THE CENTRAL ELECTRICITY GENERATING BOARD FLASK TEST PROJECT

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Abstract

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In 1981, the UK Central Electricity Generating Board set up a wide-ranging programme of theoretical and experimental work to develop a detailed understanding of the way in which Magnox flasks behave in severe transport accidents. Specific objectives of the project included an investigation into the validity of the use of scale models to represent full-size flask behaviour and the relevance of the IAEA regulatory tests in relation to real transport accidents. In all, over a hundred tests on flask components, model flasks and other test pieces were conducted, culuminating in the drop testing of a full-sized Magnox flask and a simulated rail crash test carried out in public in July 1984. The project was based on a steady progression from the study of fundamental principles to the execution of the train crash. Extensive use was made of experimental drop-test facilities and computer-aided analytical techniques, such as the finite element method. The project confirmed that, with some important exceptions, linear scalability can be applied with confidence to predict flask behaviour under impact loading. Where those exceptions were encountered, some guidance was obtained as to how it should be properly accounted for when interpreting scale model data. Good correlation was achieved between finite element analyses (carried out using DYNA-3D and ANSYS) and experimental results. The knowledge gained as a result of developing and running the finite element model proved to be invaluable in developing a high degree of understanding of flask impact behaviour. This knowledge ultimately allowed a series of very simple mathematical models to be developed and used as engineering tools in other studies.

1. INTRODUCTION

The CEGB is the world's longest established and largest transporter of spent nuclear fuel. In more than 7000 journeys made on the rail network in the United Kingdom in over 20 years of spent fuel transport, there have been no accidents involving a release of radioactivity.

Even so, there has been public anxiety about the transport of spent nuclear fuel. In particular concern has been voiced that only scale model flasks are used for proof testing and that the IAEA Regulatory tests involve impacts at speeds much less than may occur in a real accident.

The CEGB decided to set up a wide-ranging programme of theoretical and experimental work to develop a detailed understanding of the way in which flasks behave in severe transport accidents. There had been significant advances in computer analysis and in methods of physical testing and measurement, so it was decided to use the latest available technology to study flask accident behaviour from a more fundamental viewpoint than had been possible previously.

Specific objectives of the project included an investigation into the validity of the use of scale models to represent full-size flask behaviour and a study of the relevance of the IAEA Regulatory tests in relation to unlikely but real transport accidents.

The flask test project concentrated on the Magnox flask (Fig. 1), since this flask is by far the most widely used in the United Kingdom. In all, over a hundred tests on flask components, model flasks and other test pieces were conducted culminating in the drop testing of a full sized Magnox flask and a full scale rail crash demonstration carried out in public in July 1984.

The work was carried out jointly by the CEGB and Ove Arup and Partners and was reported in detail in a two day seminar sponsored by the Institution of Mechanical Engineers and the British Nuclear Energy Society [1].

2. STRUCTURE OF THE PROJECT

The project took place over a period of about four years and was based on a steady progression from a study of fundamental principles to the execution of a full scale, 100 mph[1] train crash. This progression is shown in Fig. 2 where an illustrated flow chart outlines the major features of the work. As can be seen from this figure, once the fundamental principles had been established, the main sub-division of the work was to investigate the ways in which forces acting on a flask promote permanent damage (i.e. flask modelling studies) and to study the ways in which accidents generate forces on a flask (i.e. real accident studies).

It can be seen from Fig. 2 that an essential element of the programme philosophy was the parallel development of experimental and analytical techniques. This theme was carried through all

[1] 1 mile = 1.609 km

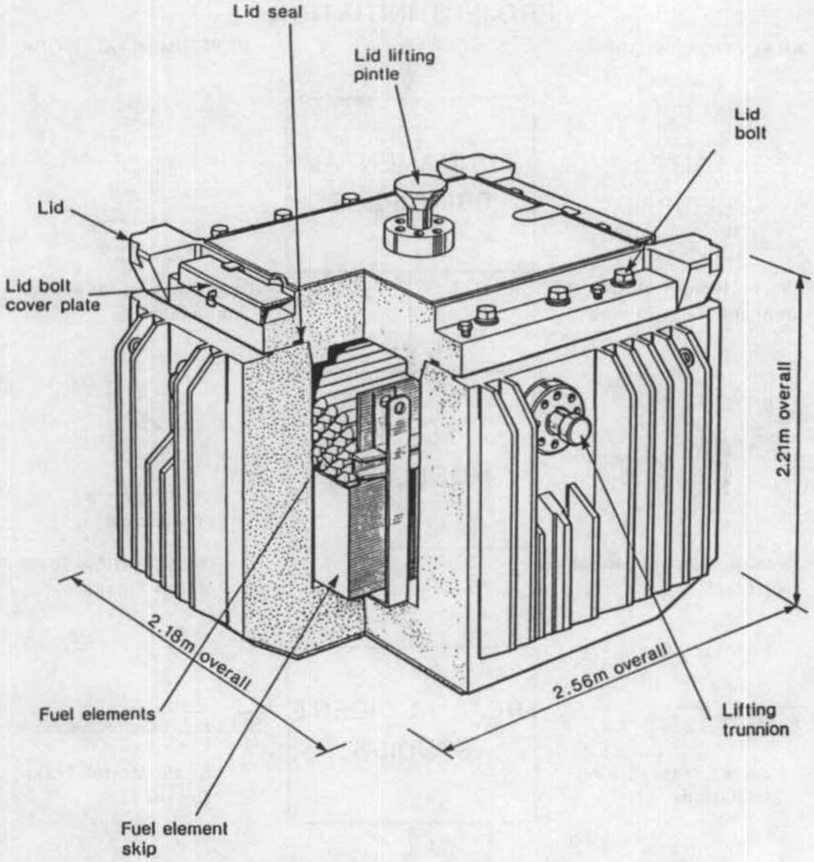

FIG. 1. Magnox irradiated fuel transport flask.

stages of the project since it was perceived from the outset that neither experiment nor analysis alone would provide the key to the level of understanding which was required. Much effort was spent correlating analytical and experimental results and validating analytical tools against progressively more complex physical models. As a consequence, a high degree of confidence was generated in the final mathematical models which were used to predict flask behaviour under regulatory test conditions and in real accident scenarios.

3. FUNDAMENTAL PRINCIPLES

In common with international practice, the CEGB demonstrates compliance with IAEA Regulations by using replica, scale model flasks. The model scale varies but 1/4-scale models are commonly used. Full-scale testing of large flasks weighing 48 tonnes or more is impractical and would be prohibitively expensive.

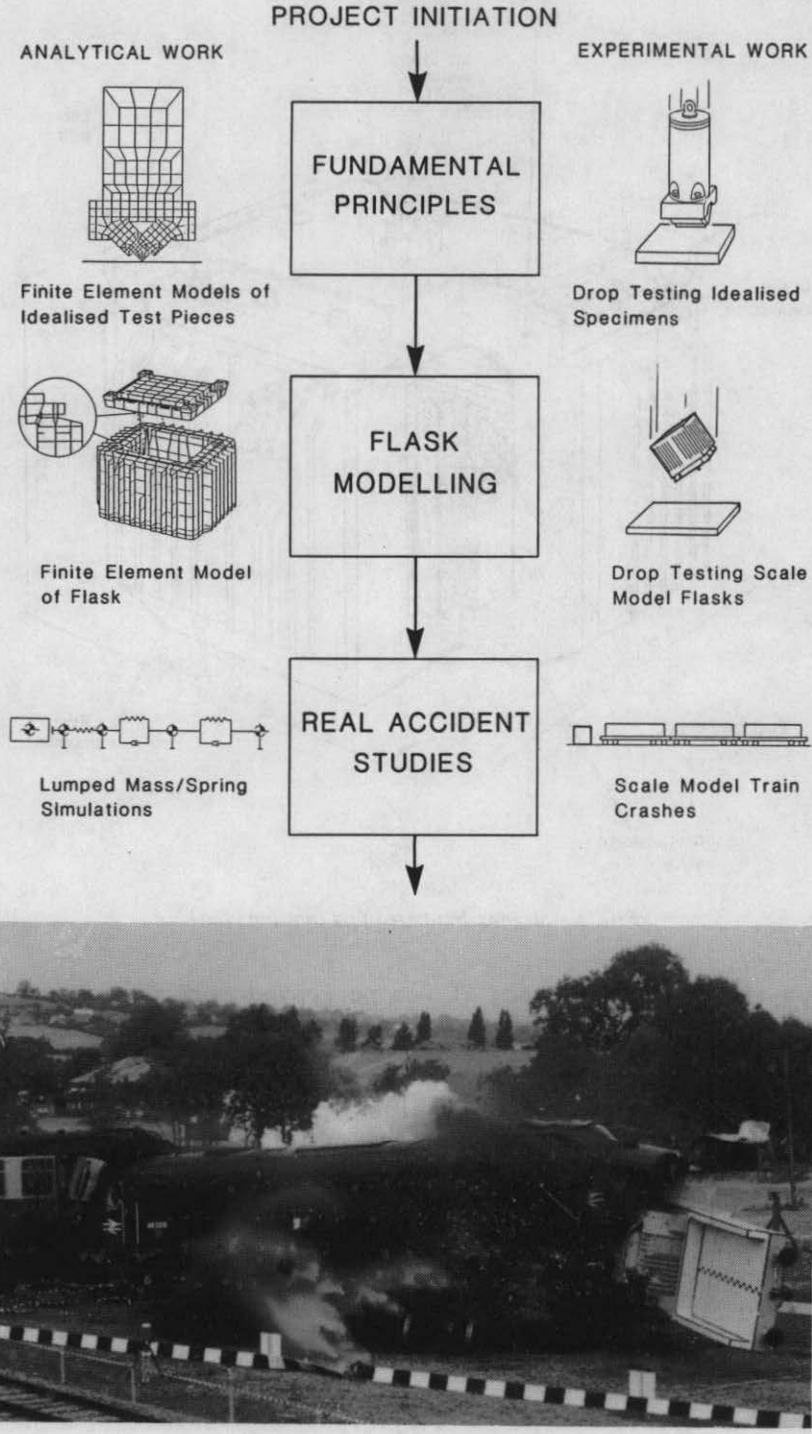

FIG. 2. Structures of the project.

However, it has always been recognised that some parameters cannot be scaled accurately and a specific objective of the first phase of the project was to study the validity of scalability in the impact environment for flasks.

Using the conventional methods of dimensional analysis [2] it can be shown that scale model tests can be carried out in a number of different ways to ensure that certain parameters scale correctly, but it is not possible to arrange for all of the parameters to scale correctly simultaneously. Using the Pi-theorem, three parameters were identified as being non-scaling within the context of flask impact testing. These were strain rate, fracture/tearing and gravity. A fourth parameter, dimensional tolerances, may also be difficult to scale, but this is a practical, rather than a theoretical, problem.

Gravity effects during primary impacts are small by inspection (since flask impacts typically generate accelerations in the order of hundreds of g) and were discounted. However, the other three parameters could not be dismissed by inspection and a series of generic tests was set up to investigate.

The Magnox flasks operated by the CEGB and SSEB are of a very solid, thick-walled construction and they rely upon the distortion of solid metal shock absorbers to limit the impact loads in certain attitudes. It was decided that the effects of strain-rate on shock absorber performance should be investigated and a series of model shock-absorbers was built at 1/16, 1/8 and 1/4 scales and drop tested. The results of the tests showed that errors arising from the non-scaling of this parameter are negligible.

A similar experimental approach was adopted for the study of fracture/tearing. In this case, a series of scale models was built in which welded plate construction was employed. This type of construction is commonly employed in protective structures (e.g. detachable shock absorbers) and fracturing in the welds plays a major part in establishing the collapse behaviour of these structures. The results of the tests showed that a marked degree of non-linearity occurs across the scales. The reasons for this are complex and relate to the form of construction. Further discussion is beyond the scope of this paper but a full description of this work and a discussion of the results may be found in [3].

A third series of tests looked into the effects of poorly scaled manufacturing tolerances. This is a particularly important issue in flasks where the fit-up between the body and its lid might involve quite tightly toleranced dimensions at full scale which are difficult to reproduce at small scale. For these tests, small scale boxes were manufactured which generally followed the dictates of true geometric modelling but which had errors in clearances and other detailed dimensions in the vicinity of the lid/body interface. The results indicated that while global parameters scale well (e.g. total indentation in the sidewall), detailed parameters were found to scale poorly (e.g. lid/body gaps).

In parallel with the experimental work, analytical studies were conducted to identify and validate the computer software needed for later, more detailed, flask impact calculations.

The first step was to establish "benchmarks" against which to assess the performance of the software and the different computational methods available. The initial analysis work was deliberately kept simple, and it was directly related to physical models that were being tested in the laboratory. The computer software was tested and validated against progressively more complex models. This exercise led to a series of guidelines being drawn up suggesting the best analytical approach for a variety of different types of structures under impact loading. These guidelines are fully described in [4]. The most suitable implicit and explicit computer codes for the analysis of the Magnox flask were found to be ANSYS and DYNA-3D, respectively.

4. FLASK MODELLING

The focus of the work in this phase turned specifically towards the Magnox flask and the need to develop a detailed understanding of its physical behaviour during impact. The approach which was adopted involved drop testing 1/8, 1/4, 1/2 and full-scale flasks onto an unyielding IAEA-style target. A family of flask models is shown in Fig. 3. The data obtained from these tests was used to guide the development of a mathematical model of the flask which was generated as part of an analytical study programmed to proceed in parallel with the test work.

The drop tests were carried out at the CEGB Structural Test Centre at Cheddar where test rigs capable of dropping from heights up to 36 m were available. Because of the need to preserve identical drop test conditions across all scales, a guidance system was developed which maintained the impact attitude within ±2° of the specified angle. This system was employed on all but the full-scale drop tests. (Guidance was not considered necessary for the full scale flask because of its very large inertia).

A considerable amount of instrumentation was carried on the flasks in each test. The instruments included accelerometers, strain gauges, displacement transducers and pressure transducers

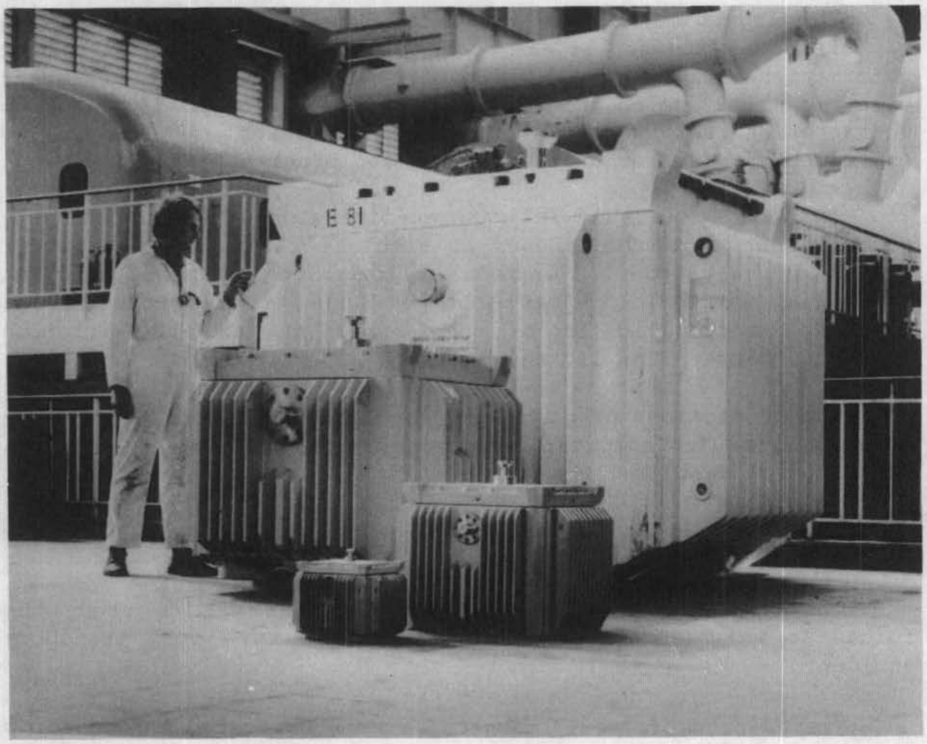

FIG. 3. Full-scale and scale model Magnox flasks.

and, in some tests, more than 30 channels of data were recorded simultaneously. Developing the techniques necessary for capturing high quality data in the impact environment formed an important part of the project and is discussed more fully in [5].

In addition to the electronic capture of transient data, permanent damage in the lid/body interface region was measured using feeler gauges and by monitoring the permanent stretch in the lid bolts. In general, linear scalability was found to apply very well.

The analytical studies began with a series of initial calculations in which the basic mechanisms of flask behaviour were explored using hand calculations and simple computer models. Once this work was complete, a full three-dimensional finite element model of the flask was assembled using ANSYS. The model employed the Wilson-formulated 8-noded solid brick element for the main body and lid of the flask, with shell elements for the fins. The fins were connected to the body using constraint equations.

The interface between the body and lid was modelled using gap elements with non-linear beam elements for the bolts. Local deformations of the flask body at the immediate point of impact were modelled using non-linear springs with load/deflection characteristics generated from the results of controlled experiments and other analyses using the program DYNA-3D.

The ANSYS model was fully three-dimensional and sufficiently general that it could be used to simulate flask behaviour under any impact attitude. The model allowed the response of each individual lid bolt to be monitored and it accounted for the movement of the lid across the spigot gap and the friction generated between the lid and body.

The predictions of global deceleration, deformation and bolt stretch from the computer model correlated very well with the experimental results.

5. REAL ACCIDENT STUDIES

The object of the real accident studies was to study the forces to which a flask would be subjected in a real transport accident.

The effects of "real" targets were investigated through drop testing using a series of shaped missiles and scale model flasks [6 - 8]. The targets used were natural rock, concrete, masonry and brickwork, and they included construction features (such as buttresses) as well as flat targets.

As well as the relief afforded by the relative strength of most real targets compared with the Regulatory unyielding target, other structural components associated with real transport accidents, such as railway wagons and locomotive structures, have additional cushioning effects. These effects were studied in a further series of 1/4-scale model crash tests and by parallel mathematical analysis [9].

Finally, a comprehensive survey of the flask transport routes in the United Kingdom was undertaken to establish the location of potential hazards. This data, together with transport accident statistics supplied by British Rail, allowed the probabilities of severe transport accidents to be estimated [10].

The results of these studies showed that, although severe transport accidents are possible, the mitigating factors associated with the strength of real targets, the energy absorbing characteristics of railway and other vehicle structures and the precise mechanics of any real accident all serve to considerably reduce the damage potential of the accident from its apparent face value. When all these factors are taken into account for Magnox fuel transport in the U.K. the probability of reaching the level of damage obtained in a Regulatory 9 m drop test was found to be exceedingly small.

As a result of the work carried out in this phase, a high speed train crash was identified as the accident scenario which had the most onerous combination of probability of occurrence and physical severity and arrangements were made to carry out such a test at full scale as a public demonstration of the integrity of Magnox flasks.

6. TRAIN CRASH DEMONSTRATION

It was decided that the public demonstration should be carried out using the heaviest locomotive currently in use with British Rail travelling at 100 mph. The Type 46 locomotive was selected and special adjustments were made to raise its top speed from its rated limit of 90 mph for the purposes of the test. It was also decided that the flask should be placed in the path of the locomotive at its most vulnerable attitude (i.e. with the lid/body interface angled towards the locomotive and the flask centre of gravity in line with the direction of impact). Care was taken to align the flask so that a valve would be in the impact zone and so that the wheels and tow-hook on the locomotive would inflict maximum damage to the lid bolts.

A considerable amount of preparatory analytical work was carried out using both lumped parameter modelling and the finite element model of the flask described in Section 4 [11]. This work was supplemented by the series of 1/4-scale model tests described in [9]. The results obtained were used to help define the attitude at which the flask should be struck in order to inflict maximum damage and to provide some prediction of flask behaviour during the event.

The crash test was monitored using a large number of high speed cameras and video recorders which were arranged to cover the test from all angles [12]. In addition to this, a purpose-built solid state data acquisition system [13] was mounted on the flask in order to monitor transient impact data using accelerometers, strain gauges, displacement transducers and pressure transducers.

The test was carried out on July 17th, 1984 in front of 2,000 spectators seated in grandstands on either side of the test track. The event was also featured live on national television. The flask survived the test with minimal damage and, during post-test examination, was found to have held its internal pressure to within 0.002 MPa of the 0.69 MPa to which it had been pressurised originally. Measurements of transient and permanent deformations in the region of the lid/body interface confirmed that the impact experienced by the flask was much less severe than that imposed upon it during a Regulatory 9 m drop onto a rigid target. The peak impact force in the rail crash test was 29 MN compared with 75 MN in the full scale Regulatory drop test.

7. CONCLUSIONS

The following conclusions have been drawn from the flask test project:

i) The use of scale models can be justified for estimating the impact performance of Magnox flasks. Some caution must, however, be exercised when doing this.

ii) Mathematical models are an essential adjunct to developing a proper understanding of flask impact behaviour. Properly validated models can be used in a predictive manner with a high degree of confidence.

iii) The IAEA Regulatory 9 metre drop test appears to cover those severe accidents which can be foreseen on the U.K. transport system. This is because there is considerable mitigation of the impact loads imposed on flasks in real accident environments.

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