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SMASH HIT ! MAGNOX LESSON FOR TODAY

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ABSTRACT

On July 17 1984 at Old Dalby in Leicestershire, UK, a spectacular staged rail crash took place between a 100mph train and a Magnox spent fuel flask. Often replayed on the media, this event makes a lasting impression on the viewer of what a “worst case” impact accident scenario would look like which might be imagined could cause a release of radioactive material during the transport of irradiated nuclear fuel by rail.

It is less well remembered that this crash test was but one part of a comprehensive programme of work carried out by the then Central Electricity Generating Board, spanning 4 years and costing some £4M of early 1980’s money. This programme clearly met a number of key objectives, to mention just a few it:-

- demonstrated the practicality and effectiveness of scale model testing to prove the impact integrity of spent fuel flasks made of ductile materials;
- showed how simple analytical and more complex computer solutions could alternatively or additionally be used to estimate and refine predictions of impact forces and damage;
- showed how route specific analysis might be used to determine the likelihood and potential magnitude of various impact scenarios, enabling typical, credible, “worst case” scenarios to be postulated and their probabilities estimated;
- enabled the severity of the IAEA regulatory tests to be compared with that of a realistic severe impact scenario; and
- produced a large body of data and developed techniques which are applicable to other designs of radioactive material packages.

This paper reviews the results of that work and recalls the major conclusions which have continuing relevance to present day programmes which are aimed at ensuring that radioactive material continues to be transported under the highest practical standards of safety.

INTRODUCTION

In the early 1980s the then Central Electricity Generating Board (CEGB) embarked on a programme of work to publicly demonstrate the impact safety of one of its types of spent fuel flasks, namely the Mk2c design, used to convey spent fuel from its Magnox power stations to the Sellafield reprocessing plant. Regulations in force at that time, based on the then current edition of the International Atomic Energy Agency’s Regulations for the Safe Transport of Radioactive Material (the 1973 Revised Edition (As Amended)) required that designs be demonstrated to comply with a series of compliance demonstration tests representing severe accidental conditions of impact, fire and immersion. Then, as is still the case under the most recent edition of the IAEA’s Regulations today, demonstration of compliance could be accomplished by any, or by any combination, of :-

- Performance of tests with prototypes or samples of the packaging as normally presented for transport, in which case the contents of the packaging for the test shall simulate as closely as practicable the expected normal radioactive contents.
- Reference to previous satisfactory demonstrations of sufficiently similar nature.
- Performance of tests with models of appropriate scale incorporating those features which are significant with respect to the item under investigation, when engineering experience has shown

results of such tests to be suitable for design purposes. When a scale model is used, the need for adjusting certain test parameters, such as the penetrator diameter or the compressive load, shall be taken into account.

- Calculation, or reasoned argument, when the calculative procedures and parameters are generally agreed to be reliable or conservative.

What was conspicuous about the CEGB's work programme was that it not only adopted a combination of all these methods but also included many elements not required by regulations including:-

- demonstrating the practicality and effectiveness of scale model testing to prove the impact integrity of spent fuel flasks made of ductile materials;
- showed how simple analytical and more complex computer solutions could alternatively or additionally be used to estimate and refine predictions of impact forces and damage;
- showed how route specific analysis might be used to determine the likelihood and potential magnitude of various impact scenarios, enabling typical, credible, "worst case" scenarios to be postulated and their probabilities estimated;
- performed instrumented impact tests of full scale flasks under both IAEA test conditions and in a demonstration train crash simulating a realistic very severe impact scenario;
- enabled the severity of the IAEA regulatory tests to be compared with that of a realistic very severe impact scenario; and
- produced a large body of data and developed techniques which are applicable to other designs of radioactive material packages.

The complete program of work was described in a series of 21 papers presented at a seminar organised by the Nuclear Energy Committee of the Power Industries Division of the Institution of Mechanical Engineers, jointly sponsored by the Power Industries Division of the Institution of Mechanical Engineers the British Nuclear Energy Society at the Institution of Electrical Engineers, 30 April and 1 May 1985[1]. In summarising that work, the current authors acknowledge full credit to the original authors of those papers, staff of the CEGB, Ove Arup and Partners (now Arup), British Railways Board and Thorn EMI Electronics Ltd.

SCALE MODEL TESTING

Theoretical Approach

A theoretical approach to scale model testing is presented by P. J. Donelan and A. R. Dowling in Paper 4[2]. Based on Buckingham's "Π" theorem and in the absence of significance fracture processes, it is shown that the 13 variables governing impact behaviour and the 8 variables describing impact response (Table 1) can be related by grouping them into a number of dimensionless groups or "Π groups". If the governing Π groups of model and prototype are equal then so too will be the Π groups defining the response to impact.

According to the Π theorem, the total number of Π groups is smaller than the number of variables by the number of fundamental units required to describe the system completely. In this case there are four fundamental units (chosen as mass, length, time and temperature) and therefore 17 Π groups

The basic dimensions defining each variable may then be entered into the dimension matrix [A] where the columns describe the exponents of the basic dimensions for each variable and the rows represent the reference dimensions.

The dimension matrix is then transformed into reduced row echelon form and the null space vectors may then be determined which satisfy the relationship:

$$\text{Null}\ [\mathbf{A}] = \{\mathbf{v} \in V : A\mathbf{v} = 0\}.$$

The set of vectors **v** then show the powers of each of the variables in each dimensionless Π group. The Π groups' formulation and physical significance is described in Paper 4 as discussed below.

Significance of the Π groups

Governing Variables:

$\Pi_1 = \lambda_{ij}/\lambda$ requires there to be an exact geometric similarity between model and prototype.

$\Pi_2 = x_i/\lambda$ requires the same relative positions of model/prototype, i.e. the same impact orientation.
$\Pi_3 = \alpha\theta$ means that for the same material in model and prototype, the same temperature is required.
$\Pi_4 = h$ requires the same temperature distribution in model and prototype.
$\Pi_5 = \beta$ requires equal damping coefficient (satisfied by identical materials).
$\Pi_6 = \mu$ requires equal friction coefficients (where sliding friction is a significant factor).
$\Pi_7 = \rho V_0^2/E$ requires, for identical materials, that the impact velocities are equal.
$\Pi_8 = \rho g\lambda/E$ for same materials, requires equal size model and prototype, when gravity effects significant.
$\Pi_9 = kV_0/\lambda$ requires, for strain rate sensitive material, that impact velocity is scaled to size (not compatible with Π_7).

Response Variables:

(For a model reduced in scale by a factor m (>1) and constructed of identical materials)

$\Pi_{10} = P/E$ shows equal pressures in model and prototype.
$\Pi_{11} = T_0V_0/\lambda$ shows impact duration is smaller for the model by a factor = m.
$\Pi_{12} = t/T_0$ shows that all times are reduced for the model by the factor m.
$\Pi_{13} = V_t/V_0$ shows that velocities are equal in model and prototype at equal corresponding times.
$\Pi_{14} = \delta_i/\lambda$ shows that deflections on the model are proportional to its size.
$\Pi_{15} = \varepsilon_{ij}$ shows equal strains on model and prototype.
$\Pi_{16} = \dot{\varepsilon}_{ij}T_0$ shows a larger rate of strain in the model by a factor m.
$\Pi_{17} = \sigma_{ij}/E$ shows equal strains in model and prototype.

Table 1. Governing and Response Variables

Governing Variables	E	Youngs Modulus (N/m^2)
	k	Strain Rate sensitivity coefficient (sec)
	ρ	Density (kg/m^3)
	α	Thermal expansion Coefficient (deg^{-1})
	μ	Coefficient of Friction (-)
	β	Damping Coefficient (-)
	λ	Typical dimension (m)
	λ_{ij}	Distance between points i & j (m)
	x_i	Position of point i at impact (m)
	h	Coefficient determining temperature distribution (-)
	θ	Temperature (deg)
	V_0	Impact speed (m/s)
	g	Acceleration due to gravity (m/sec^2)
Response Variables	P	Pressure applied to package (N/m^2)
	T_0	Duration of Impact (sec)
	t	Time elapsed after Impact (sec)
	V_t	Speed at time T (m/sec)
	δ_i	Deflection at point i (m)
	ε_{ij}	Strain between points i & j (-)
	$\dot{\varepsilon}_{ij}$	Strain Rate between points i and j (sec^{-1})
	σ_{ij}	Stress between points i & j (N/m^2)

Hence for a scale factor m, the fundamental dimensions of mass length and time scale as follows:
Model mass = 1/m^3 of prototype mass, model dimensions = 1/m of prototype dimensions and model time durations = 1/m of prototype times. From these fundamental dimensions the scaling of all other properties can readily be derived.
Complete similarity between model and prototype is thus shown not to be possible due to fracture effects, strain rate sensitivity, and gravity effects (it is practically impossible to simultaneously equate the Π_7, Π_8 and Π_9 for a reduced scale model and prototype).
In the case of the material of construction of the Magnox fuel flask it was shown that the effect of strain rate on the essential strength properties of the BS1501-224-400B body material was modest, even at a scaling factor of 8 (equal to the ratio of strain rate in the model versus the prototype) which would generally be considered too small a model to produce definitive results. The properties of the bolt material (BS 970-722M24) were also shown to be insensitive to strain rate at rates typically observed in model drop testing. For other materials of construction, strain rate sensitivity should be determined as this might limit the scale factor which can reasonably be applied to the model.

The non-scaling of gravity is unlikely to negate the validity of model tests as it is of significance only in determining the (different) attitude of secondary impacts in the model where there is significant rotation after the primary impact, which is of little interest as secondary impacts are less severe than those usually investigated (impact attitudes of “centre of gravity over point of impact” and “slap down” being the norm).

Fracture effects, which depend on absolute size of the defect or ductile tearing, do not scale. Assurance that failure will not occur in the prototype rests on materials testing under appropriate conditions and inspection to verify the absence of significant defects.

Experimental Model Testing

Experiments were performed to verify the validity of the theory and investigate the significance of departures from perfect scaling noted in the theory above. Tests were carried out on a series of mild steel wedges, cones and pyramids, representative of the hard shock absorbing features of Magnox fuel flasks at a variety of scales (full, $^1/_2$, and $^1/_4$ scale) and impact velocities (13 – 18 m/sec). These showed that a scale factor of four is insufficient to affect global response for strain rates in the order of 10-100 sec^{-1}.

Tensile tests of bolts at various scales (1/8 to full scale) confirmed that minor differences, e.g. incomplete similarity of threads are not significant. However, an unexpected result showed that bolts with a central drain hole showed reduced elongation to failure, indicating that detailed modelling of seemingly insignificant features may be important in some cases. Tests of simplified box like structural models with side walls thinner than those of Magnox fuel flask confirmed the linear scalability of global deformations over a range of scales 1/3, 2/3 and full scale.

Tests of plate structures where buckling and tearing modes of failure were encountered showed marked departure from scaling, with reduced scale models under predicting the deformation of full scale prototypes. This indicates that it may be important to test certain structures, such as may be encountered in components such as internal fuel support frames at full scale where buckling and/or tearing modes of failure are likely to be approached.

Drop Testing of Scale model Magnox Fuel Flasks

A series of drop tests were carried out on $^1/_2$, $^1/_4$ and $^1/_8$ scale Magnox fuel flasks (Figure 1) at drop heights of 9 metres and 18 metres in both side edge and lid corner impact attitudes onto a regulatory anvil. These tests further confirmed that the global impact parameters of acceleration, velocity and displacement were shown to scale in accordance with the scaling laws derived from Buckingham’s Π Theorem.

Full Scale Drop Testing of a Magnox Fuel Flask

Full scale 9 metre drop testing was carried out on a production Mk2c Magnox Fuel Flask in March 1984 (Figure 1) and is described in Paper No. 7, by J. H. Barnfield and P. J. Donelan[3]. The purpose was:

- to validate the use of scale models for drop testing;
- to demonstration to the public the ability of the Magnox Fuel Flask to meet the regulatory 9 metre drop test; and
- to provide a basis for comparison to the damage experienced in an extremely severe transport accident [simulated in the train crash demonstration].

The test results confirmed the predictions of the earlier model tests and demonstrated full compliance with the IAEA 9 metre drop test.

Figure 1. Full scale, and $^1/_2$, $^1/_4$ and $^1/_8$ scale model, Magnox Fuel Flasks

Conclusions concerning Scale Model Impact Testing

It was concluded from theoretical, component testing, full scale and reduced scale model testing at various scales that identifiable non-scalable variables do not significantly affect the impact behaviour of Magnox flask models over a scale range as much as eight. Careful experimental control, attention to accurate reproduction of relevant detailed features were, however, found to be essential.

ANALYTICAL STUDIES

Paper No. 5 by P. R. B. Dallard[4] describes analytical studies carried out to gain a better fundamental understanding of the impact behaviour of the Magnox flask and to develop an analytical approach that could be used to calculate flask impact damage.

Until that time, impact performance of flask designs had to be developed and proved experimentally. Benefits were perceived in performing tests and analysis as complementary activities and recent developments in computers and analysis programmes (e.g. DYNA 2D and DYNA 3D) had led to an increased interest in analysis as solutions could be obtained for a wide range of problems.

Dallard describes how an understanding of the fundamental aspects of flask impact behaviour was achieved. Methods of analysis were developed to determine:

- the amount of energy to be absorbed in the impact;
- the impact loads generated;
- the forces set up within the flask – arising from inertia loads, initial internal pressure loads, fluid load, fuel load, spigot forces and bolt loads; and
- the permanent bolt extensions that may result, considering the inertia effects, sliding at the spigot, elastic flexure and lid jacking.

It was recognised that, to gain a complete understanding of flask behaviour, aspects of the behaviour of greater complexity need to be considered. Dynamic response of the lid once the spigot gap has closed, and the effects of this on lid flexure, lid-body opening, and bolt stress were their concern. Hand calculations then became increasingly intractable and FE analyses were required.

Extensive assessments were carried out to evaluate the FE programmes and to select those to be used for the analyses. The FE programmes were then used to analyse the same simple cantilever beam bending problem and the results compared with theory. The FE programmes were then used to analyse three series of experiments, and the results were compared with the test results and with each other. ANSYS was chosen for the analysis of the overall flask behaviour while DYNA 3D was chosen to model the area local to the point of impact.

Simple element tests were carried out to understand the behaviour of different element types. Model tests of the flask lid were carried out and the analysis models were benchmarked to these tests. Bolt characteristics were obtained by benchmarking against tensile tests. The model was designed based on a good understanding of the expected behaviour of the flask. A total of five dynamic transient analyses were performed in the lid edge and side edge orientations. The analysis results were thoroughly interrogated and understood. They were then compared with test results and any discrepancy understood and explained.

Although computational power and the explicit transient FE technique have developed beyond recognition in the quarter of a century since the Magnox flask work was carried out, the approach still represents good practice which remains very relevant to this day, namely:

- A good understanding of impact behaviour is a necessary precursor to FE analysis. A thorough understanding of the behaviour of the flask was sought before any attempt was made to model it. Hand calculations and simple analytical procedures were developed to quantify basic loadings and behaviour before FE analyses were carried out. This avoided the all too common pitfall of too easily giving up trying to understand the behaviour of a flask before deciding how to model it without first coming to an understanding of the expected behaviour resulting in important flask details and behaviour being missed or misrepresented in the model.

- Secondly they tried to understand the behaviour from the FE analysis. With the increasing power and capabilities of modern computers and FE codes, and the size and complexity of FE models that accompany this trend, it is easy to be lulled into accepting all results without question. In fact the opportunities for bad engineering increase as the complexity of the computer model increases. Computer models sometimes produce surprising results because the initial expectation was wrong, and sometimes because it is behaving incorrectly. It is vital to interrogate the analysis results and judge whether the results are reasonable, and so it is vital to try to understand the behaviour from the results.

- The limitations of the analysis codes were understood. It is vital to work from a good understanding of the code. If there are uncertainties, tests must be carried out to assure that the code has been used correctly. Since FE codes are becoming increasingly complex and the source code is not normally available to the user, the expertise of FE code developers should be utilised.

- Uncertainties were taken into account. A common problem with FE analysis – i.e. not knowing the limit of a FE code, the limitations of an analysis, or the error and accuracy of an analysis.

- The design the FE model based on a good understanding of the expected behaviour. With massive increase in computing power and sophistication in automatic meshing tools, it is tempting to use automatic meshing to generate the model. However, a good model must be designed taking into account the expected behaviour of a flask, including the expected locations of gradients and variations in stresses and deformations, etc - engineering considerations which come from an understanding of the flask behaviour which an automatic mesher cannot provide.

FLASK TRANSPORT IMPACT HAZARDS

Paper No. 8[5] by M. C. Cook, J. C. Miles and M. Shears contains a comprehensive study of possible impact hazards and the probabilities of such impacts occurring. The study looked at all of the road and rail routes travelled by vehicles carrying Irradiated Fuel Transport Flasks in the UK in the 1980's covering a total distance of 1535 km. The probability analysis was based on 672 loaded flask movements per year.

Hazard Analysis

The hazard analysis set out to determine what impact hazards existed on the rail routes which were routinely used by the flask traffic. The data for the analysis was derived from detailed Ordnance Survey and geological maps. More detailed studies using reconnaissance were carried out on selected routes which were representative of a mountainous route, a typical rural route, a section of highly populated urban route and a high speed high traffic route. The hazards were subdivided into fixed hazards and mobile hazards. The fixed hazards identified as significant were:

- Trackside geology including rock outcrops
- Tunnel and Bridge abutments
- High bridges

The trackside geological study data from geological maps took no account of the benefit that might be gained from soft natural deposits such as topsoil on the underlying rock.

Tunnel abutments were considered to be a more robust hazard than man made bridge abutments and of these brick or stone faced portals were determined to be less of a hazard than bare rock portals.

The map study identified 937 underbridges (bridges which the flask traffic passed over) and 77 of these were visited. Of these 55 were found to have structures higher than 9m, the highest being 50 m above the lowest ground.

The main mobile hazards identified as significant were, not surprisingly, railway collisions and road collisions. The road routes were found to be of low risk due to the low speeds of the road vehicles and the controls imposed on them. Interestingly a number of airfields were identified as being close enough to the routes to make aircraft impact a significant hazard.

The following hazards were considered in the initial study but were discounted as being of too low a risk to be significant:

- Explosions and flying debris from industrial sites
- Landslides
- Earthquakes and Tsunamis

Accident Probability Analysis

The accident probability analysis was based on rail incident and accident data for a complete decade. The rail data was gathered from two sources, the rail operator and the government's rail regulator. Air incident data was gathered from the Civil Aviation Authority (CAA) and air traffic details were obtained from individual airfields.

Pulling this data together in a meaningful form was a significant task in itself and is perhaps under-represented by the few lines it received in the original report. A proportionate probability was determined for each possible outcome for an event and then the probabilities were combined in a fault tree analysis to determine the overall probability of an extreme event. For example the proportion of all railway collisions in which involved a train on an adjacent line impacting a derailed wagon is 0.11 and the proportion of flask train derailments in which the flask wagon would derail is 0.44. Combining these figures with the probability that a derailed wagon would not be protected by other wreckage (0.5) gives an overall proportion of flask train collisions in which the flask is struck by a locomotive on an adjacent line of (0.11x0.44x0.5) 0.011. Fault tree analyses were carried out for each significant impact scenario, determined from the route hazard analysis described above.

Significant results

Of the scenarios studied the most likely accident was determined to be a Flask wagon derailment with no other impact. The predicted probability for this event was of the order of 7 x 10^{-2} per year. The least likely event was a secondary impact of a flask onto rock from a height exceeding 20m with a probability of 10^{-8} per year. The probability of the train crash scenario simulated by the crash test was determined to be 13.4 x 10^{-6} per year. Or, to put it another way, for a flask traffic of 672 loaded movements per year on the 1535 km of track in use at the time of the study, with the rail, road and air traffic conditions considered in the study, there would be an accident of the severity simulated by the crash test once every 75,000 years.

ORGANISATION OF THE CRASH TEST

Much has been written in many other papers about the data collected from the research programme which led up to the crash test and how it has supported the regulatory impact test requirements. What is often overlooked, however, is what a tremendous engineering achievement the test was itself. Between the first discussions with the rail operators in January 1983 to the test in July 1984 a team of 20 people were tasked with mounting a potentially dangerous demonstration in a manner which could be viewed safely and satisfactorily by an invited audience and which would not hazard persons unassociated with the exercise. A further major consideration was the knowledge that everything needed to work first time – the exercise could not be repeated. Outlined below are some of the significant factors which had to be considered during the planning of the test.

Timing

It had been determined that high quality film and video footage would be obtained from the test (R. Knight, Paper No. 20[6]), both for analysis and public relations purposes. The high speed cameras to be used required high levels of illumination and, since the cameras were going to be mounted to cover events along a 200m length of track the use of artificial lighting was not going to be practical option. The only period during which sufficient natural daylight is available in the U.K. is 3 hours either side of midday between mid June and mid August. The demonstration took place at 12.18 GMT on 17 July. A three week slippage in the programme would have taken the event outside of the possible photography window.

Photography

As outlined above the test was to be photographed for both analysis and publicity purposes. Previously package drop tests, with a typically 25 millisecond primary impact duration, had been filmed at speeds up to 5000 frames per second under high power artificial lighting. However the expected duration of the crash test of 200 milliseconds with lower levels of natural lighting demanded a less complex solution. The primary impact was, therefore, filmed at 1000 frames per second with the subsequent behaviour being recorded at 400 frames per second. The cameras were ground and helicopter mounted. Additionally 19 “sacrificial” cameras were mounted on the train and close to the flask to record the moment of impact. The footage from these cameras has probably been in video or still format at every PATRAM since.

Instrumentation

The nature of the event was such that it was going to be impossible to rely on fixed wires or telemetry to retrieve data from the instrumentation on the flask. Therefore special ruggedised flask and train mounted recording equipment was developed to withstand the conditions in the impact, described by D. C. Thomlinson, P. J. Donelan, E. P. S. Tufton and R. Pryer in Paper No. 19[7]. The maximum recording duration of this was 3 seconds. Triggering this recording equipment to come on at the time of impact was a challenge in itself.

Safety

It was soon concluded that debris from the impact could travel several hundred metres and become a significant hazard to the observers and public in the vicinity of the test (R. A. Blythe and E. P. S. Tufton, Paper No. 19[8]). It was established that methods for predicting the range and trajectories of such debris did not exist, even in military circles. A conservative semi analytical approach was therefore adopted to develop an exclusion zone around the impact site. A similar analysis was used to determine a no fly zone for the photographers’ helicopters.

Publicity

The event was witnessed by over 300 invited reporters and photographers and was recorded by seven TV film crews. As was concluded by R A Blythe and E P S Tufton[8] “It is seldom that the engineer has to conduct his affairs in such an exposed manner”. It is a testimony to those 20 engineers in the project team that within 24 hours this event, which was neither a man made or natural disaster, nor a professional entertainment production, had been witnessed by hundreds of millions of television viewers around the world. It has, of course, been viewed by many more since.

RESULTS OF THE CRASH TEST

In Paper No. 21, J. D. Hart, R. A. Blythe, I. Milne and M. Shears[9] describe the results of the Flask Crash Demonstration within the wider context of the ongoing studies of fuel transport flasks being undertaken by the CEGB in the mid 1980's. Described as, first and foremost, a visual spectacle, the 100 mph train crash into the derailed flask/flatrol projected the flask some 55 metres forwards with the locomotive coming to rest 100 metres from the point of impact. These results were broadly in line with the earlier predictions of T. C. K. Molyneaux and E. P. S. Tufton in Paper No. 16[10].

The flask internal pressure, which had been set at 0.69 MPa prior to the test was measured immediately after the crash to be 0.688 MPa, which if the 0.002 MPa loss is considered to be real (this pressure change is barely within the limit of accuracy of the 0-1.0 MPa pressure gauge used and could also be accounted for by the different static head of water within the flask pre and post test), would be explained by the loss of ~ 0.5 litres of water from the flask which would, in a real event, be radiologically insignificant.

One of the most technically significant results to emerged from the crash test was to be seen from the measured primary acceleration trace (Fig. 7 of Ref. 7) which showed a peak acceleration of the flask of 49 g at 10 milliseconds from impact. Transformed into the equivalent peak force acting on the flask in the crash test of 29 MN, this is far below (~ 40% of) the peak force during the regulatory 9 metre drop test of 75 MN (Fig. 7 of Ref. 9).

CONCLUSIONS

In the very last paragraph of the very last paper described here (Ref. 9) there is the following conclusion:

> "In conclusion we believe that we have demonstrated an understanding of the behaviour of flasks in accidents with sufficient thoroughness as to:-
>
> i) validate the Board's methods of compliance with the Regulations, and
> ii) validate the Regulations in providing sufficiently stringent design criteria for adequately safe transport."

That conclusion remains just as true to this day.

ACKNOWLEDGMENTS

The authors wish to acknowledge the original work of all the authors and contributors to the papers included in Reference 1, not all of whom has it been possible to recognise explicitly by name in this short paper.

REFERENCES

1. The Resistance to Impact of Spent Magnox Fuel Transport Flasks, Papers presented at a Seminar held at the Institution of Electrical Engineers on 30 April and 1 May 1985, Mechanical Engineering Publications Ltd, The Institution of Mechanical Engineers, 1985.
2. Ibid. P. J. Donelan and A. R. Dowling, Paper No. 4, The use of scale models in impact testing.
3. Ibid. J. H. Barnfield and P. J. Donelan, Paper No. 7, Demonstration Drop Test.
4. Ibid. P. R. B. Dallard, Paper No. 5, Flask Analytical Studies.
5. Ibid. M. C. Cook, J. C. Miles and M. Shears, Paper No. 8, A study of flask transport impact hazards.
6. Ibid. R. Knight, Paper No. 20, Photography for the Crash Demonstration.
7. Ibid. D. C. Thomlinson, P. J. Donelan, E. P. S. Tufton and R. Pryer, Paper No. 19, Instrumentation for the Train Crash Demonstration.
8. Ibid. R. A. Blythe and E. P. S. Tufton, Paper No. 17, Design and Organisation of the Crash.
9. Ibid. J. D. Hart, R. A. Blythe, I. Milne and M. Shears, Paper No. 21, A summary of the CEGB's flask accident impact studies.
10. Ibid T. C. K. Molyneaux and E. P. S. Tufton, Paper No. 16, Predictive Estimates for Behaviour in the Train Crash Demonstration.