3. Dillinger
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Dillingen

Titel:
ECOPRESS – Economical and safe application of modern high strength steels for pressure vessels

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1. Introduction

Manufacturing of PV is a world wide market and the decision to buy a PV is mainly governed by:

- economical aspects (e.g. low working costs, long life, reduced maintenance costs)
- technical aspects (high technology and quality workmanship)
- regulatory aspects (e.g. safety requirements against catastrophic failure)

The European strategy to encounter this challenge is to improve the competitiveness by developing the technical knowledge to apply new high potential steels like HSS-QT, \(^1\) TMCP \(^2\), and DUPLEX \(^3\) for economical PV-design and manufacturing. Although these steels, which have been successfully developed by the European steel industry during the past 3 decades, are available today, the full utilisation is restricted mainly due to a lack of experience resulting in conservative design rules for PV building with such steels. Figure I.1 shows the effect of the high safety factor put on such steels today, which results into a relatively high loss of possible design strength. To overcome these obstacles which are part of the new European PV design code EN 13445 the research project has concentrated on the application of the method Design By Analysis (DBA). Figure I.2 shows the advantage of this method in terms of utilization of higher design strength to derive the necessary requirements which have to be fulfilled for the application of the modern steels.

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1. High Strength Steel-Quenched and Tempered (Yield strength >460 MPa)
2. Thermo mechanical controlled rolled steels
3. Ferritic-Austenitic corrosion resistance steel
Before this background the project aimed at the extension of the European leadership in pressure vessel and steel manufacturing by providing recommendations that allow to utilise the full potential of these modern steels for safe design. It is supported by the European Pressure Vessel Research Committee (EPERC).

The major aims of ECOPRESS are summarised in Figure I.3 A consortium of in total 17 members (Figure I.4) which represents steel manufacturers, pressure vessel designers, producers and end-users together with industrial founded research institutes and universities has been working in this project.

**Figure I.2**: Advantage in terms of design strength when DBA is applied
An extensive small and large scale experimental test programme together with numerical simulation of a typical example pressure vessel has been performed to support the innovative development of structural models that allow the quantification of the most important limit state conditions:

- Brittle Fracture,
- Ductile Fracture and
- Ductile Instability.

**Figure I.5** give an overview on the project working strategy. Beside the possibility of direct use of the results by any end-user and third parties, it is on the way to implement the results into the next revision of EN13445.

The performed works were directly related to the life chain of a PV from **design over fabrication and testing to operation**. Within 8 work packages (WP1-8) each of this aspects was covered in a separate subtask. **Table I.1** gives an overview.

The project started with a review of existing national design limitations and design requirements for the application of the new steels for Pressure vessels and in comparison to that in related fields of application like steel structures (**WP1 and WP2**). A survey on material properties as available from former projects and welding possibilities was performed in addition. The latest trends in application of structural integrity concepts have been included in this work which was finished during the first year. Parts of this work served for the selection of steel grade and plate thickness and appropriate welding procedures. A new PWHT resistant welding consumable has been developed for P690. In **WP3** steels were procured and the weldments and the dished end were fabricated. The conditions in which the steels should be tested and the test methods were selected (**Figure I.6**).

This was followed by an extensive experimental program for all materials (**WP4**) applying both basic testing and fracture mechanic testing. It is stepwise performed, starting with the evaluation of Base Metal properties of QT-HSS, TMCP and DULEX, going on with welded plates in the As Welded condition and ending with tests on the PWHT condition. Additionally, tests in the cold formed (different degrees from 2 to 15 %) and aged status were performed. A specific test program was performed for TMCP steels with respect to the problem of cold forming of dished ends which cannot be heat treated (normalised) anymore after the cold forming. For DULEX 30 and 50 mm thick plates were examined and additionally plates in thickness of 4 and 6 mm were used to evaluate a material strain hardening law for bi-axial behaviour with bi-axial and bulge tests. All tests were evaluated statistically with respect especially to the problem of toughness correlation.
## Work Package 1
### Code reviews
- **Task 1.1**: typical design examples
- **Task 1.2**: manufacturing and material degradation
- **Task 1.3**: Structural integrity and End of Life design
- **Task 1.4**: Safety factors and Failure modes

## Work Package 2
### Design requirements
- **Task 2.1**: Functional requirements and geometrical properties
- **Task 2.2**: Fabrication effects (welding, forming, heat treatment)
- **Task 2.3**: Appropriate test methods applicable for new steels
- **Task 2.4**: Assumed loads, temperatures, environment and life time under static, dynamic, cyclic loading

## Work Package 3
### Welding
- **Task 3.1**: Selection of material welding procedure, consumables
- **Task 3.2**: Plate/Forgings-manufacturing and delivery and welding of test material
- **Task 3.3**: NDT and secondary stresses
- **Task 3.4**: Conformity with EN Welding Codes

## Work Package 4
### Material characterisation
- **Task 4.1**: QT-HSS plates and weldments
- **Task 4.2**: TMCP plates and weldments
- **Task 4.3**: Duplex stainless steel plates and weldments
- **Task 4.4**: Forgings of QT, Duplex
- **Task 4.5**: High strain rate
- **Task 4.6**: Statistical evaluation and correlations

## Work Package 5
### Modelling
- **Task 5.1**: new design aspects for new steels and design of test vessels
- **Task 5.2**: Quantification of typical welding and forming effects and FEM Simulation of residual stresses
- **Task 5.3**: Adoption of structural integrity concept, statistics, correlation
- **Task 5.4**: FEM Simulation for representative structural parts, vessels under typical load scenarios

## Work Package 6
### Validation
- **Task 6.1**: Fabrication of component like large scale specimen
- **Task 6.2**: Testing of component like large scale specimen

## Work Package 7
### Development of safety concept
- **Task 7.1**: Quantification of extreme loading parameters and other basic variables
- **Task 7.2**: Quantification of effects of material degradation
- **Task 7.3**: Statistical verification of structural integrity concept
- **Task 7.4**: Assessment of Life time and inspection intervals

## Work Package 8
### Design recommendations
- **Task 8.1**: Development of design tools for future code and practice implementation
- **Task 8.2**: Preparation of main project output for publishing

### Table I.1: Overview on Workpackages and Subtasks within ECOPRESS

See: [www.ecopress.org](http://www.ecopress.org)
Results have been used needed as input for the modelling and the development of a PV-specific safety concept developed in WP 5. As Design by Analysis is based on limit condition design principles, it was the task of WP5 to propose and develop calculation-models for the quantitative description of the most important limit states in PV design (Figure I.7) which are:

- Brittle Fracture,
- Ductile Fracture and
- Plastic Instability.

This work is supported by FEM simulation of full PV including cold deformed dished end made from TMCP and critical constructional details (Figure I.8).

The simulation of the wide plate tests have been used for the validation of the fracture mechanic approach in WP5.

A new models for brittle fracture is ready as a result of the project an will allow the inclusion of the HSS-QT- steels and the DUPLEX steels which have been exclude until nos. The ductile failure concept provides explanation how to perform a fracture mechanic analysis correctly for upper shelf behaviour, This could be important for the pre-calculation of the pressure tests with realistic failure assumptions. For the plastic instability case the focus was on the simulation of the advantage of using HSS with lower safety factor as could be possible with DBA.. The FEM calculations of the dished end demonstrate that highest cold strained areas are not subjected to pure tensile loading but more to bending loading, which makes the plastic instability case less likely to occur. FEM on a Duplex example vessel show the advantage of using stress strain curve with strain hardening against the linear elastic-ideal plastic material law proposed within the DBA method.

The new models were validated with the help of large scale component like wide plate tests on the HSS of the base metal, the As Welded plates and the Post Weld Heat Treated plates in WP6 (Figure I.9). These tests have been evaluated in view to the derivation of safety factors that allow to cover scatter and model uncertainties on a semi probabilistic basis analogous to the brittle fracture model used for welded steel structures (WP7) (Figure I.10).
Operational parameters of PV’s, like e.g. elevated temperatures, corrosion assisted mechanisms or other possibly degrading mechanisms have not been considered. However, from all results obtained within ECOPRESS, recommendations have been derived for all three types of materials related to the life cycle of a vessel (WP8). These recommendations are supported by a set of Background Documents which provide the full information on all results obtained within ECOPRESS.

The new models have been validated with the help of large scale component like tests with base metal plates of HSS, welded and PWHT plates in WP6 to evaluate safety factors that allow to cover scatter and model uncertainties (WP7). Finally within WP8 all results are used to provide recommendations with respect to a better utilisation of the new steels. In addition to the recommendations all results are described in Background Documents in detail. The Consortium Agreement clearly foresees a widespread dissemination of results by means of a CD-Rom, conference presentations, scientific publications and implementation into CEN-TC 54 standardization groups.

2. Objectives of the project

The intention of the consortium to perform this research project on the utilization of modern steels with the following objectives:

1. technical and economical optimization of pressure vessels made from this steels,
2. application of modern structural integrity models for the quantitative evaluation of pressure vessel limit conditions and inclusion of probabilistic reliability methods, which were used for the EUROCODES for steel structures (prEN1992),
3. to draw conclusions from the obtained results in a way that unnecessary conservatism existing in current rules can be removed,
4. to make proposals in form of technical reports, publication and presentation on special seminars on PV that allows to disseminate the results into public and influence the making of new standards.

was also a result of the discussions within the European PV-community represented by the European Pressure Equipment Research Committee (EPERC, here the Technical Task Force group TTF2, High Strength Materials).

It becomes obvious that highest impact from the expected project results will be achieved from the influence on the standardization work for the European standard EN13445, which is worked out within the CENTC 54 committee and the relevant working groups related to each
part of the standard. Before this background supporting actions to achieve this aim have been undertaken already during the time that the project was running as follows:

- the results are permanently discussed within a group of PV specialists in the frame of the EPERC (European Pressure Equipment Research Committee),
- two members of the ECOPRESS consortium are actively working as convener of Subgroups responsible for low temperature design (IWT, Peter Langenberg) and Design (Guy Baylac),
- same persons have become the convener of CENT54 working groups on Materials (JWG B, P. Langenberg) and Design by Analysis (TG DBA, G. Baylac),
- the industrial partner in the consortium are mostly working within PV-business and directly can exploit results for the promotion of PV made from new steels.

3. Scientific and technical description of the results

3.1. Overview of the specific project philosophy and working strategy

The project philosophy was influenced by the situation that EN13445 was officially published in May 2002 and included a proposal for performing Design By Analysis (DBA) as an alternative to Design By Formula (DBF) and allowing for a reduction of the safety factor on tensile strength from 2.4 to 1.875 (see Figure I.1 and I.2). The reduction of the safety factor was one of the important requirements for economical utilisation of modern High strength steels with yield strength higher than 355 MPa. Figure I.2 shows the potential gain in stress utilisation (higher pressure) or other way round reduced wall thickness and following reduced working costs especially from welding or avoiding PWHT.

The application of DBA on the other hand requires higher effort in design and testing (e.g. FE-analysis, 100% NDT, more testing) and requirements for steels evaluated here are of the over conservatively formulated due to lack of knowledge. An agreement within the consortium therefore was that:

- DBA is accepted for conventional steels but obstacles for the application on HSS, TMCP and DUPLEX must still be removed based on the results of ECOPRESS,
- Improvements on knowledge of materials properties after fabrication (welding, cold forming, PWHT) and quantitative description of limit state condition which must be avoided during lifetime of a vessel such as brittle fracture, ductile fracture and plastic instability must be used to support application of DBA,
- Implementation of the results into standards and open distribution of results into the pv-community must be guaranteed (see: Consortium agreement).
- DBF for the steels investigated with lower safety factor is a future task building up on experiences which can be achieve from the application of DBA:
4. Results and conclusions

The results of the ECOPRESS project can shortly be summarized as follows:

1. It was found that the most promising way of including the modern high strength steel into application now is the use of Design by Analysis (DBA). This option has become official part of the EN13445 during the project was running in May 2002.

2. The application of DBA requires specific provision for design, testing and materials. As main focus of ECOPRESS was on material and quantitative description of relevant limit state conditions such as brittle fracture, ductile fracture and ductile instability it is possible to use the achieved results from material testing, FEM and modeling to formulate this provisions. Two project partner act as convener of relevant CENTC54 Working groups (JWG B: Materials, P. Langenberg, IWT and TG DBA, G. Baylac) and started to integrate the results into the revision of EN13445.

3. Three limit states under static loading have been examined in respect to actual developments in the structural integrity derivation (e.g. SINTAP, 4th framework program that produced a European approach for deriving structural integrity based on fracture mechanics or the Basic Safety concept developed by MPA Stuttgart for German nuclear power reactors which contains a part that allows the calculation of ductile failure) and proposals have been worked out:
   a. The revision of the existing brittle fracture concept based on the experiences of the existing one and including the latest fracture mechanic analysis tools like master curve and transition temperature correlation and Failure Assessment Diagram and treatment of secondary stresses. With the help of this proposal it is possible to extend the existing limits on strength from max. 460 MPa to 690 MPa steels and to include Duplex steels.
   b. The methodology to predict ductile failure based on a fracture mechanics method for upper shelf behaviour and on an upper shelf toughness correlation between upper shelf Charpy toughness and the fracture toughness at the physical initiation point of stable crack growth.
   c. The reduction of the safety factor on tensile strength from 2.4 to 1.875 when applying DBA is supported from the results on plastic instability. Plastic instability as a failure is excluded by limiting the max. plastic strain at a critical point of the vessel to 5%. The intensive FEM calculation on an example vessel up to this criterion showed that with reduced safety factor as proposed when using DBA the modern steels could be economically utilized. In case of the plastic instability further investigations on the effect of geometrical imperfections are necessary to derive the true limitations.
   d. Cold forming of steels saves a lot of money and in case of TMCP any recovery from annealing at temperatures above Ac1 is not possible. This excludes TMCP from PV building because the heads can only be formed at temperatures below Ac1. One part of the project dealt with this problem and it could be demonstrated that the loading situation at highest deformed regions in a cold formed head is not pure tension but bending and is always below the loading in the cylinder. In combination with the material properties which were found to be sufficiently high (above the requirements) even after highest cold deformation, it seems to be most promising that TMCP heads could be used.
   e. Also for HSS and DUPLEX steels this result provides a basis for the discussion of reducing the existing limitations on cold forming.
4. Three types of modern steels, namely HSS (P500QL1 and P690QL1), TMCP(P420ML) and DUPLEX (2205) have been examined intensively. For each steel there were obstacles and reservations against utilization resulting from a missing knowledge and experience with this steels. The problem of possible material degradation from fabrication and the high Y/T ratio are often the main reason. The opportunity for repair is an important measure for the economic use of the steels. Finally it was found that forged parts from HSS are not available in the market. To demonstrate the effect of material degradation on the properties and to discuss the relevance for the safety of the vessel an intensive material testing program including the derivation of basic mechanical properties with standard tensile- and charpy test and an advanced program performing fracture toughness test was performed. The material was tested after different fabrication states like: As Welded, Post weld Heat Treated, Cold Formed , Aged. For HSS and DUPLEX this states have been produced artificially in the lab. For TMCP specimen have been taken directly from large dished ends containing weldments. The results from testing were used on the one hand to demonstrate the effect of material degradation and on the other hand to validate the application of master curve and transition temperature correlation for the new brittle fracture concept.

a. For HSS steels three major obstacles are existing. First the question of increasing Y/T ratio that strikes the limit state of plastic instability, second the exclusion from the simplified of material selection in EN13445. part 2, Annex B and third the problem of reduced toughness that might result from PWHT in the root of weldments. In case of P500, which is a steel that on the basis of ASME already can be fabricated and that European PV fabricators have a good experience in working with this steel, the ECOPRESS research result support that this steel normally has excellent mechanical properties also after fabrication. In case of P690 the mechanical properties showed also excellent results in toughness and weldability after fabrication. But more care than for P500 must be taken in case of welding where under-matching may occur if the true strength is too high above the nominal strength. This may affect the plastic instability. Second PWHT may cause a loss of toughness in the root of the weldments depending on the combination of base material composition (especially V-content) and welding procedure (energy, bevel preparation, welding speed). Here a new electrode with higher PWHT resistance was developed. It is recommended to select the alloying concept and the welding procedure carefully to avoid any detrimental effects from pick up of elements in the root that may cause a loss of toughness. The effect of cold forming on toughness seems to be lower as known for conventional steels and aging was no problem. Consequently it should be checked if the limitations on degree of cold deformation and on max. thickness from where PWHT must be applied could be changed. The new brittle fracture avoidance concept as described above was validated for P500 and P690 both on the resistance side as master curve and transition temperature correlation is concerned and on the component side by means of wide plate tests.

b. For TMCP it is well known fact that the base metal yields excellent toughness high above the nominal requirements. On the other hand there is no possibility to recover the same material properties after any process like welding or cold deformation. Only Post Form Heat Treatment can recover the properties somehow. Within ECOPRESS a huge variety of possible states of fabrication and recovery by PFHT was tested. The result was such that all possible cases except one were better than the requirements on toughness. The one case which fall below the requirements (20 %cold formed blank weld with notch in HAZ showed lower toughness) the properties could be recovered
by PFHT. Clearly, PFHT was also beneficial for all other cases. The TMCP steels can also be included into revised brittle fracture concept. As a consequence of the research it is now important to perform full scale pressure tests with cold formed dished ends to support this findings.

c. Duplex stainless steel is treated like an ferritic steels in terms of the limit conditions stated above. From the tests it could be demonstrated that the extremely good toughness with transition temperatures as low as for Ni-pressure vessel steels is reduced from welding but remains on a high level. Therefore it could be shown that the exclusion of DUPLEX from the simplified material selection to avoid brittle fracture in EN13445 part2, annex B is not necessary and that this steels shall be include in the revision of this standard. It was also shown in tensile tests that the ductility is better than for ferritic steels and that cold deforming degrees up to 7,5 % have only little influence on the ductility reserve. This enables the discussion of reducing the safety factor on strength in direction to the austenitic steels.

5. Dissemination of results amongst the PV public is planned by means of CD-ROM that can be distributed and includes all detailed results, by presentation during conferences as full session (e.g. MPA Seminar, 8. and 9.10. 2003, ESOPE conference Paris September 2004) due to the consortium agreement and a web site [www.Ecopress.org](http://www.ecopress.org) which will also contain results as download.

5. Dissemination of results

In Work package 8 it was discussed how the project results shall be worked out and who shall be addressed with the results. **Figure III.77** shows the plans for dissemination in terms of who shall be addressed. In that respect it is an important fact to mention that the consortium has agreed on an extremely open consortium agreement to allow for a full publication of the results by all partners. The most powerful way of influencing the PV-business is given by the introduction of the results into standards. Two project partners are convenor of relevant CENTC54 groups and have started to introduce the results into the process of first revision of EN13445. EPERC has become the leading European organisation for PV specialists and the ECOPRESS results will be distributed with the help of EPERC to the interested European PV-public. The web site produced for ECOPRESS will be kept for a while and information in terms of downloads will be provided there. This probably is the action undertaken which allows the whole world to get in contact. Finally every partners has gained from the research work first from the collaboration on a European level and second from the results which due to the open consortium agreement (all data will be distributed amongst the partners) can be used by every partner for his/her own purposes and marketing strategy.
Further the consortium has agreed on the following means of dissemination. They are divided into direct and indirect means. The direct means are those which will directly come out of the project as the result of it. **Figure III.79** gives an overview. The indirect means are those that will be undertaken by the project partners individually or in smaller groups. This indirect means are shown in **Figure III.80**.

**Figure III.77**: Dissemination overview

**Figure III.79**: Direct means of Dissemination
WP 8 Means of Dissemination (Indirect)

2. Indirect project deliveries and access

2.1 EPERC Bulletin, September (EPERC members)
2.2 Scientific Publications in journal, conferences (public)
2.3 Company-specific technical marketing information (customers)
2.4 Seminar on a national level using
   ECOPRESS presentations (customers public)

Figure III.80: Indirect means of Dissemination

From Figure III.79 one can see that the detailed result will be a set of Background documents (BDs). This will in total be a mass of over 1000 pages of paper, which cannot be printed in one book. Therefore all BDs are presented on a CDROM using a user friendly surface similar to the ECOPRESS web site. A synthesis report will be produced to allow for a quick overview to the results of ECOPRESS. The overview on all Background Documents is given in the following table.

<table>
<thead>
<tr>
<th>Backgr.-Doc. No.</th>
<th>Title</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Recommendations for the Economical and Safe Application of modern Steels for Pressure Vessels</td>
<td>Baylac, PSP, LTH, FCP, CMP</td>
</tr>
<tr>
<td>2</td>
<td>General description of testing types</td>
<td>RWTH, MPA, ITMA, VTT, LTH, KTH</td>
</tr>
<tr>
<td>3</td>
<td>Material and Welding data, properties and test results</td>
<td></td>
</tr>
<tr>
<td>3.1</td>
<td>High Strength Steels, P500 and P690</td>
<td>RWTH, DH, Industeel, MPA, ITMA, FCP, CMP</td>
</tr>
<tr>
<td>3.2</td>
<td>New welding electrodes for P690</td>
<td>AL</td>
</tr>
<tr>
<td>3.3</td>
<td>Forgings from High Strength Steel</td>
<td>Industeel</td>
</tr>
<tr>
<td>3.4</td>
<td>TMCP Steel</td>
<td>RR, VTT</td>
</tr>
<tr>
<td>3.5</td>
<td>DUPLEX Stainless Steel</td>
<td>KTH, LTH, Avesta, ITMA, MPA</td>
</tr>
<tr>
<td>4</td>
<td>Statistical test data analysis</td>
<td>VTT, RWTH, IWT, MPA</td>
</tr>
<tr>
<td>5</td>
<td>FEA modelling</td>
<td></td>
</tr>
<tr>
<td>5.1</td>
<td>HSS Example vessel</td>
<td>UP</td>
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<td>5.2</td>
<td>HSS Wide plate</td>
<td>ITMA</td>
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<tr>
<td>5.3</td>
<td>HSS Residual stresses</td>
<td>ITMA</td>
</tr>
</tbody>
</table>

See: www.ecopress.org
5.4 DUPLEX - Bulge and bi-axial tests, example vessel  
5.5 TMCP - Dished end and example vessel  
6 Component like tests  
6.1 HSS, Wide plate tests, P500 and P690  
6.2 TMCP, Notch bending tests  
6.3 DUPLEX, Bulge test  
7 Limit State Models  
7.1 Brittle Fracture  
7.2 Ductile Fracture  
7.3 Design check against plastic instability and fatigue (EN 13445-3-Annex B)  
8 Semi-Probabilistic approach for pressure vessels with HSS  
9 Pressure Vessel inspection and maintenance guidelines  

<table>
<thead>
<tr>
<th>Table III.32: Overview on Background Documents produced as result of ECOPRESS</th>
</tr>
</thead>
</table>

Finally, a research seminar has been organised for the 19 and 20th of May at Aachen. There was only little resonance to it so that this date had to be cancelled. The reason for the low amount of registrations was found in the date in May which for most Engineers is extremely busy and where a lot of other conferences and meetings take place. Nevertheless the consortium agreed on the last meeting to have to afternoon sessions about ECORESS at two upcoming international conferences:

1. 9/10 Oktobre; MPA seminar, Stuttgart
2. September 2004 ESOP conference in Paris

On the individual dissemination of the results there will be probably contributions to conferences and scientific journals during the next month. E.g the new brittle fracture concept shall be published in international journal of pressure an piping. The results from High Strength steels shall be published in steel research. The FEM results will be presented on a mechanics an computation conference in Greece in the next year.

6. Acknowledgements

The support of the project with means of funding from the 5th framework by the European Commission is greatly acknowledged.

7. Contact

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