost data. In addition, the sofware permits further cost savings since it optimizes the dimensions of the tank taking into account the initial size of as produced industrial plates.

Adding savings due to the absence of coatings to savings due to the better corrosion resistance of stainless steels lead to final investment costs which appeared very competitive compared to coated CS.

Among stainless stels, duplex grades thanks to their higher yield strength are even more cost effective than austenitics.

If one consider the LCC, our analysis clearly demonstrated that CS is never competitive, even if compared to the very corrosion resistant UNS 31803/UR 45N grade. Such an advantage provided by duplex grades is furthermore increased if production shortages are taken into account.

Numerous storage tanks made of duplex grades UNS 32304 and 31803 were built these last years for application in pulp and paper and chemical industry in replacement of coated CS. Several actual cost analysis conducted by end users quite confirmed the cost benefits induced by using duplex stainless steels instead of coated CS tanks. Particularly, investment costs were actually found to be comparable in the worst cases and generally lower for UNS 32304 grade. After only 2 or 3 years service, UNS 32304 and even 31803 were generally found to be cost much cheaper since maintenance operations were completely avoided.

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