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Reactor Pressure Vessel Steel Surveillance
New methodology - New Equipments

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Introduction

The seven pressurized water reactor plants, operated in Belgium by the utility ELECTRABEL, represent a total capacity of more than 5500 MW. In 1993, they assured the production of 60 % of the country's electricity.
The main characteristics of these units and the status of their pressure vessel surveillance programmes are summarized in the following table:

Plant	Capacity MWe	First operation	Number of capsules	Capsules withdrawn
Doel 1	400	1974	6	4 (1977,80,89,93)
Doel 2	400	1975	6	4 (1977,82,82,91)
Doel 3	975	1982	6 (*)	2 (1986,88)
Doel 4	1010	1985	6 (*)	1 (1989,94)
Tihange 1	870	1975	8	3 (1979,85,92)
Tihange 2	900	1983	6 (*)	2 (1986,89)
Tihange 3	1020	1985	6 (*)	1 (1988)

(*) 4 capsules in the reactor vessel and 2 in standby for delayed insertion

Table 1: The Belgian nuclear units and the status of their suveillance programme

All surveillance capsules retrieved are tested at the Reactor Materials Research Unit of SCK•CEN, the Belgian Nuclear Centre.

The test matrix within these capsules scopes the future embrittlement status of the reactor pressure vessel. The actual information on the vessel embrittlement, evaluated according to nationally accepted regulations and standards, indicates that the embrittlement of the vessels should remain acceptable largely beyond 40 years of operation. As a consequence, a modified withdrawal scheme for the remaining capsules in the Belgian NPP was adopted. This schedule allows to investigate the embrittlement status beyond the design end-of-life date.

On the research side, the shortage of vintage material for the older plants and the interest to revisit some destructively tested materials, called for optimized use of the material stock. Besides opening a vast area for development - from reconstitution to miniaturization - the information from classical tests has to be maximized, promising test techniques have to be evaluated and correlations with the classical tests have to be established.
This approach leads to an extended surveillance methodology where non-arbitrary indexation parameters are used to evaluate the embrittlement of the reactor pressure vessel material. This methodology is complemented by the development of physical models of embrittlement and validated on test results on reference reactor pressure vessel steels (RPVS), to come to relevant fracture toughness indexation procedures.

1 Irradiation Embrittlement and Regulatory Implications

The reactor pressure vessel material is subjected to neutron irradiation in the core region, which results in a progressive embrittlement.
The precise microstructural degradation mechanisms involved are still subject to much research.
Basically, defects and defect clusters, are created by neutron bombardment, are stabilized by precipitation of impurities (Cu, P, ...) and restrict the movement of dislocations. On macroscopic scale this appears as an increase in hardness and yield, and a decrease in fracture toughness.

The qualification of this irradiation induced degradation is given hereafter.

Reactor pressure vessel steel is brittle at low temperature and ductile at operating temperature. The transitional behaviour can be related to the "Nil Ductility Transition Temperature" (NDTT), measured by the conventional Drop Weight Test (DWT), or to the Reference Temperature of Nil Ductility Transition (RTNDT), defined on Figure 1.

The property that governs the material resistance to brittle fracture is the cleavage initiation fracture toughness, established by testing rather large specimens (ideally up to full wall thickness of a pressure vessel).
It is generally assumed that the effect of the neutron irradiation is to shift the fracture toughness versus temperature curve to higher temperatures, the shape of the curve being unaffected.

However current reactor pressure vessel steel surveillance programmes do not directly determine this property under service exposure, but rely on the C_v notch impact test for its estimation.
In fact the temperature at which 41 J is absorbed (TT41) is used to 'index' the crack initiation (K_{Ic}) and arrest (K_{Ia}) fracture toughness, two exponential functions of temperature T.
These functions are assumed to be universal for RPV steels, depending only on T-RTNDT, where RTNDT is a reference temperature characterizing the ductile-brittle transition temperature (DBTT).
It is furthermore assumed that, during service, RTNDT increases as TT41.
This methodology of US vintage, and adopted by many countries including Belgium, is summarized in Figure 1.
Regulations also refer to predictive correlations (trend curves), by which the effect of service exposure on TT41 (thus on RTNDT) is described in function of neutron fluence and the steel chemical composition - namely, its content of copper, nickel and phosphorus.
Whenever surveillance results exceed the upper bound of such correlations, the steel is considered an 'outlier'; this may entail severe penalties when defining the margins to be applied for consistency with today's prevailing empiricism.

The Research & Development (R&D) efforts of the SCK•CEN. Pressure Vessel Steel Project are primarily born from the need to address steel "outlier" behaviour in a more scientific manner.

It is found that the major underlying cause of apparent anomaly is the inadequacy of the 41 J - C_v fix for toughness indexation. More generally, it is concluded that this indexation does introduce distorsions and unwarranted scatter into present engineering correlations of embrittlement.

A new strategy for improved LWR pressure vessel surveillance has been proposed[1] incorporating statistical fracture mechanics and damage modelling while taking maximum advantage of the data generated by conventional surveillance practices.
Available reconstitution and miniaturization techniques allow to implement such strategy with minimum material inventory.

2 The Pressure Vessel Surveillance Programme

The pressure vessel surveillance programme of the Belgian NPP was designed according to ASTM-procedure E185 and is, besides some slight modifications, executed according to E185.

2.1 The capsules

The reactor surveillance capsules are placed in the beltline region towards the inner surface of the nuclear reactor vessel. As the specimens are located closer to the core than the vessel wall, they experience an accelerated exposure, representative for the vessel irradiation at a later time.
Every capsule contains Charpy-V bars, tensile specimens and fracture mechanics samples, prepared from the actual materials (base, weld, heat affected zone) of which the vessel was manufactured. Their heat treatment is representative for the beltline material.
Various dosimeters and temperature monitors are inserted at selected positions into the capsule.
At the time of the vessel fabrication, reference 'baseline' tests were made on similar non-irradiated specimens.

2.2 Information from RPV capsules

The capsule is dismantled at the LHMA hot cells of SCK•CEN. Visual inspection of the low melting point eutectic temperature monitors tells whether the upper temperature limit has been exceeded, but gives no information on the excess time nor on the lowest temperature during irradiation (this is not less than the water temperature around the capsule, 290 °C; the melt wires used have melting points of 304 °C and 310 °C) . The neutron dosimeters are, depending on their nature, analysed with spectroscopic methods combined with radiochemical techniques. The response of these detectors is converted, via an analytically determined neutron spectrum, to an equivalent fast neutron fluence received by the samples. Neutron transport codes then allow to relate the surveillance dose to the actual vessel condition. We will not consider neutronic aspects in this presentation further.

Tensile testing, primarily according to ASTM E8, is performed at reactor operating temperature, yielding the stress-strain curve of the irradiated vessel material. Instrumented Charpy-V impact tests, for the non-instrumented part according to ASTM E23, are performed as a function of temperature, to obtain the brittle-ductile transition curve of the irradiated

materials. The compact tension fracture mechanics specimens have not been tested until now, as no requirement exists from the regulatory side.
In general, neutron exposure of vessel material induces an increase in hardness and other strength properties, and reduces the ductility of the material. These properties are commonly detected: in tensile specimens as an increase in tensile strength, while fracture occurs at lower strain values; in the Charpy test: the strength increase is seen as a shift in temperature of the Charpy-V energy curve as a function of temperature, combined with a lowering of the maximum energy needed to break a fully ductile specimen (upper shelf energy, USE).

The Charpy impact test gives also information on the lateral expansion of the broken sample (LE) and the percentage of crystallinity of the fracture surface (also expressed by its complement: the shear fracture appearance (SFA)). The functional dependence on temperature is similar to the one for fracture energy: both LE and SFA shift after irradiation.

For Belgium, the vessel surveillance and integrity evaluation is mainly in accordance to the US Nuclear Regulatory requirements.
For the Charpy-V impact energy curve, the temperature shift of the brittle-ductile transition curve after irradiation, ΔT_{41J}, is indexed at 41J. Similar temperature shifts, $\Delta T_{.89mm}$, respectively $\Delta T_{50\%}$, are indexed at LE=.89mm for the lateral expansion curves, respectively at SFA=50 % for the shear fracture appearance.
The temperature shift at 41J, an arbitrary conventional 'measure' for the embrittlement of the vessel material, is used to update the Reference Temperature of Nil Ductility Transition (RTNDT), as was indicated in item 1.

Another surveillance programme result is the upper shelf energy (USE). Here the Regulatory requirements impose the initial USE of the vessel materials to be not less than 102J and to be not less than 68J at beltline throughout the vessel lifetime. These requirements are normally satisfied for the Belgian plants; if not, J-resistance fracture toughness tests are mandatory.

3 The Research Programme

The surveillance programmes need to be backed by research in order to verify and to understand irregularities, observed in testing the capsule material. Uncertainties can stem from a variety of causes, like dosimetry evaluation, irradiation temperature, number of specimens (statistics), representativeness and orientation of the specimens.
More fundamentally, the test techniques used in the surveillance programme can be questioned and - as indicated above - the toughness indexation methods applied, although conservative, are arbitrary.
Therefore a more general research programme concentrating on the development, correlation and justification of improved experimental techniques and theoretical models for evaluating the in-service behaviour of RPV steels was launched.
A basic reference for this research will be the reactor surveillance material of the seven nuclear pressure vessels of the Belgian PWR's, conventionlly tested to meet the current Regulatory requirements relative to the vessel fracture toughness. The ability to use minimum amounts of crucial material is a central issue from the beginning, which did lead to a documented elaboration of the technique of Charpy-V reconstitition and miniaturisation, qualified on reference steels in different material conditions. A thrust of these developments

is the determination of irradiation-induced shifts using precracked C_v-size specimens for fracture toughness evaluation. In parallel, full advantage is taken from all data generated from quasi-conventional surveillance tests: in particular, the instrumented Charpy-V traces and the Shear Fracture Appearance data, are interpreted in terms of a Charpy-V indexation procedure, based on the evolution of the load diagram of the material.
These mechanical test results are supplemented with micro-structural information to allow for an overall interpretation at light of physical models of embrittlement.

3.1 The instrumented impact test and interpretation of the load signal

The classic general principles of RPVS embrittlement modelling in the ductile-brittle transition temperature range are summarized on Figure 2. To first approximation, the ductile-brittle transition temperature (DBTT) can be considered as the temperature corresponding to the intersection between the general yield curve and the micro-cleavage fracture stress. Irradiation does, generally, not affect the micro-cleavage fracture stress, but raises the general yield curve. This leads to the so-called DBTT shift, a measure for RPVS embrittlement. In surveillance capsule programmes, this shift is by contrast taken at an arbitrary level of absorbed energy (e.g. 41J).

Charpy impact machines, instrumented with strain gages, measure - as a function of time t - the load P exerted by the impacting tup on the Charpy sample. The (P,t) Charpy impact curve can contain, depending upon the test temperature, several characteristic load points: P_{GY}, the general yield load; P_m, the maximum load; P_u, the brittle crack initiation load; P_a, the crack arrest load[2].

For our analysis purposes, the instrumented signal is subdivided in several parts, schematically illustrated in Figure 3. Three or four critical temperatures and a related energy partitioning can experimentally be determined to reasonable accuracy from the impact traces[1, 3, 4].

T_D: 'brittleness' temperature = the onset of 'energy fraction A'. Above this temperature, plastic deformation of the sample is necessary to cause fracture.
T_I: ductile crack initiation temperature = the onset of ductile crack growth, i.e. the temperature at which the SFA starts to exceed 0 %.
T_N: 'ductility' temperature = the onset of 'energy fraction B'. In the transition region, this ductile tearing can suddenly change to unstable brittle crack propagation (point 'u' on the impact trace).
T_O: the onset of the C_v upper shelf, i.e. the temperature at which brittle crack initiation and crack arrest loads coincide.

At high strain rates, such as in the C_v-test, T_D is generally close to T_I.
Energy fraction B contains mainly plastic deformation energy, but 'measures' also the specimen's capability to sustain ductile stable crack growth; most of the scatter in the transition region for the C_v-test is associated to this fraction. Conversion from ductile to brittle behaviour stems from the interaction with 'trigger' particles under the strain field triaxiality, prevailing in conventional Charpy-V specimens. Upon irradiation, fraction B diminishes drastically: the reduction in ductility favours the conversion to brittle behaviour and reduces the statistical variation. Fraction C indicates the ability to stop a fast crack and to return to the tearing mode, but under plane stress conditions, characterized by shear lip formation.

The load diagram as a function of temperature, Figure 3, is the more adequate reference for indexation. Especially T_I AND T_O are physically-grounded measures of the DBTT: T_O is especially suited for indexation of the crack arrest fracture toughness K_{Ia} , while T_I is adequate for indexation of the dynamic initiation fracture toughness K_{Id}.

Figure 4 shows, as an example, the instrumented C_v-impact load diagram and SFA for a specific PVS base material. As is apparent, there exists a one-to-one correlation between the C_v-impact load diagram and the shear fracture appearance, bound by the two characteristic temperatures T_I and T_O. A fit of the experimental SFA-data can be derived from the load diagram as:

$$SFA\ (\%) = \left[1 - (P_u - P_a)/(P_m + k(P_m - P_{GY}))\right] \times 100\ \%$$

where, $0.4 \leq k \leq 0.6$[1]. Most tests show that k=0.5 tends to be a good approximation.

An example of the evolution of the load diagram after irradiation is shown in Figure 5. In this figure the shift between the baseline and irradiated condition for the specific material corresponds to the Davidenkov diagram, establishing the relationship between hardening and DBTT-shift of the steel (shift of T_I in this case).

It has been confirmed by our experimental work that elaborate use of the instrumented C_v-signal brings also new insight into the embrittlement mechanisms of RPV steels.

* *Equipment*

A modern, instrumented impact test system based on updated standard requirements, fitted with a temperature chamber and automatic specimen positioning system is installed in a new hot cell. More information is given in item 4.

3.2 *The reconstitution technique*

SCK•CEN has developed a stud welding technique to reconstitute broken Charpy specimens[5,6,7,8] . The method, schematically illustrated in Figure 6, has been qualified extensively on various pressure vessel materials in non-irradiated and irradiated conditions. The principle consists of welding two studs to an insert made of pressure vessel material with subsequent remachining into a 'new' specimen. For now, two geometries are commonly prepared: a 10x10x55 mm Charpy bar and a small tensile specimen of gage length 20 mm and diameter 3.6 mm. Proper choice of insert lengths allows to increase the statistics, i.e. the number of test samples made of representative material, by a factor of 3.

To avoid influences of the welding procedure on the inserts, reconstitution weldments are carried out on dummy specimens before and after reconstituting 'real' inserts. The dummy specimens contain a (brazed) thermocouple that measures the temperature at 4 mm from the weld interface. At all times this temperature has to remain below the normal operating temperature of a nuclear reactor, i.e. 300 °C. The qualification tests give confidence that the reconstitution technique is properly designed in order to avoid any biases with the original specimens.
SCK•CEN plays a major role in the ASTM Round Robin on Reconstitution, designed to update ASTM guideline E-1253 on Reconstitution of Charpy-V bars.

3.2.1 Charpy-V impact specimens

The original qualification tests were executed on 20 mm inserts. No deviation in energy, lateral expansion and shear fracture appearance between as-received and reconstituted Charpy-V impact tests were observed. However, to maximize the available amount of material, the insert length should be minimized. An interesting insert size is 10x10x10 mm since it allows to reorient a Charpy sample - for example: from L-T to T-L - see Figure 7. However, for such small insert length, the impact test reveals that, from a certain test temperature on, the plastic flow is constrained by the welds. Indeed, these weldments are situated at less than 5 mm from the sample notch, while hardness testing on broken as-received specimens suggests that, at upper shelf test temperatures, the plastic flow can spread 8 to 10 mm from the notch. Consequently, the loss in plastic flow energy causes the recorded fracture energy to be less than for an as-received sample. Initial two-dimensional finite element calculations confirm this behaviour.

Figure 8 shows the energy reduction for unirradiated HSST-03 material in the L-T and T-L orientation. The apparent shift in temperature after reconstitution is - on Figure 8 - primarily a direct consequence of the lower USE.

Another source for energy differences with small inserts comes from the impact hammer geometry - DIN or ASTM - used for breaking the samples[6,7]. The edgy ASTM tup can introduce a Brinell type of deformation on the impact side of as-received samples and spends energy with this process. However, with reconstituted samples made from small inserts, the hard weld zones will interact with the ASTM-tup and the Brinell deformation disappears.
Consequently an additional reduction in the fracture energy is detected. The smooth round DIN-tup does not suffer from this effect as the considered Brinell deformation is not introduced on as-received or reconstituted samples.

A regulatory requirement is to have Charpy results on weak T-L oriented specimens.
With only L-T specimens available, the T-L as-received energy cannot be derived by simply testing L-T →T-L reconstituted specimens; one needs to test L-T →L-T reconstitutions too.
The conceptual approach to find the T-L as-received energy was tested for HSST-03 and is illustrated in Figure 9. Considering the losses due to plastic constraint and to the hammer as isotropic, the difference in energy between the L-T as-received and the L-T reconstituted curves can be added to the experimentally determined T-L reconstituted curve; this leads to a predicted T-L 'as-received' curve, in excellent agreement with the experimentally determined one.
It has been found that, with the application of the reconstitution technique of 10 mm long insert to materials with different upper shelf energy, the maximum losses, recorded after testing at upper shelf temperatures, depend on the upper shelf energy of the material, as expected.
Further on, energy losses can depend also on the hammer geometry.

3.2.2 Tensile specimens

Mini tensile specimens were reconstituted from Charpy remnants of 22 mm in length[9,10]. The gage length-to-diameter ratio of the reduced part was identical to the ratio for the ASTM E8

defined Pin-Loaded Tension Test Specimen with 2 inch gage length; the latter specimen is present in the surveillance capsules.
Qualification tests on as-received and reconstituted mini tensile specimens, together with tensile tests on the E8 specimen size were conducted. This resulted in a one to one correspondence for the tensile properties of all specimens.
Quite obvious that this technique opens new perspectives for overall material embrittlement evaluation.

* *Equipment*

The continuous effort to improve the technique of reconstitution welding led to grounded thermocouples for the temperature control measurements; the response time being reduced and the temperature more accurately determined in this manner.

The purchase of a continuous-wire electric-discharge machine opens new possibilities for finishing reconstituted samples and (cutting) sectioning insert pieces. Up to now, remanufacturing of specimens imposed a lot of milling operations in the hot cell.
Demonstration activities have been performed on unirradiated material.
Design of a lead shielded confinement has started for machining on irradiated material.

3.3 *Miniaturization of Charpy-V specimens*

Miniaturized Charpy-V specimens are an alternative for optimizing the use of surveillance material. Moreover, in special situations, like e.g. scoping an operational reactor vessel through boat sampling, the maximum size of the specimens is limited. Actually, some interest goes to the DIN50115 standard specimen with dimensions 3x4x27 mm.
Validation of these specimens requires correlations with data obtained from the standard 10x10x55 mm specimens.

The toughness behaviour of these small specimens (MS) has been characterized by several authors[11,12] with index temperatures like $T_{1.9J}$, $T_{3.1J}$, $T_{0.3mm}$ [11], respectively corresponding to the empirical indices T_{41J}, T_{68J}, $T_{0.9mm}$ of the standard 10x10x55 mm size specimens (SS). This leads to a seemingly simple empirical formula, $T_{SS}=T_{MS}+70K$, the mean correlation of a rather large data base whose scatter band[11] is shown in Figure 10.
Mini-Charpy specimens of a base and weld material, prepared with the electric discharge technique, were tested with instrumented equipment to verify the scatter of mini specimens and to check the proposed correlation. As can be estimated from Figure 11, the scatter of the mini-Charpy impact results turns out to be comparable to the scatter for the standard size specimen. The correlation result for this base material is within the scatter band of Figure 10. However, although the temperature shift of the energy curves indexed at 1.9J and 41J is only 33K and although the lateral expansion gives a similar result, the shift indexed at 50 % shear (for both geometries) corresponds to about 77K - as illustrated in Figure 11.
Consequently, caution should be taken to introduce empirical indexation shifts with large error bars (moreover, the initial indexation is already empirical). The indexation approach should take information from the instrumented signal on mini and standard specimens, combined with the physical differences between the two geometries, like volume effects and strain rates into account[1].

From an experimental viewpoint, it should be mentioned that the thermal mass of mini C_v-specimens is much lower than for standard C_v-specimens. The specimen transit times from thermal bath to impact should therefore be drastically reduced.

* *Equipment*

A fully automated mini Charpy-V impact tester, equipped with a custom-designed temperature chamber and specimen transfer system was ordered and commissioned.
The total time between the transfer of the thermalized mini-specimen and its fracture on the impact machine remains below two seconds.
This minimizes any change in the temperature of the mini Charpy specimen with low thermal mass.
The impact test system is installed in the new hot cell of LHMA.
More information is given in item 4 of this report.

3.4 *Fracture Toughness*

As was said before, fracture toughness is the most important property when considering pressure vessel integrity.
The essential requirement of a fracture toughness test is to measure the load versus displacement behaviour of the specimen involved and the corresponding crack growth.
In the elastic regime, crack growth is generally unstable but in the elastic-plastic and plastic regimes crack growth usually occurs with no clearly identifiable features to indicate crack initiation. Then it is necessary to measure the crack length during the test in order to evaluate initiation followed by crack growth.
Considering the geometry of the specimen and the materials involved, the J-integral concept provides a method of fracture toughness determination, which is probably best suited for the testing of irradiated specimens in a shielded facility.

In LHMA a three-point bending arrangement has been prepared allowing fatigue precracking and crack resistance testing of Charpy-type specimens[13]. The crack growth is evaluated by the unloading compliance technique (ASTM Standard E813 - for determining the elastic-plastic toughness parameter J_{Ic} for ductile materials).
The method requires that a specimen is unloaded periodically during a test and subsequently reloaded, i.e. the Single Specimen Partial Unloading Compliance method (SSPUC).
Crack length is then calculated from the analytical elastic relationship between the load and load point displacement, using the elastic unloading compliance measured from the slopes of the unloading and loading cycles (straight fronted crack growth).
Load point displacement is measured with a clip gauge mounted across knife edges machined in the specimen surface.
This mouth opening displacement must be converted to an equivalent load point displacement.
In a first approach, both clip gauges, mounted directly into the specimen, and remote LVDT, associated to the actuator of the test load frame are used in our system to derive the crack length.
A typical test recording of such a geometry is given in Figure 12.
After testing, the specimen is heat tinted and then further broken at low temperature.
The initial and final crack length is then optically measured and compared to the estimated one.
The hot cell facility and test frame is further described under item 4 of this report.

3.5 Damage modelling and fracture micromechanics of RPV steels

In depth understanding of factors influencing RPV mechanical properties under service conditions is of prime importance. Along with the combination of the mechanical property test procedures and the microstructural analysis of the materials, involved modelling forms the key stone in the evaluation of the overall condition of the RPV steel.
The main objectives of our physically-based modelling activities are:

- to significantly reduce current uncertainties and insure against technical surprises in the future, as plant life management beyond design life becomes a growingly implemented option;
- to address outliers, i.e. materials behaving in ways hardly interpretable by, or contradicting, present, empirical, predictive formulations;
- to help turn pressure vessel annealing into a licenseable PLEX technology.

The methodology aims at incorporating statistical fracture mechanics and damage modelling while taking maximum advantage of the data generated by the instrumented Charpy-V and conventional uniaxial tensile tests [1].
Two complementary approaches are simultaneously followed:

* Improved Transition Temperature Concept

The thrust here is to rely on an improved definition of the ductile-brittle transition temperature DBTT for toughness indexation along existing Regulatory lines.
The approach combines the C_v-impact load diagram and fracture appearance data to determine two physically-grounded transition temperatures (ref. item 3.1) whose shift upon service exposure does correctly trace the corresponding shift of dynamic fracture toughness K_{Id}.
The K_{Ic} shift is then derived by accounting for the strain rate effect estimated by comparing the uniaxial tensile properties to the C_v- impact load diagram.
The concept is particularly well-suited in terms of damage modelling considerations, because it allows to analyse the shift in terms of the Ludwig-Davidenkov diagram, i.e. hardening (yield strength increase) and micro cleavage fracture stress (item 3.1; Figure 5).

* Micromechanics-based Fracture Toughness Indexation

The approach here is to use advanced statistical micromechanics for the evaluation of small specimen K_{Jc} fracture toughness measurements, in combination with some enhancement of current, commercial suveillance test matrices.
Both static and dynamic initiation toughnesses are addressed as well as their scatter and lower bound definition.
Available reconstitution technique allows to implement such strategy with minimum material inventory.

The performance of both approaches is being demonstrated in cooperation with international programmes using reference materials for which extensive K_{Jc}, K_{Ia} and NDT (drop weight) measurements have been performed with large specimens, including in the irradiated condition.

Further applications of the new strategy will entail specimens trepanned out of decommissioned pressure vessels.

4 New Test Facilities

Facing this new strategy on pressure vessel steel surveillance and R&D activities imposing sophisticated technologies, it was necessary to have a continuous upgrading of the hot cell equipments.
New test facilities are therefore under preparation.

The new instrumented Charpy impact test facility at the RMR-laboratories is based on a Wolpert pendulum impact machine for both standard- and subsize specimen geometry. The heating- and cooling unit for both impact testers, of 300J and 20J capacity, is a Severn Furnace installation.
The instrumentation, specimen alignment control system and impact analysis software are also supplied by the same manufacturers.
The following Figures 13 & 14 illustrate the hot cell lay-out and installed test equipment.

For the fracture toughness test facility, the apparatus loading the specimen is a servohydraulic Instron closed-loop system.
Force and displacement are recorded autographically, and by a AD convertor data acquisition is performed by computer.
Data are stored and J evaluated on line. After each unloading cycle of the specimen, the actual increase in crack length and the corresponding J value are evaluated and plotted.
The hot cell facility with load frame is schematically shown on Figure 15.

Finally, the design of a shielded facility for the EDM-equipment installation is in progress. Considering the complexity of EDM machining remotely, emphasis will be given to easy accessibility of the system.

5 Conclusion

The Belgian Activities on Pressure Vessel Steel Research make elaborate use of the 'normal' surveillance programmes of the Belgian Nuclear power plants to develop an advanced research programme on the characterization and modelling of Reactor Pressure Vessel Steels. The research activities question the actual arbitrary indexation methods for steel embrittlement, and put forward a methodology - based on the information contained in the instrumented Charpy-V signal - to come to physically based indexation procedures. On the technical side, advanced specimen preparation and analysis techniques make use of limited amount of material to optimize the use of the material stock available.
New hot cell facilities for Charpy-V impact testing on standard - as well as on subsize specimens are under preparation and advanced test techniques are being developed to measure fracture toughness on small specimen sizes.

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Fig. 1 REGULATORY INDEXATION OF FRACTURE TOUGHNESS FOR RPV STEELS

- Crack Initiation and Arrest Toughness Taken as Unique Functions of Temperature Indexed to
  REFERENCE TEMPERATURE RT_{NDT}

- Lower Bound Toughness (ASME XI Code):

  K_{Ic} (MPa√m) = 36.5 + 3.084 exp[0.036x(T+56−RT_{NDT})]

  K_{Ia} (MPa√m) = 29.5 + 1.344 exp[0.026x(T+89−RT_{NDT})]

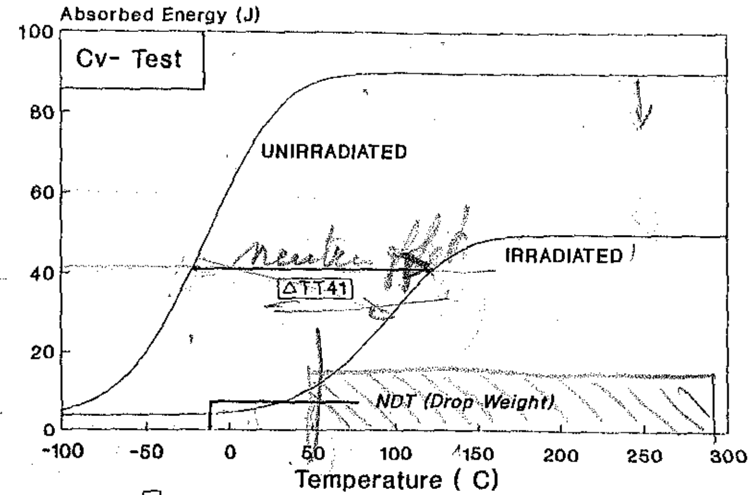
  Temperatures in °C

- Un-Irradiated RT_{NDT} Equal to
  Drop Weight NIL DUCTILITY TEMPERATURE
  NDT
  Unless Charpy Impact Energy at NDT+33°C Lower than 68 J

- Embrittlement Shifts Toughness Curves According to Recipe

  $\Delta RT_{NDT} = \Delta TT41$

  i.e. Shift of Cv- Impact 41J Temperature



Low Upper Shelf Axial Weld
At PTS Screening Criterion

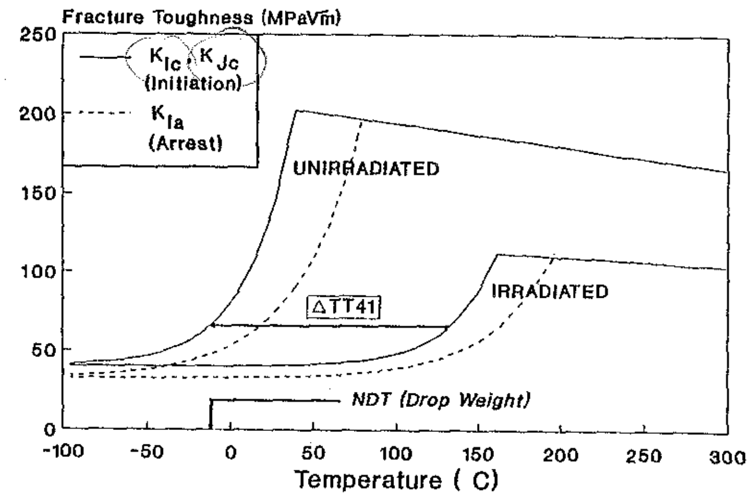


Fig. 2 GUIDELINES TO DAMAGE MODELING OF RPV STEELS

DUCTILE- BRITTLE TRANSITION TEMPERATURE *(DBTT)*

- *GENERAL YIELD STRESS*
  - *CLEAVAGE FRACTURE STRESS*
- For Temperature > DBTT:
  Strain Hardening Needed for Fracture
  (Plastic Deformation)

"CLASSICAL" MATRIX HARDENING

- Irradiation Creates Obstacles to Movement of Dislocations (for ex., Precipitates)
- Material Flow Is Hampered i.e. Yield Stress Increases
- *DBTT INCREASE PROPORTIONAL TO YIELD STRESS INCREASE*

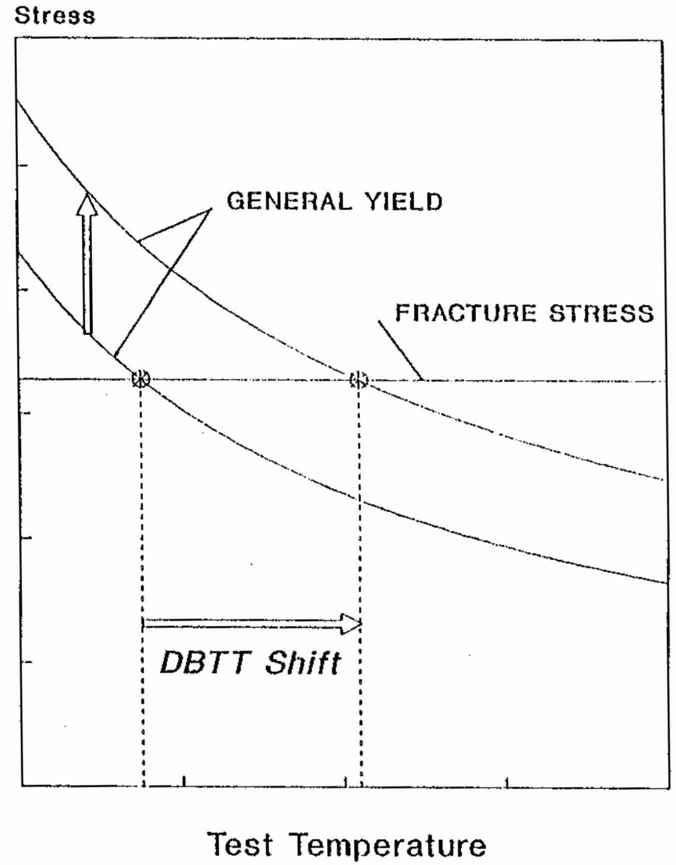
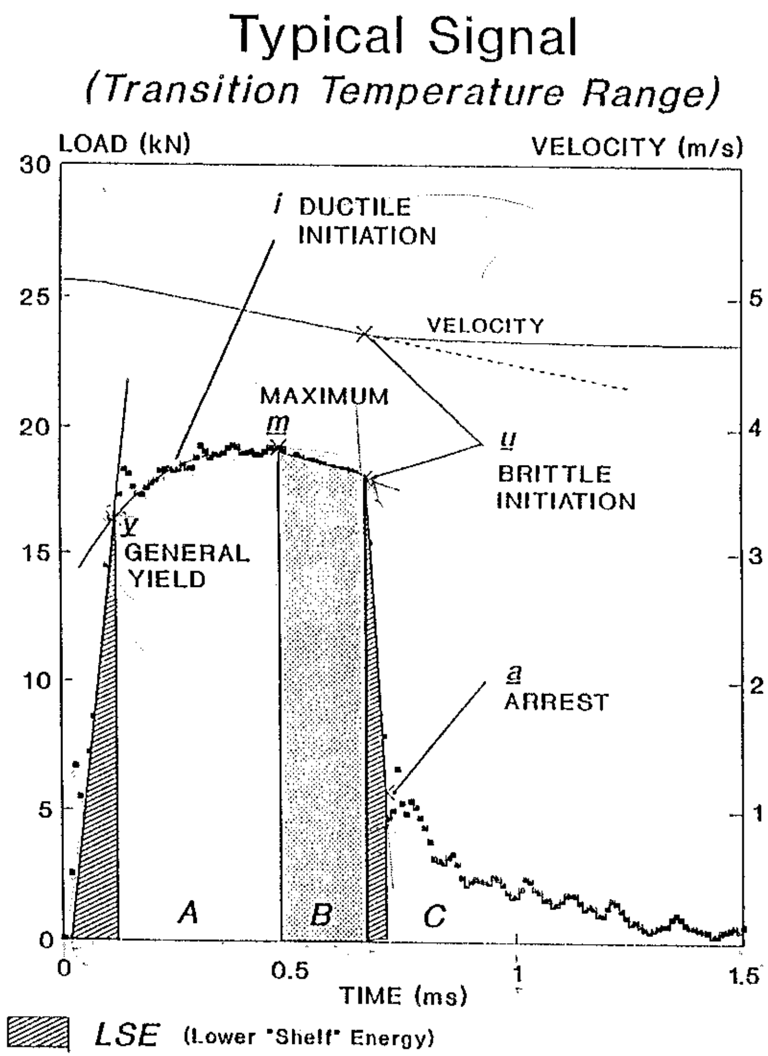
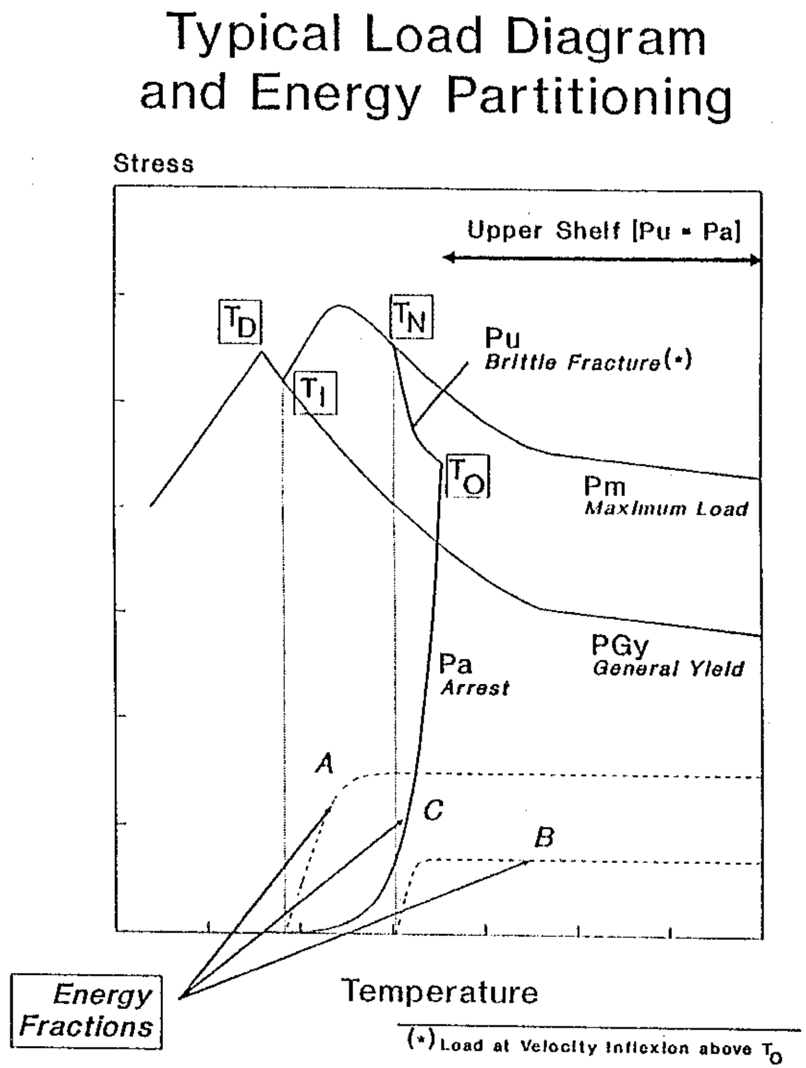


Fig. 3 **USE OF INSTRUMENTED CHARPY-V LOAD-TIME TRACES**





Cv- Load Diagram and Fracture Appearance Define Toughness Indexation Temperatures

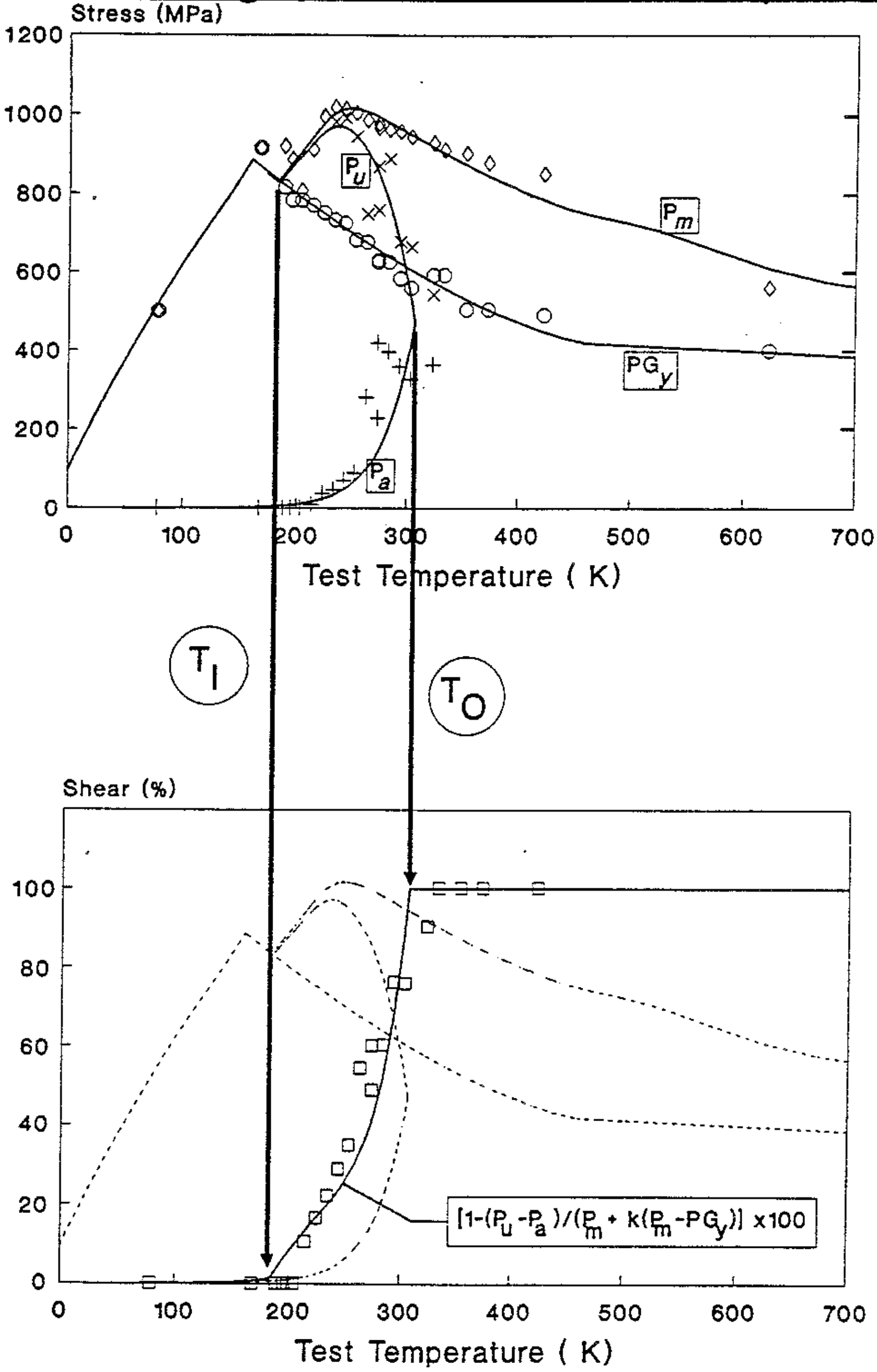


Fig. 4

Instrumented Cv-Impact Test Is Used for Damage Modeling

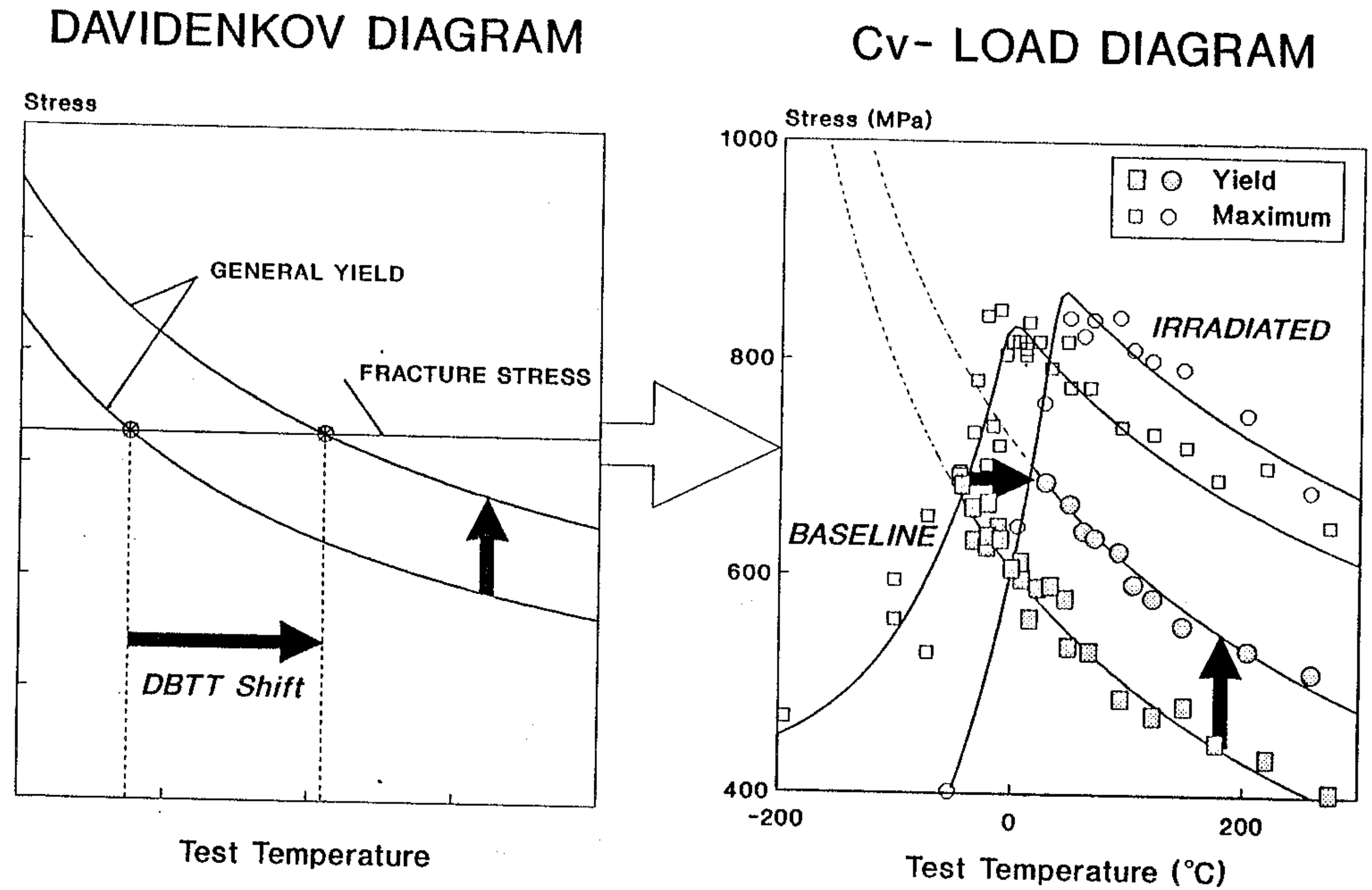


Fig. 5

Fig. 6 SCHEMATIC PROCEDURE FOR THE RECONSTITUTION OF CHARPY SPECIMENS. THE INSERT LENGTH IS VARIABLE.

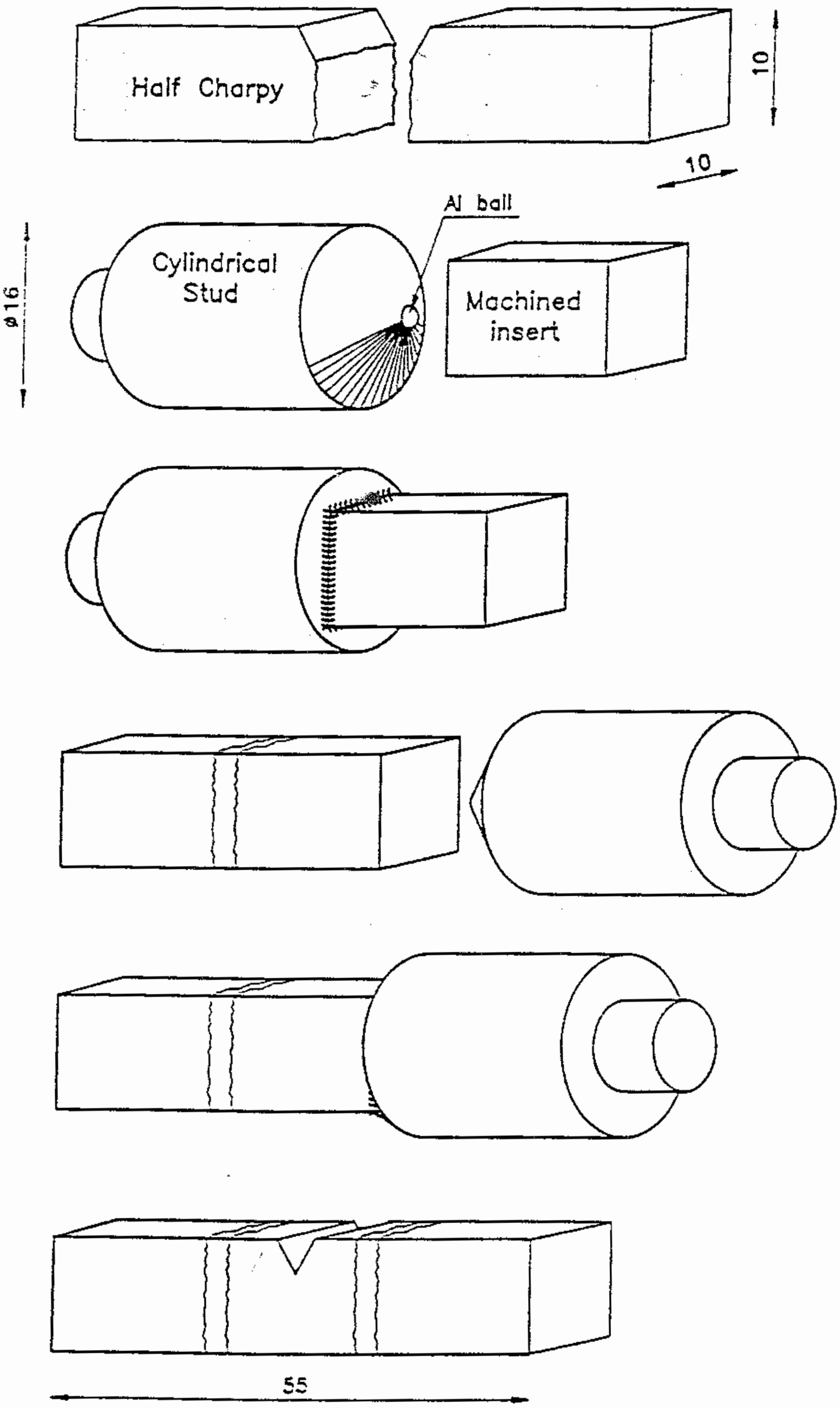


Fig. 7 THE RECONSTITUTION OF 10mm LONG INSERTS

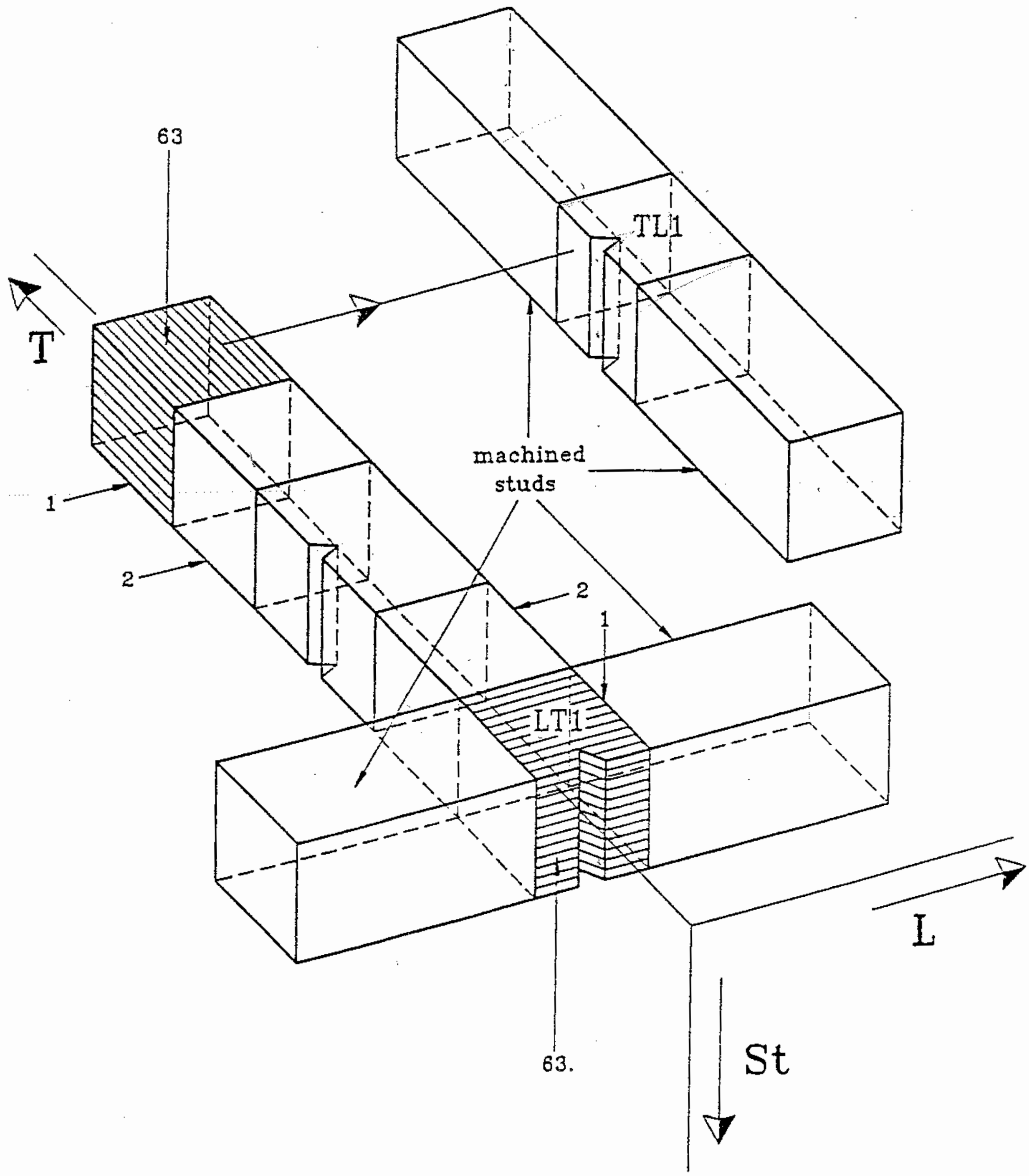
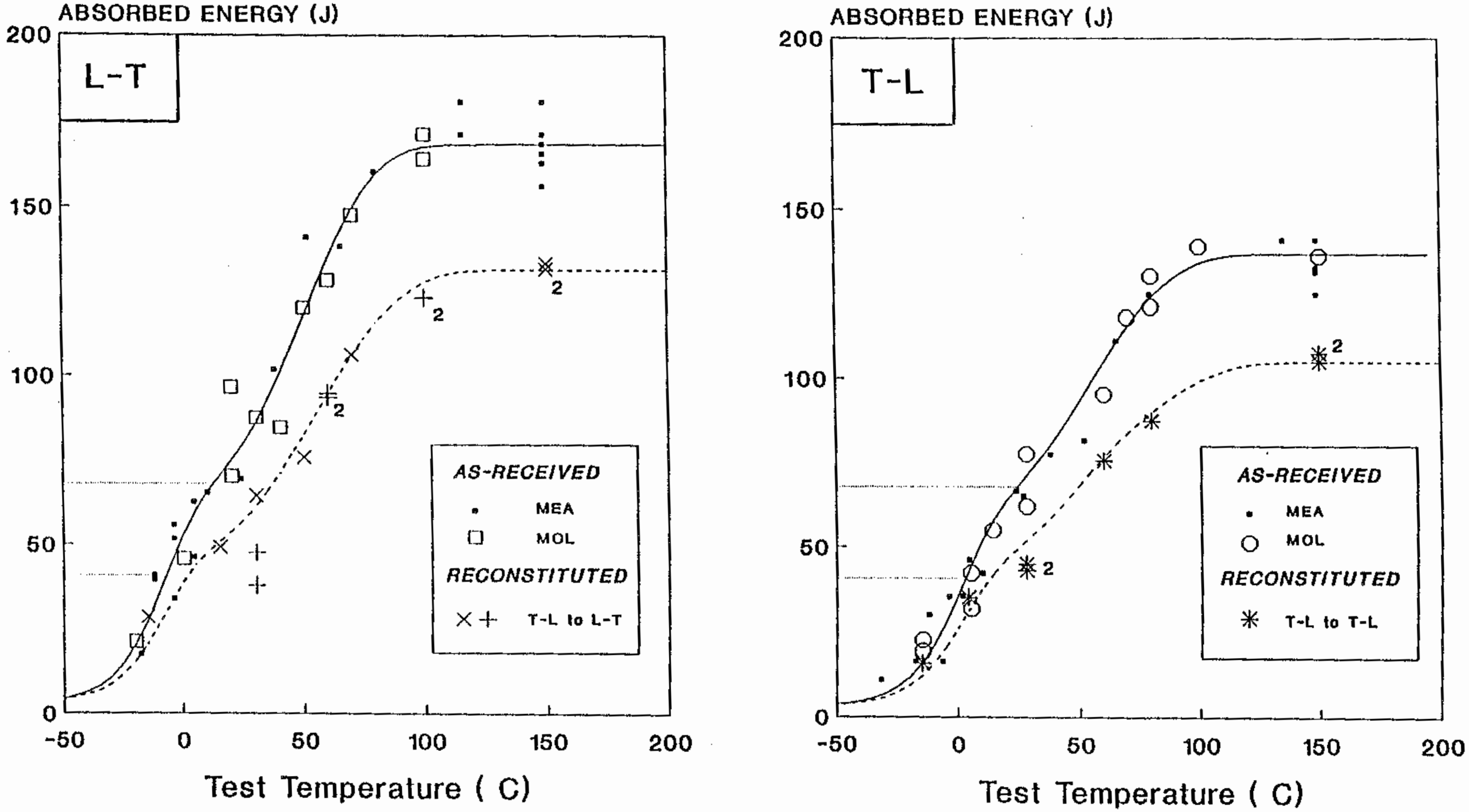


Fig. 8 DEFORMATION CONSTRAINTS BY HARD WELDED ZONES* AND NOTCH ORIENTATION CAUSE SIGNIFICANT ENERGY DIFFERENCES IN Cv- IMPACT TEST



* Cv- Reconstitution: 10x10x10 MM REMNANTS, Plate HSST-03
Un-irradiated Condition STUD WELDING TESTS PER ASTM E23

Fig. 9 CORRECTION SCHEME FOR NOTCH RE-ORIENTATION

(BY RECONSTITUTION OF 10x10x10 MM CHARPY-V REMNANTS)

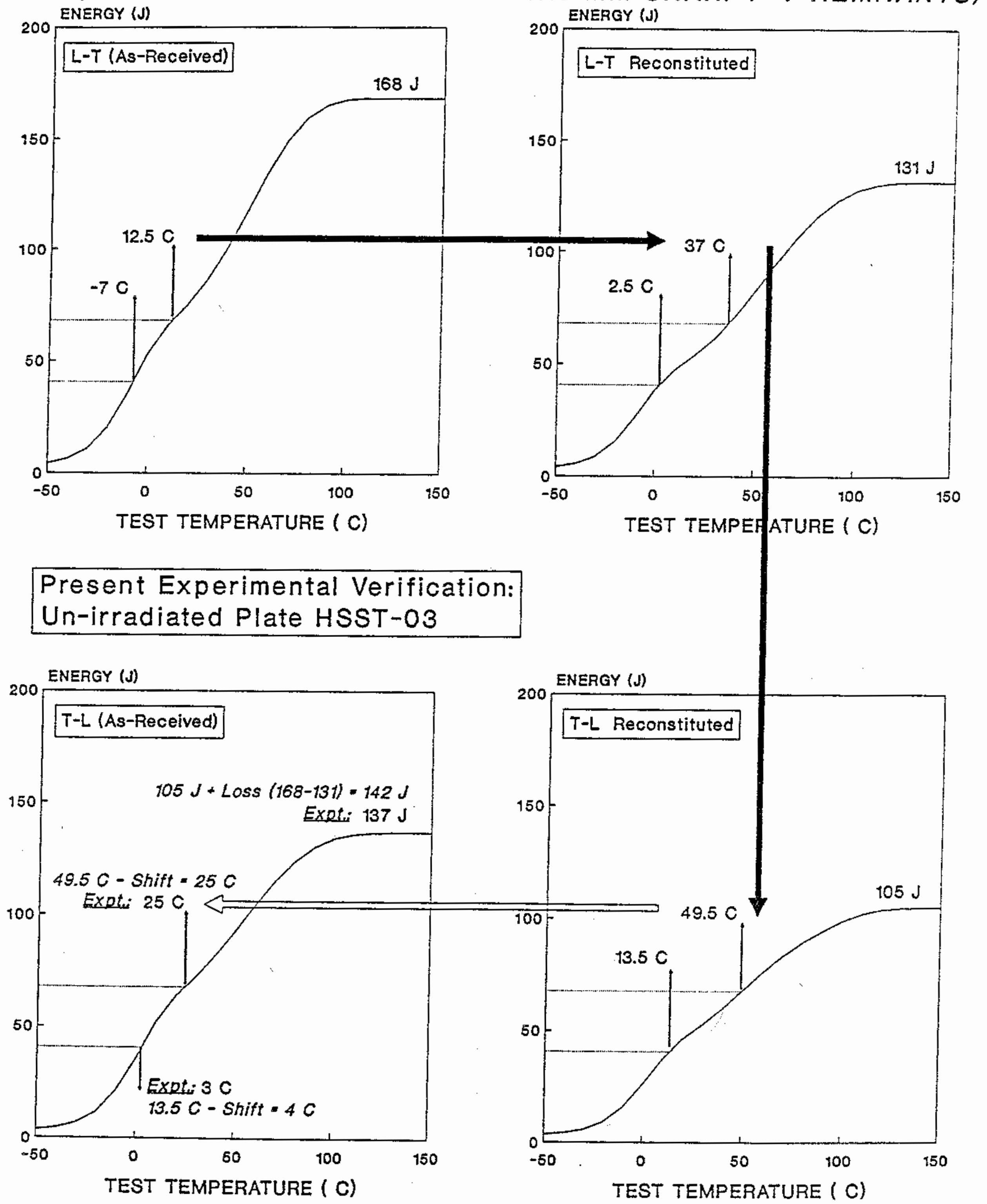


Fig. 10 EVALUATION OF MINIATURE Cv- TEST RESULTS

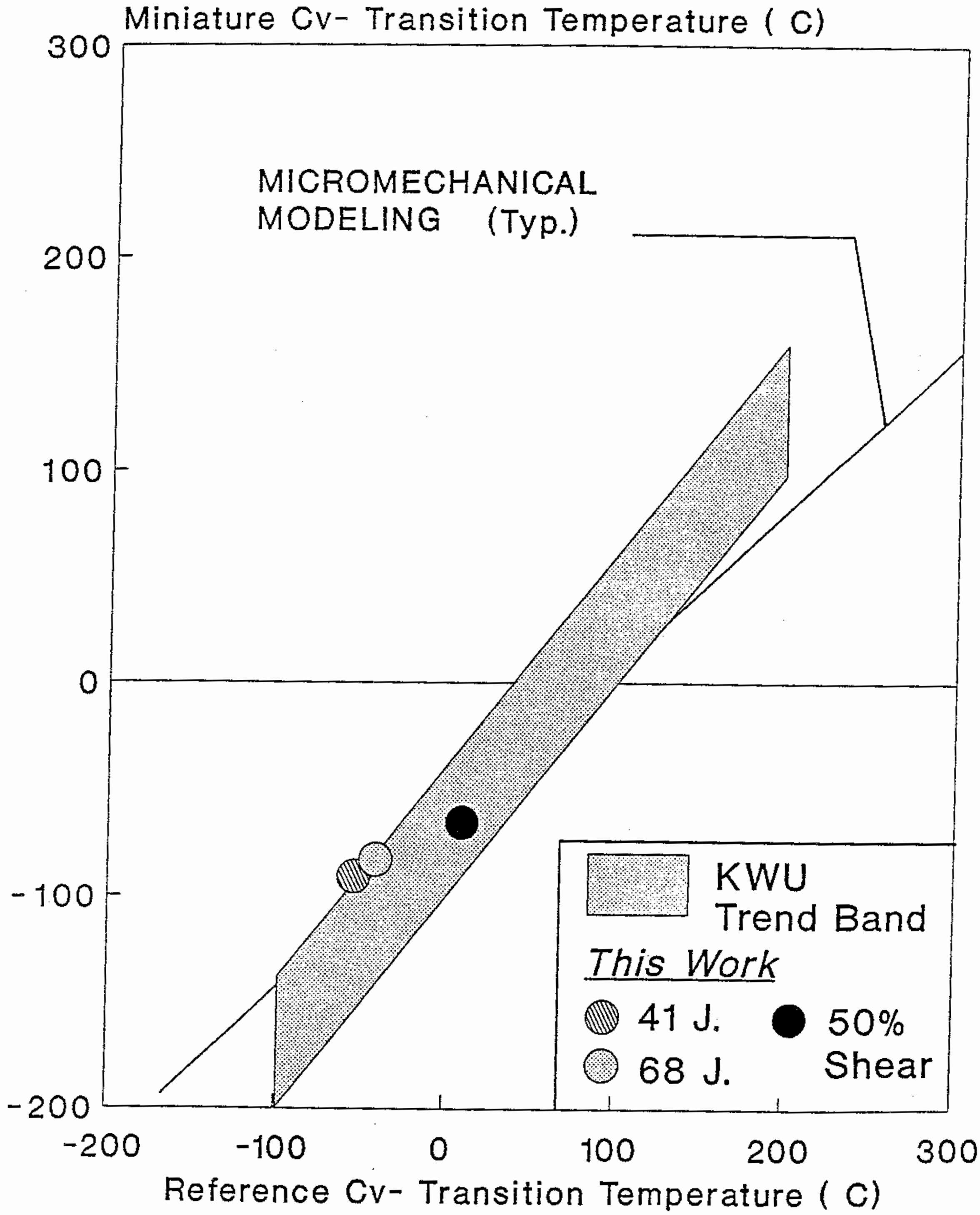
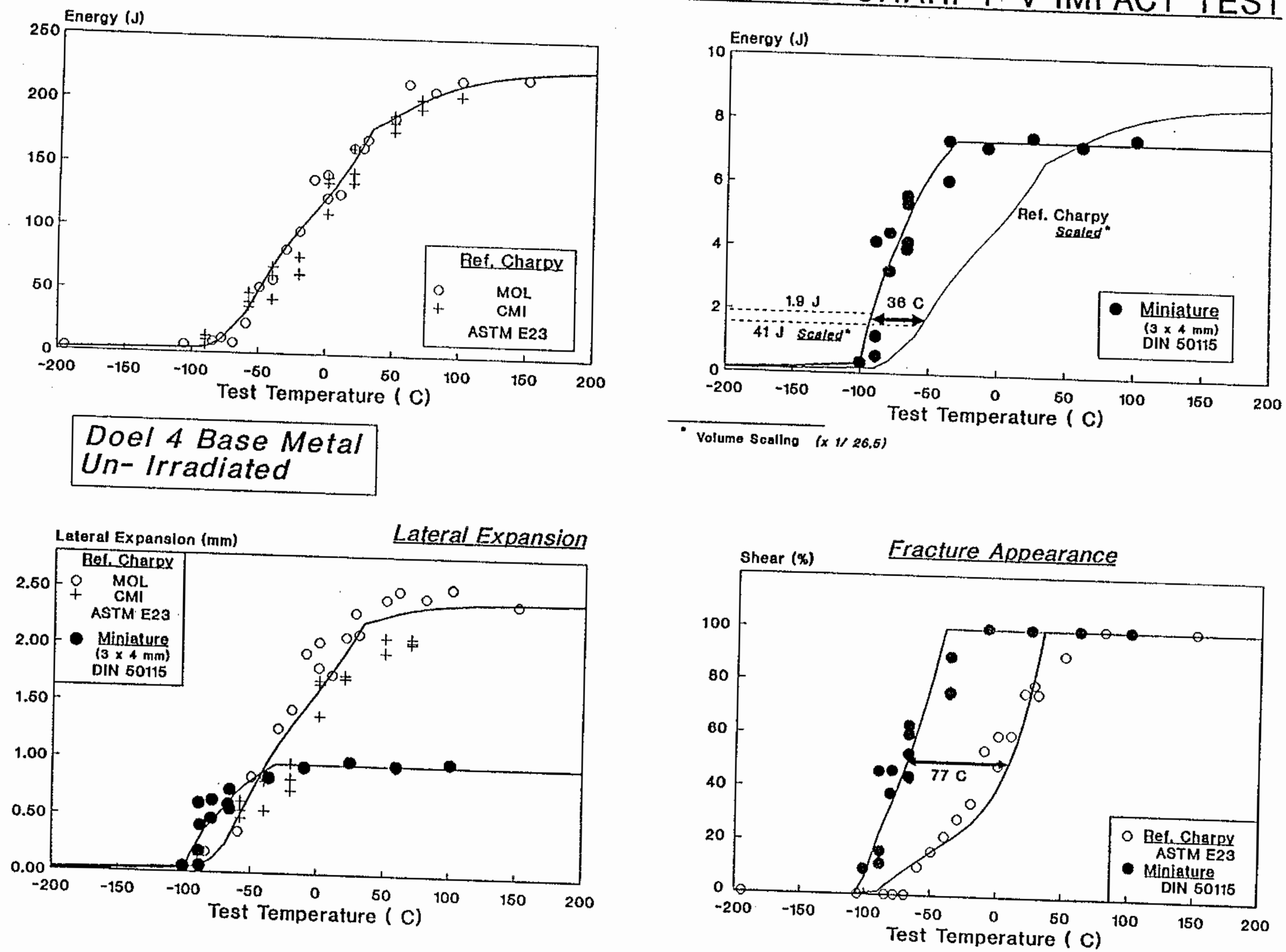
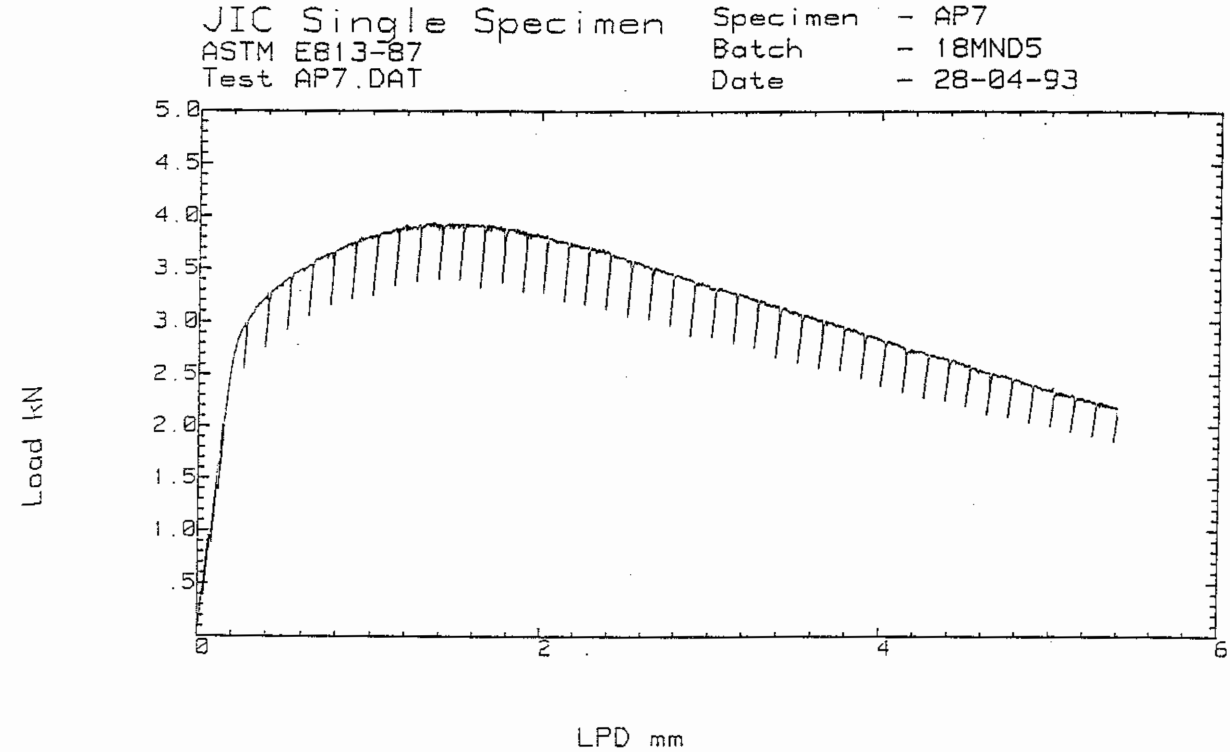


Fig. 11 INITIAL CALIBRATION OF MINIATURIZED CHARPY-V IMPACT TEST





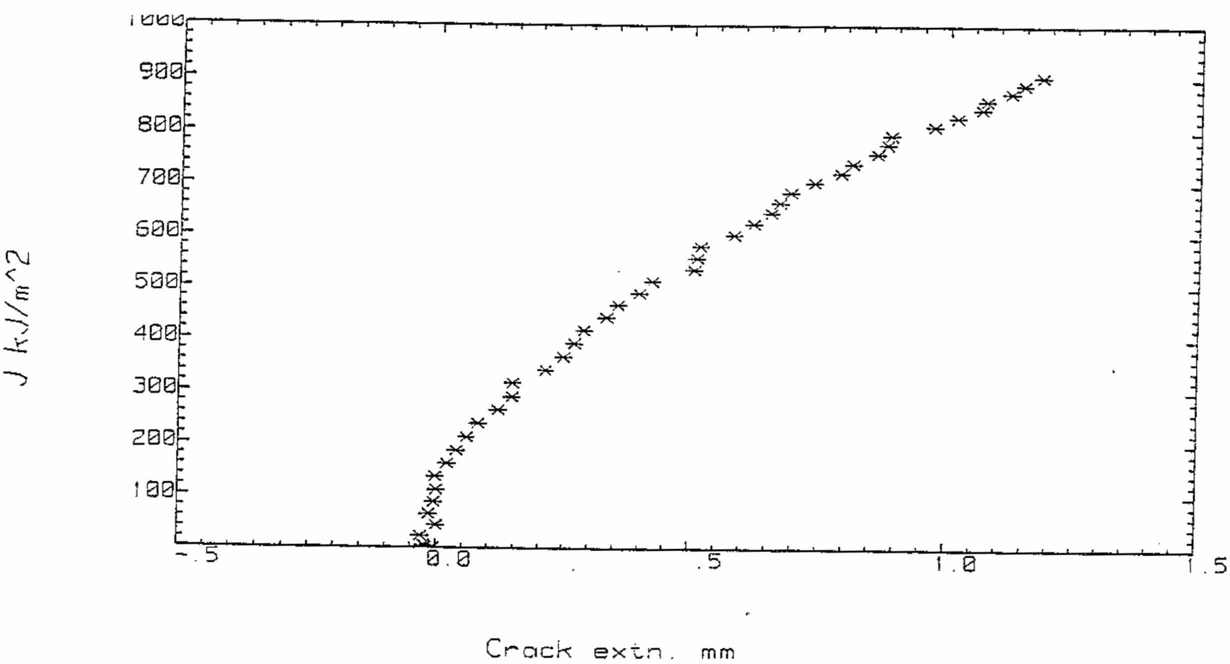


Figure 12 Typical test recording

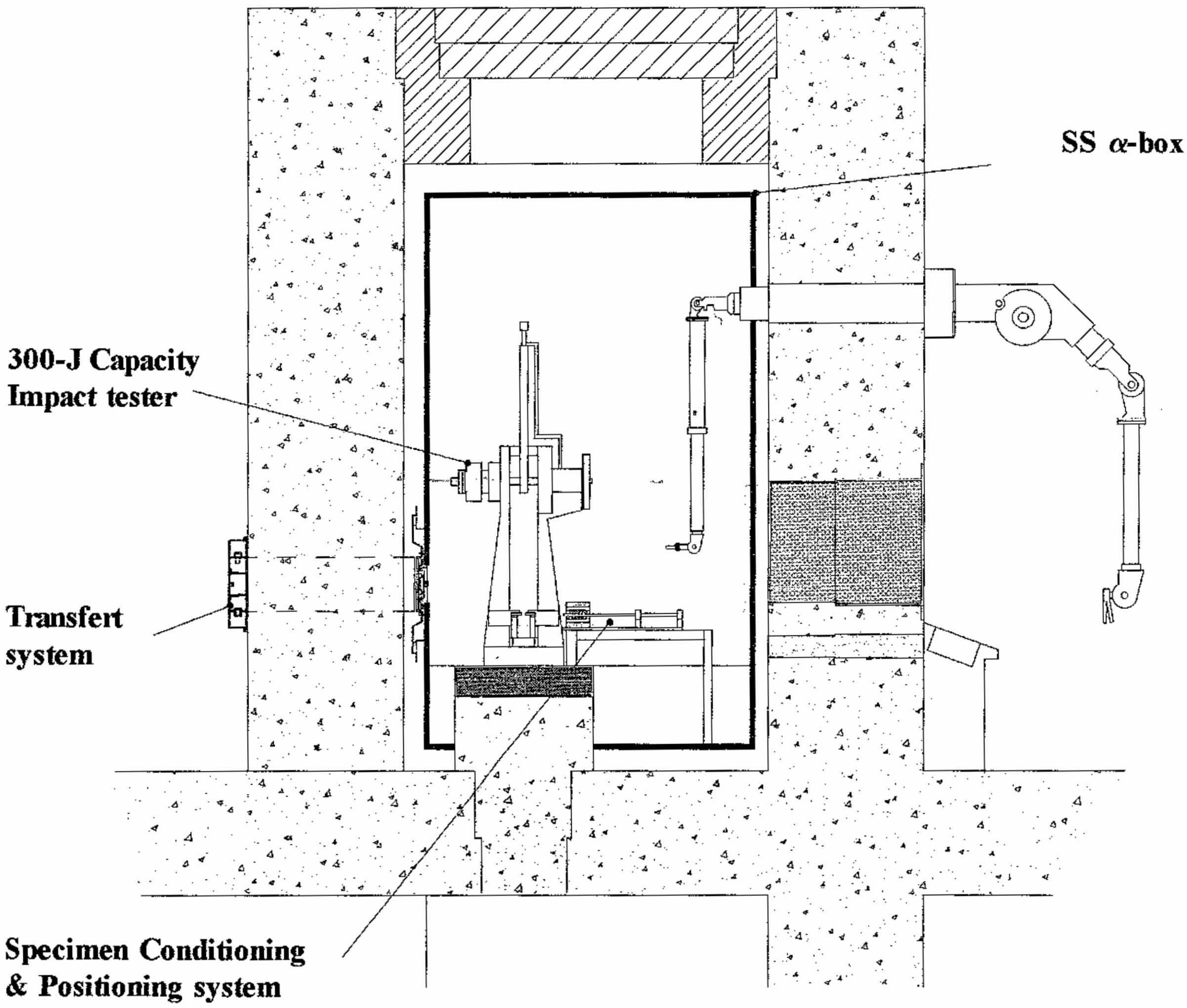


Fig. 13 Hot cell facility for Impact testing

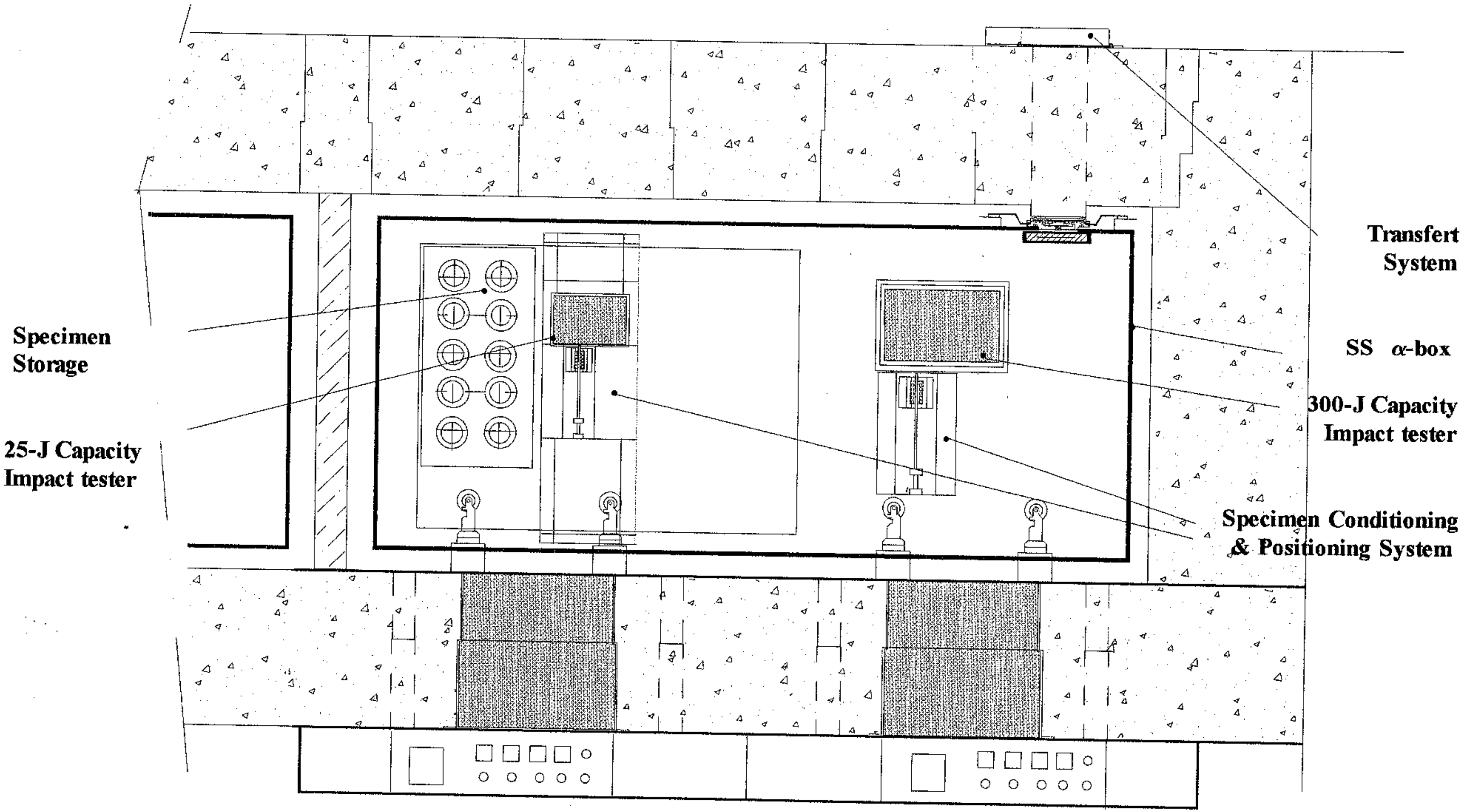


Fig. 14 Hot cell facility for impact testing

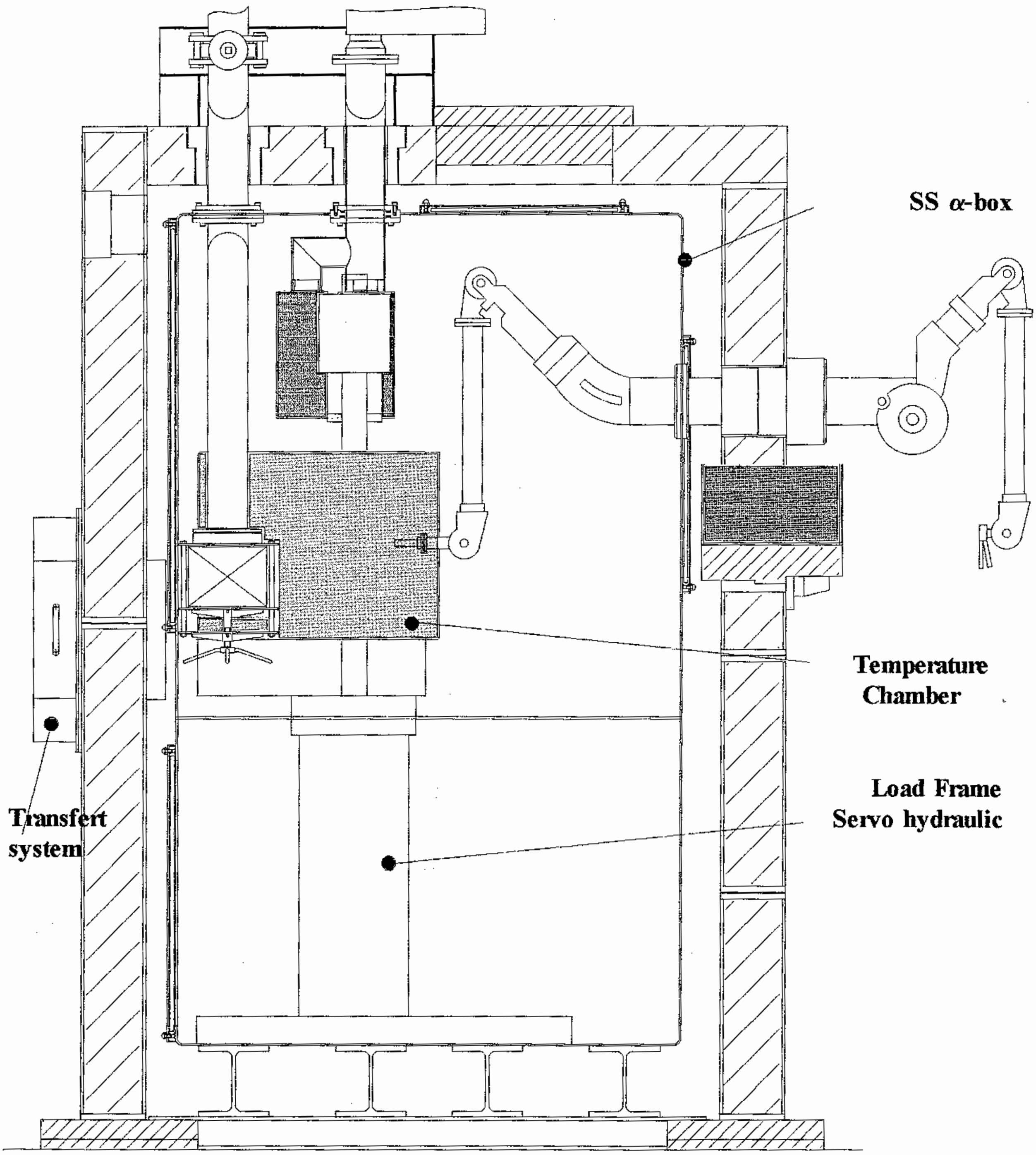


Fig. 15 Hot cell facility for Fracture Toughness testing