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VOCALIST – AN INTERNATIONAL PROGRAMME FOR THE VALIDATION OF CONSTRAINT BASED METHODOLOGY IN STRUCTURAL INTEGRITY

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The pattern of crack-tip stresses and strains causing plastic flow and fracture in components is different to that in test specimens. This gives rise to the so-called constraint effect. Crack-tip constraint in components is generally lower than in test specimens. Effective toughness is correspondingly higher. The fracture toughness measured on test specimens is thus likely to underestimate that exhibited by cracks in components. A 36-month programme was initiated in October 2000 as part of the Fifth Framework of the European Atomic Energy Community (EURATOM), with the objective of achieving (i) an improved defect assessment methodology for predicting safety

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margins; (ii) improved lifetime management arguments. The programme VOCALIST (Validation of Constraint Based Methodology in Structural Integrity) is one of a 'cluster' of Fifth Framework projects in the area of Plant Life Management (Nuclear Fission). VOCALIST is also an associated project of NESC (Network for Evaluating Steel Components). The present paper describes the aims and objectives of VOCALIST, its interactions with NESC, and gives details of its various Work Packages.

Participants in VOCALIST

The participants in VOCALIST, and the various contributions of these participants, are shown in Figure 1 below:

AEA Technology (Multi-national and multi-disciplinary contract R&D and consultancy services provider)	-Leader of WP1: Co-ordination and project management -Contributor to WP2 and WP4
BNFL Magnox Generation (UK nuclear utility)	-Leader of WP6: Programme evaluation
CEA (French Government-funded R&D organisation)	-Contributor to WP3 and WP4
EDF (French national electrical utility)	-Contributor to WP 4
Framatome (Multi-national group; designer, manufacturer and exporter of PWR plant)	-Leader of WP5: Synthesis of results and update of best practice Handbook -Contributor to WP2 and WP4
MPA Stuttgart (State Material Testing Institute (MPA), University of Stuttgart)	-Leader of WP3: Procurement and execution of Features tests and piping Benchmark test -Contributor to WP4 and WP5
Framatome ANP GmbH (Multi-national designer, manufacturer and constructor of nuclear power plants)	-Leader of WP4: Design of Features tests; prediction of Benchmark tests -Contributor to WP3
VTT (Technical Research Centre of Finland; independent multi-disciplinary R&D organisation)	-Contributor to WP3 and WP4
JRC-IAM (EC scientific and technical research centre)	-Leader of WP2: Compilation of best practice Handbook -Contributor to WP3
Oak Ridge National Laboratory (Multi-disciplinary research laboratory owned by the US Department of Energy)	-Contributor to WP4
E.ON Kernkraft (Operator of nuclear and fossil-fired power plants)	-Contributor to WP2 and WP5

Figure 1: Participants in VOCALIST

In the case of Oak Ridge National Laboratory and E.ON Kernkraft, participation is on the basis of in-kind contributions. For all other participants, participation is on the basis of a cost-sharing action, managed on behalf of the European Commission by DG.RTD. A description of the various work packages (WP) is presented later in the paper.

Aims and Objectives

The integrity of the primary pressure boundary of a nuclear reactor is essential to its safe operation. Rupture of the boundary (which includes the reactor pressure vessel) has the potential to cause a massive loss of coolant, overheating of the reactor core, and a subsequent major release of radioactivity to the environment. As part of the assurance of structural integrity, fracture mechanics analyses consider the behaviour of defects under normal and abnormal loading conditions to assess safety margins and component lifetimes as materials become degraded by irradiation and (or) thermal ageing. In essence, these analyses compare load and resistance terms to demonstrate that the crack driving force does not exceed the material fracture toughness. It is usual for fracture toughness data to be derived from tests on standard (deeply-notched) specimens and conservative validity criteria designed to ensure data representing high hydrostatic stresses near the crack tip (high constraint) and plane strain conditions. This is to provide a lower bound material property independent of specimen size. However, there is ample evidence that in many cases the loading on defects in components leads to lower hydrostatic stresses at the crack tip (lower constraint) with an associated increase in fracture resistance (e.g. shallow crack effect) [1-3]. Comparison between the crack driving force on a defect in a component and fracture toughness data from standard, high-constraint specimens then has two major consequences:

- a potentially over-conservative assessment of the margins associated with the loading to which the component is subjected
- a potential economic penalty due to under-estimation of the component safe lifetime

The aim of VOCALIST (Validation of Constraint-Based Assessment Methodology in Structural Integrity) is to develop and validate innovative procedures for assessing the level of, and possible changes to, constraint-related safety margins in ageing pressure boundary components. An iterative process of experiment and analysis will address this overall objective.

The following enabling objectives, which relate to the various phases of the project, support the overall objective:

1. Provide a concise summary of current evidence for constraint effects in as-received and aged materials. Determine the benefits of allowing for these effects in assessing defects in components.
2. Provide a concise summary of current analytical procedures for performing constraint-based defect assessments.
3. Perform an initial assessment of whether constraint benefits are likely to erode as flow and fracture properties change with component ageing.
4. Provide a concise summary of current limitations and gaps in knowledge and understanding.
5. Based on Items 1 to 4 above, establish current best-practice advice in the form of a Handbook for performing constraint-based fracture assessments of ageing components, covering brittle and ductile fracture and possible interactions between these two modes of failure.
6. Address the issues raised in Item 4 above via an iterative programme of analysis and structural Features tests. The latter tests will be designed to mimic the states of crack-tip constraint applicable to well characterised and documented large-scale fracture (Benchmark) experiments for as-received and degraded materials.
7. Use the comparisons between analytical predictions and experimental results in Item 6 above as the basis for improved predictions of the 'adopted' Benchmark experiments.
8. Use the results in Items 6 to 7 above to verify and validate the constraint-based analytical procedures.

9. Based on a synthesis of the results obtained in Items 5 to 8 above update the Handbook of best-practice advice for performing constraint-based fracture assessments of ageing components.

10. Provide overall Conclusions, and Recommendations for Codes and Standards and (or) future NESC large-scale fracture experiments.

VOCALIST is an associated project of NESC and there will be an interchange of results between VOCALIST and NESC as described below. Moreover, the large-scale Benchmark experiments already carried out under the auspices of NESC are among those considered for 'adoption' in the work of VOCALIST (see Item 6 above). The association between VOCALIST and NESC is with the objective of ensuring:

- Maximisation of the R&D cost benefit derived from EC funding
- Continuous peer review of the project by NESC Steering Committee members representing key institutions within the European nuclear forum
- Enhanced development and exploitation of innovative constraint-based methodologies in fracture assessment
- Enhanced dissemination of practical information to end-users
- Transfer of methodology to practical applications
- Identification of future R&D needs to meet outstanding issues

The measure of the overall success of the project will be the extent to which it has provided Europe's nuclear plant operators and their regulators with a practical methodology for making/considering:

- Improved assessments of safety margins for aged pressure boundary components under normal and abnormal loadings
- Improved lifetime management arguments for aged pressure boundary components consistent with maintaining current safety standards

Assessment of the project against the above objectives is at two levels:

- By independent evaluation of results and achievements in identified reports to DG RTD of the EC throughout the lifetime of the project
- By an ongoing process of peer review by virtue of the association between VOCALIST and NESC

Description of Work Packages

The project consists of the following six work packages (WP):

WP1: co-ordination and project management.

WP2: compilation of Handbook. In this initial phase Issue 1 of a Handbook is being produced detailing the application of constraint-based fracture mechanics procedures based on current best practice. Gaps in knowledge and understanding which currently limit the assessment of defects in ageing components are being identified.

WP3: adoption of Benchmark tests and performance of structural Features tests. First, existing large-scale fracture experiments are being identified in relation to the issues raised in WP2. Particular reference is being made to the NESC series of tests. Archive materials are being located physically and basic material properties data are being compiled. Second, innovative fracture experiments (structural Features tests) will be designed, procured and executed using the relevant archive materials to simulate, in reduced scale tests, the constraint conditions applicable to defects in the corresponding large-scale Benchmark experiments.

WP4: analysis. This work package interacts strongly with WP3. The initial analyses will be concerned with calibrating fracture models using basic properties of the archive materials. The calibrated models will then be used to design the structural Features tests and predict their outcome. Data from the Features tests together with the results from further analyses will be used to produce improved predictions of the original Benchmark experiments. Comparisons between the analytical predictions and experimental results during the various phases of this process will be used to verify and validate the constraint-based procedures.

WP5: synthesis and update of best practice. The improved methodology assessing defects in aged components will be based on an overall synthesis of the results obtained in WP2 to WP4. This methodology will be detailed in Issue 2 of the Handbook of best practice originally produced as part of WP2.

WP6: programme evaluation, including Conclusions and Recommendations.

The general 'top down' philosophy of VOCALIST in addressing constraint-based assessments is shown in the following figure:

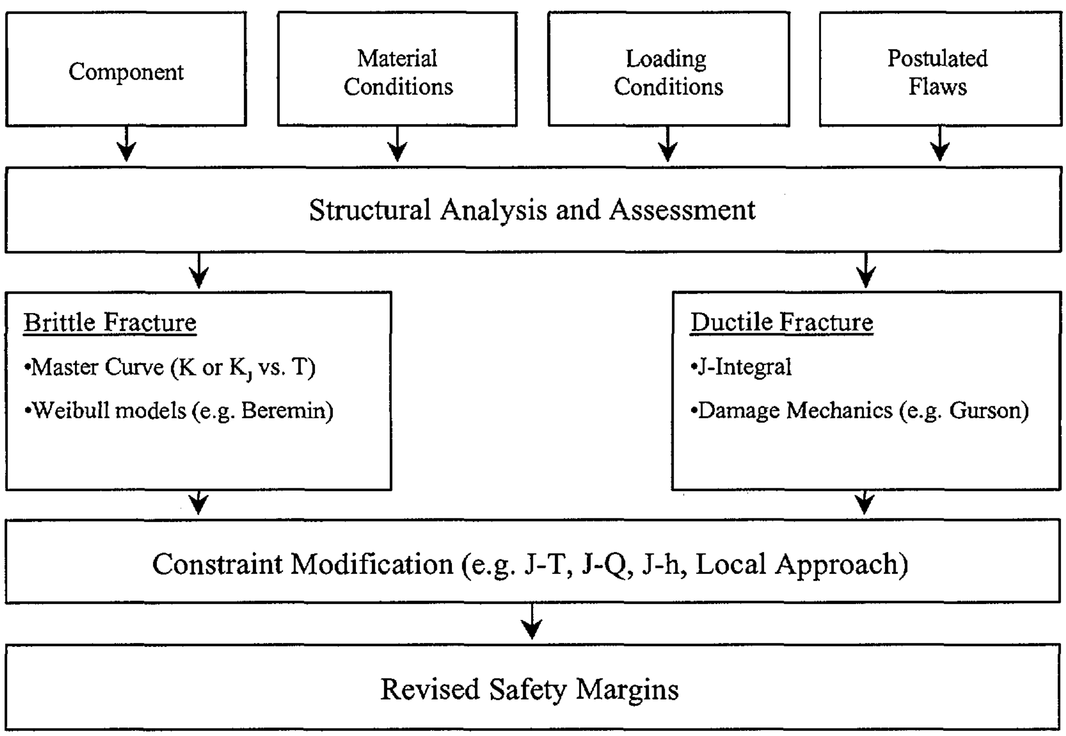

Figure 2: Top-Down Philosophy to Constraint-Based Assessment Adopted in VOCALIST

The figure below shows schematically some of the interactions (integration) in the development of constraint-based fracture mechanics methodologies that are expected to result from the work of the VOCALIST group.

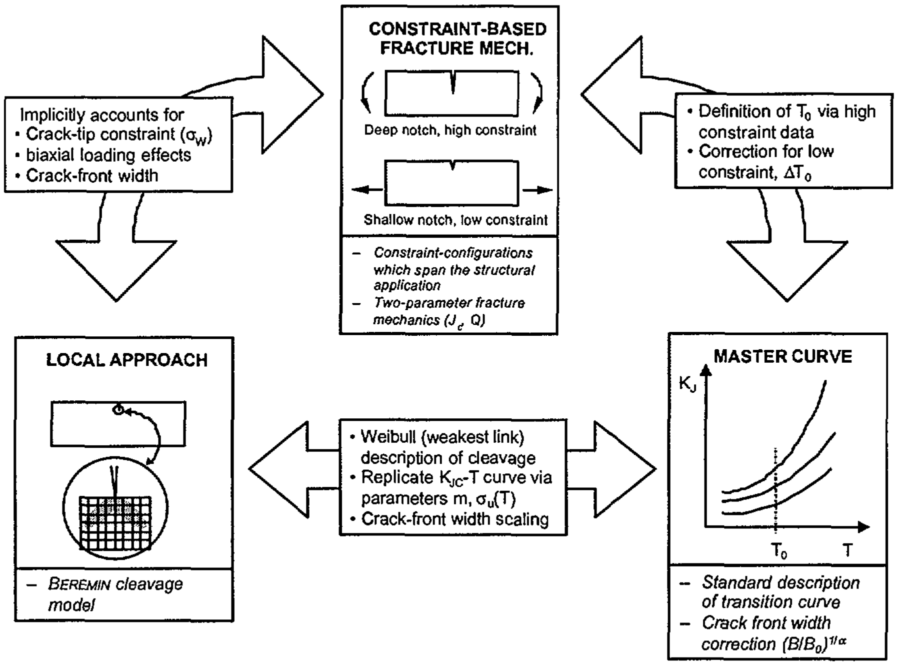

Figure 3: Schematic Illustration of interactions (integration) in the development of constraint-based fracture mechanics methodologies expected to result from the work of the VOCALIST group.

Work to date has focussed on the following areas:

1. Identification and assessment of current issues affecting the application of constraint-based fracture assessment methods
2. Identification of specific Benchmark tests and test data
3. Material selection

Item 1 includes consideration of brittle and ductile fracture in ferritic steels, and the interaction between these failure modes at temperatures in the brittle-ductile transition range. The coverage of issues is under the broad headings of:

(a) Effects of geometry, including crack size and shape
(b) Effects of load type and loading configuration
(c) Changing response of crack-tip material to different constraint states with in-service changes in flow and fracture properties
(d) Assessment of current models and modelling issues

The adoption of specific Benchmark tests within VOCALIST (Item 2) from available information on large-scale tests is being made with reference to the following requirements

- Relevance of test geometry and flaw to a nuclear power plant (NPP) component
- Relevance of loading conditions compared with the loadings on an NPP component
- Documentation of the test data and materials properties data consistent with the needs of numerical modelling
- Availability of archive material for further investigations within the VOCALIST project (i.e. for further characterisation tests, and the execution of structural Features tests)

Three materials will be tested within the project as follows:

Material 'A' a ferritic RPV steel with properties corresponding to a NPP at start of life

Material 'D' a ferritic steel with degraded properties by virtue of chemical composition and heat treatment

Material 'P' a ferritic piping steel

The following additional selection criteria apply to the various large-scale Benchmark tests that correspond to each of these materials:

Benchmark Test on Material 'A'. Demonstration of the effects of a multiaxial stress state on crack initiation and cleavage instability at temperature(s) in the upper range of the brittle-ductile transition.

Benchmark Test on Material 'D'. Demonstration of brittle failure at temperature(s) in the transition range, with predominantly thermal loading simulating a pressurised thermal shock (PTS) transient in an RPV.

Benchmark Test on Material 'P'. Demonstration of crack initiation and tearing leading to failure at a temperature where fracture toughness is in the ductile upper shelf range. Loading representative of the mechanical loads experienced by NPP piping.

Ideally, in all of the above cases, the crack-tip constraint state by virtue of geometry and loading configuration, etc should be quite different to that associated with standard, deeply-notched fracture toughness specimens tested in bending.

Material 'A'. The material chosen as Material 'A' was originally manufactured for the pressure vessel of a German nuclear power plant. It is a forged, quenched and tempered large ring segment of the ferritic steel DIN 22 NiMoCr 3 7, which corresponds to ASTM A508 Grade 3 Cl 1. The relevant material properties in terms of tensile test data, Charpy impact test data and fracture mechanics transition temperatures are summarised in the following table:

Property	Measured Mean Value
R.T. Yield Stress [MPa]	488
R.T. Ultimate Strength [MPa]	626
R.T. Fracture Strain [%]	75
Temperature at 41 J Charpy Energy [°C]	-51
Temperature at 68 J Charpy	-36

Energy [°C]	
Temperature at Lateral Extension of 0,9 mm [°C]	-38
Temperature at 50% Shear Fracture [°C]	-20
NDT-T [°C]	-17
$RT_{KIC\,mean}$ [°C]	-99

Table 1: Mechanical Properties of Material 'A'

There are two main advantages in using this material. Firstly, it is a highly qualified forged nuclear pressure vessel steel. Secondly, it has been used in several European projects as a reference material. To this extent, a significant body of relevant materials properties data is already available. In addition, data relating to the parameters of local approach models used in assessing fracture behaviour in the brittle and ductile regimes are also available.

The particular benefit of using this material within the VOCALIST project is that it has already been investigated comprehensively within the European project "Fracture Toughness of Steel in the Ductile to Brittle Transition Regime" [4]. In this latter project, more than 750 fracture mechanics tests, involving specimens with different geometries, were conducted at various temperatures in the brittle-ductile transition range.

A number of options are currently under consideration regarding which Benchmark test(s) to adopt in relation to Material 'A'.

Material 'D'. Based on work to date, the material most likely to be chosen as Material 'D' is a 17 MoV 84 steel. The steel received a special heat treatment, resulting in increased strength, reduced toughness and a high transition temperature. The resulting micromechanistic mode of failure is attributable to the presence of Vanadium Carbides. The corresponding Benchmark tests under consideration by VOCALIST are the tests designated NP1 and NP2. These tests, conducted at MPA Stuttgart, involved loading by a combination of constant internal pressure, a constant axial tensile force and an imposed thermal transient. NP1 featured an internally clad hollow cylinder containing two circumferentially oriented through-clad defects (in each case a/t = 0.1, 2c = 60mm). NP2 also featured an internally clad hollow cylinder, but with a 360° circumferentially oriented sub-clad defect (a/t = 0.04). In each case, the cylinders had an outer diameter of 785mm and a wall thickness of 192.5mm. The detailed material properties data and test results for NP1 and NP2 were obtained as part of the NESC-2 programme, and are available for use within VOCALIST.

Material 'P'. Material 'P' is French ferritic piping steel (tu52b) with mechanical properties representative of the start of life condition in a NPP. The Benchmark test for this material was specified during the project-planning phase. It will involve testing a pipe containing a through-wall crack in four-point bending at room temperature. The results of this test will be used to validate global (J) and energy-based models of ductile tearing in ageing components. Tests on small-scale fracture mechanics specimens and notched-tensile specimens at upper shelf temperatures will be used to calibrate analytical models of ductile tearing.

Interactions between VOCALIST and NESC

As noted above, VOCALIST is an associated project of NESC. All of the Consortium participants are members of NESC, and JRC-IAM, Petten acts as Operating Agent for this network. Through NESC, all of the participants have extensive experience of working together on the various Task Groups set up as part of the NESC-I and (or) NESC-II large-scale fracture experiments. A recent development of particular relevance to the work of VOCALIST is the launch of the NESC-IV project. The purpose of NESC-IV is to provide support to materials characterisation and analytical efforts in association with a programme of clad cruciform tests that ORNL are performing for the US NRC (Nuclear Regulatory Commission). PTS events produce multiaxial stress states in an RPV wall that are approximated by the cruciform specimen developed by ORNL under the HSST (Heavy Section Steel Technology) Program. Shallow flaws and multiaxial loading both affect fracture toughness properties compared with data obtained by testing conventional deep flaw specimens under uniaxial loading. There will be a free exchange of data and information between the VOCALIST and NESC-IV projects that will help to develop a Multiaxial Fracture Model and bring it to the level of maturity needed for application to RPV integrity assessments. This interaction is greatly enhanced by the fact that the most of the organisations participating in VOCALIST will also participate in NESC-IV.

A related Fifth Framework project in the EURATOM 'ageing cluster' is ADIMEW, which is concerned with the assessment of dissimilar metal welds. ADIMEW is also an associated project of NESC, and extensions to ADIMEW based on 'in kind' contributions will be made via the NESC-III project, which has just been launched. A mutual exchange of information and ideas between VOCALIST and ADIMEW is therefore encouraged by the NESC link.

Concluding Remarks

A brief overview has been presented of VOCALIST, a recently launched project of the Fifth Framework of the European Atomic Energy Community. The aim of VOCALIST is to develop validated procedures for assessing crack-tip constraint in ageing nuclear pressure boundary components under normal and abnormal loading conditions. The project features a close collaboration between leading structural integrity experts in Europe and in the US, and is an associated project of NESC. The close links between VOCALIST and the various NESC projects, and in particular the NESC-IV project, will help to develop constraint-based fracture mechanics to the level of maturity needed for application to RPV integrity assessments. This in turn will help lead to industry-wide acceptance of improved predictions of safety margins and lifetime management arguments.

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