ASSESSMENT OF THE SAFETY OF RADIOACTIVE MATERIAL TRANSPORT PACKAGES. THE FRENCH APPROACH TO PROBLEMS RELATING TO THE RISK OF BRITTLE FRACTURE OF MATERIALS

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I. INTRODUCTION

The recommendations made by the IAEA in 1985 (IAEA Regulations, 1985) require that applicants seeking approval of type B packages must demonstrate that the integrity of the containment of the radioactive materials contained in the transport containers is maintained for the worst conditions liable to be encountered during transport, i.e., accident conditions at an ambient temperature of -40°C. The same applies to the radiological protection.

The demonstration concerns the so-called confinement closure walls as well as functional components such seals, covers, stoppers, fasteners, etc... and also the casing containing the radiological protection materials.

The purpose of this paper is to present the approach followed by the French Competent Authority in the field of the prevention of brittle fracture risks of the materials used for transport containers, and to communicate the experience gained over the last years from actual applications on various types of containers.

II. POSITION OF THE PROBLEM

The problem of brittle fracture is inherent in all types of materials, ranging from cast iron to titanium and including certain aluminum alloys, numerous plastics and elastomers as well as certain ferritic steels.

The IPSN, which is the technical support of the French Competent Authority, has developed an approach to the brittle fracture risk which is intended to be a global one: all types of materials must be reviewed as well as all types of configurations liable to be encountered in their utilization. We are looking for acceptance criteria which could be applicable in all fields where brittle fracture can occur.

It has to be remembered that in our view, nuclear safety falls essentially within the container designers' and users' province, and that they assume the responsibility thereof. Therefore, they have full liberty to select the methods of the demonstration of safety for the technical and/or technological solutions of which they recommend the application. On the other hand, they are under the obligation to present all the qualification factors of the methods they have chosen. Then, the Competent Authority analyses the said demonstrations, case by case, on the occasion of the application for approval, and delivers an opinion, limited to the case it has been presented with. It is within this framework that we have been led to take into consideration the case of a material never used until then in the manufacturing of containers of radioactive material and for which no appropriate standardizing documents were available.

Such an approach necessarily leads to a constantly evolving situation. We find on the one hand what could be called the state of the art of safety rules, resulting from the permanent upgrading of knowledge gained from the R&D and carried-out by the designers as well as by the experts of the Safety Authorities. On the other hand, we have to consider standardizing documents periodically upgraded and which are more or less almost always restricted in scope, or issued later, with regard to the above mentioned state of the art.

III. STATE OF IAEA REGULATIONS RELATIVE TO BRITTLE FRACTURE

They are essentially limited to Appendix IX of the Safety Series N°37 (IAEA Advisory, 1985) written before 1985.

Materials such as ferritic steel, ductile cast iron, some aluminum alloys, plastics and elastomers are considered liable to have a fragile behaviour.

The Charpy specimens are offered as examples for the determination of the transient temperature in order to choose the temperature of utilization.

Partial information is given in order to carry-out checks :

. High stress occurs only when the behavior is ductile.

. Elastic linear mechanics is to be applied by experts only.

. Material toughness can be determined only by using standardized characterization procedures.

. As the distribution and the evolution of stresses or strains in the course of time cannot be accurately known in accident conditions, the fracture mechanics will be of little use.

. Scale mockup cannot be used for demonstrations.

. The identification of standards for the selection of the defects to be considered is important.

. Thick walls are less sensitive to brittle fracture at low temperatures than narrow ones.

. Austenitic steels and some aluminum alloys are not liable to fragile behaviour.

IV. PROBLEMS ENCOUNTERED WHEN APPLYING THE IAEA 1985 RECOMMENDATIONS

The information provided in the existing documents does not explicitly give a clear and general description of the mode of ruin associated with a brittle fracture behavior. The latter is illustrated via examples which cannot provide us with a general and practical rule.

The more general rule proposed consists of using packing materials only at temperatures higher than the brittle to ductile transient temperature. The temperature is determined with the help of Charpy apparatus on different specimens at various temperatures. The transient temperature is determined on the resulting curve which shows the evolution of fracture energy as a function of temperature.

The method is not accurate in some cases. Ductile and fragile plateau may be more or less distant from one another, more or less flat; the value of the lower plateau may be more or less low. To select a transient temperature, one must sometimes make conservative choices, thus increasing the authorized temperature.

The Charpy energy test is not explicitly a characterization test of brittle fracture, since it does not take into account, amongst other things:

- the actual geometry of the container under consideration,
- the actual strain rate,
- the size of the defects liable to be initiated,
- the actual loading endured.

The developments brought into the field of the elastic or elastoplastic fracture mechanics now permit the achievement of finer analysis and analysis more representative than the sole consideration of the Charpy energy. While it does not exist at the moment, a fully standardized method for the analysis of brittle fracture absolutely unquestionable in all cases, the new developments may in some cases supply sure and practical results.

V. CRITERION OF BRITTLE FRACTURE

A risk of brittle fracture may occur when a defect which can be equated to a crack, existing in a container, can, under the strains generated during the impact, initiate and spread through the thickness of the wall bringing about a lack of tightness.

It can be demonstrated that said risk does not appear when using methods borrowed from the fracture mechanics. When using the linear elastic mechanics, the stress intensity factor K_I is calculated in the vicinity of the defect under consideration .

The analysis consists of calculating the stress intensity factor K_I applied and in comparing this value to a value of the material, the toughness K_{Ic}.

It is admitted that the initation (and therefore the rupture) is avoided if :

$$K_{I\ \text{applied}} < K_{Ic\ \text{material}} \quad (1)$$

So, the criterion contained in the equation (1) requires calculation of the $K_{I\ \text{applied}}$ and to experimental determination of the material toughness by respectively qualified calculations and qualified experimental methods. In particular, this means that the methods are to be validated in the impact conditions for the considered container. To do so, the following must be taken into account:

- the temperature effect: generally speaking, toughness decreases with the temperature,

- the thickness effect: the characterization of the toughness requires specimens of the same size (thickness) as the container walls,

- the notch effect (dimensions, area, sharpness, position within the thickness, orientation, uncertainty on the size).

- the strain effect: one must use actual strain distributions and take into account their evolution in the course of time, in order to take the most penalizing one.

- the strain rate effect, which affects tensile and compressive constitutive laws, and the material toughness.

With sufficiently low stresses (below yield stress) and small defects (1/10 of thickness), the linear elastic fracture mechanics can be used. In the other cases, it is recommended to use the fracture elastoplastic mechanics and a criterion such as J.

An important validation work has been done in the field of containers with a view to establish, in particular:

- stress dynamic calculation methods,

- dynamic toughness characterization methods.

The validation of the conservatism of these methods has been obtained on thick wall containers where stresses are below the yield stress. Such results allow to select the size of the defects to be controlled as well as the period of the inspections.

VI. R & D PROGRAMME INITIATED IN FRANCE

In the absence of a satisfactory rule in our initial analyses and to obtain a better understanding of the mechanical behavior of containers in parallel with the safety dossier analysis process, the IPSN decided to begin a Research and Development programme on representative containers. This is still in progress with the assistance of the Technology and Mechanics Department (DMT) of the Saclay Nuclear Research Centre and the Experimental Department of the Aquitaine Technical and Scientific Studies Centre (CESTA) of the CEA. The purpose of the programme is to establish rules for characterization of materials, for calculating stresses and for carrying out drop tests. The scope of application of these rules must be as wide as possible. The programme also includes qualification of laboratory procedures particularly by the use of instrumented Charpy apparatus for the industrial characterization of the dynamic toughness of materials.

It has been possible to apply the complete theoretical and experimental approach to several materials and different types of containers. The global aspect of this work has made it possible for us to draft the "Règles de Conception des Emballage" (RCE) (design rules for containers), the purpose of which is not to standardize but to uniformize the analysis procedures utilized in France by the designers of the containers and by the Safety Authorities. This approach is intended to be similar to that followed in the field of nuclear reactors with the drafting of the RCC.M and RCC.MR rules (AFCEN, 1983).

VI.1 Some of the research and development results

We have simultaneously progressed in the following parallel and complementary directions :

- calculations,
- instrumented tests,
- laboratory tests for the characterization of materials.

Here we shall briefly consider the most significant results.

VI.1.1 Modelling calculations

The action consisted in qualifying the tools used for calculating the behavior of containers in drops. We chose the PLEXUS code which was developed by the CEA to study dynamic phenomena, including high speed impact and puncturing. It is an explicit finite elements code, which means that it is capable of calculating strains as a function of time. It was applied and verified on the occasion of all our drop tests. Furthermore, it has been compared to codes from other countries including DYNA 3D of American origin and LAGAMINE developed by the University of Liège in Belgium. An example of a comparison between calculation and test results for a test involving a drop onto a bar from a height of one metre was presented at the ASME-PVP conference at Nashville (USA) in 1990 (Moulin et al., 1990). This code enables precise analysis of the mechanical behavior both of the bodies of containers and of shock absorber systems. It makes it possible to easily calculate the results recorded during a test (accelerations and strains). It remains for us to study a certain number of points, such as the reason for the over-estimation of strain. This may be associated with the modelling of real targets which do not behave like the theoretical "rigid" target.

During this work, we also noted the need to accurately determine the boundary conditions in the impact zone (lines of slip and initial contact surface). The same applies to knowledge of dynamic properties (tensile and compressive curves) which need to be used in modelling the inelastic behavior of materials.

VI.1.2 Instrumented tests

This activity had three goals :

- qualification of calculation models,
- qualification of the experimental procedure for carrying out instrumented tests on containers,
- qualification of the brittle fracture criterion by obtaining initiation of a machined notch under drop conditions.

The tests have been carried out on compact cast iron and ferritic steel containers. They were instrumented with strain gages and accelerometers on the containers and with strain gages and movement sensors on the target. Opening of the crack was measured at the surface by a suitable movement sensor.

They showed that plastic strain in compression of the container is essentially concentrated in the areas close to the impact surface. In the strained area of the containers, it is difficult to detect measurable characteristics of the damage. This part is not accessible to the instrumentation during the test.

During some drop tests, with increasing of the height of the drop, we have measured no significant increase of the degree of strain in the container. Strain remained in the elastic region in the greater part of the volume of the container. Inelastic strain remains limited to the areas in the immediate vicinity of the impact points (and is purely compressive). This helps to justify the use of linear elastic fracture mechanics in the case of this experiment for analyzing the behavior of the crack.

VI.1.3 Material characterization tests - Laboratory tests on specimens

This activity was carried out to verify the methods used for characterizing the cushioning and cask materials used in the mechanical analysis. These methods essentially relate to the following fields: traction tests, compression tests, puncturing, impact strength (Charpy) and toughness.

There are test methods which are adequately validated if the loading is static. But these methods must be verified if it is wished to make allowance for the strain rates specific to drop conditions. Similarly, it is necessary to carefully consider the notch effect of the specimens which are generally far smaller than the container wall thickness.

By way of an example, we presented at the SMIRT conference in 1991 in Tokyo (Moulin et al., 1991) intermediate results obtained after a ductile cast iron characterization session. We demonstrated that, under static loading, toughness J_{Ic} varies only slightly with temperature. At -40°C, its value is practically the same as at room temperature.

The value of J_{Ic} varies only slightly with the thickness of the specimen. It is however difficult to define crack initiation when the thickness is great. This may affect the value of J_{Ic} determined.

As concerns the effect of faster loadings, we have not been able to draw any firm conclusions. This effect is being studied by means of tests on instrumented Charpy apparatus.

However, it seems that the reductions of toughness due to dynamic effects obtained with the instrumented Charpy test are not so important that an preliminary analysis could show.

VII. CONCLUSION

The prevention of brittle fracture of materials used in radioactive material transport containers is a key element in safety analysis. In this paper, we have partly described the approach followed by IPSN over the last few years to establish a state of the art technique covering all the fields constituting parts of this demonstration: properties of materials, methods for measurement of properties, stress calculation methods (particularly in dynamics), representativeness of regulatory trials.

The method thus finalized has been applied in a number of actual cases on the occasion of applications for approval. This has enabled us to adopt positions validated by the results of the on-going research and development programme. This programme, which was begun on a national basis, has made fruitful exchanges possible with experts of other countries over the last two years. The findings of it have been that there is real similarity in the preoccupations and in the results which it has already been possible to compare. Study of the brittle fracture question has recently been taken up by the IAEA. An international working group has been formed and is in a position to draft a document introducing significant changes relative to Safety Series No.37. Concerning this matter, a consensus exists which is based on the above mentioned criteria.

We now consider it important to increase the coordinated nature of the different research and development actions currently being conducted in different countries, so as to be in a position to reach a broad consensus prior to any recommendation from the IAEA. Common analysis of the results obtained during tests on full-scale casks with cracks is extremely important and the work to experimentally obtain initiation of crack propagation must be continued.

We are open to active participation in the activities of a future international working group with a view to determine the framework of such co-operation, the first stage of which could be limited to numerical simulation, using the different codes, of the experimental results obtained in the drop tests already carried out with cracked containers.

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