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DESIGN LOADING FACTORS IN ROAD TRANSPORT OF VERY HEAVY PACKAGES

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ABSTRACT
The vast majority of shipments of radioactive material in Europe are small in bulk and mass, representing medical isotopes, laboratory instruments or industrial radiography sources. These are generally carried in packages of mass only a few kilogrammes, and certainly less than a few tonnes. Conveyances used will generally be road vehicles of appropriate size, such as light and medium vans, or light trucks. It is evident that the payloads in these vehicles are usually small in proportion to the vehicle mass, and of necessity the vehicles are loaded within their certified limits such that they continue to comply with all relevant Construction and Use regulations.

This paper discusses some of the issues that become relevant to the safe securing of a load when the package mass becomes a significant proportion of the gross vehicle mass, specifically when a heavy package takes the gross vehicle weight beyond the 44 tonnes routinely permitted in parts of Europe under Heavy Goods Vehicle regulations. The focus is on shipments where a very heavy package is carried on a relatively lightweight trailer. Examples could be where boilers from decommissioned civil nuclear plant are carried on multi-axle trailers, but also heavy packages for used fuel can fall into this category.

Conventional approaches for the design of securing systems are discussed, and their relevance to these heavy load cases is considered. Alternative approaches are suggested, such as for reduced load multiplication factors where instability or overturning could result from the use of more general road transport load factors, and the adoption of so called ‘weak link’ attachments for the control of package configuration under hypothetical accident conditions of transport.

1. THE REQUIREMENT

A fundamental requirement from IAEA[2 & 6] is that under 'Routine' conditions of transport the package must not be released from the conveyance. Rather surprisingly there is no such imperative stated for 'Normal' conditions of transport. As the definition of 'Normal' within IAEA[2] includes relatively common events such as "*minor impacts with vehicles and obstacles*", the pragmatic approach taken in the latest version of the UK Transport Container Standardisation Committee's document TCSC 1006[1] is to strongly recommend that packages are not released under either Routine or Normal conditions.

2. STANDARDS USED FOR TIE-DOWN AND DESIGN ACCELERATION FACTORS

Designers of tie-down systems for packages containing radioactive material will be aware of a plethora of modal-specific standards that could be applied in meeting the requirements of IAEA regulations to prevent release of a package from the conveyance. Several of these standards and codes of practice relevant to road transport are summarised below in Table 1. There are some differences in the headline figures, but on closer inspection it becomes apparent to the designer that differing expectations are implicit in matters such as permissible stress in the various elements of a system. There may also be differing levels of conservatism.

Considerable effort has recently been applied by TCSC to rationalise these various modal figures from worldwide sources, and a revised Code of Practice TCSC 1006[1] has been published. This is now widely considered to be the most relevant code of practice for the securing of packages during transport. The relevant figures for road transport from TCSC[1] are included as the bottom line in Table 1 for comparison with other texts. Studies reported in this paper have adopted the TCSC standard, and it is the expectation of Rolls-Royce that TCSC modal figures will be used as the basis for all relevant proposals and discussions with the UK Competent Authorities.

Table 1 – Sources of Tie-Down Acceleration Factors for Road Transport

Source Document	Longitudinal [1]	Lateral	Upwards [2]	Bounding Mass
TS-G-1.1 Appendix IV Table IV.1[2]	2g	1g	1g	Not stated
USDOE F8-11T [3] Note4	1g	0.3g	1g	50 tonne
Safety of Loads on Vehicles, Dept for Transport, London [4]	1g	0.5g	0g	Not stated
BS EN 12195-1 [5]	0.8	0.5g	0g	Not stated
TCSC 1006 Table 2 [1] Note5	1g	0.5g	0g	~30 tonne [3]

Notes for Table 1:
1. The worst direction is given for the longitudinal factors.
2. Gravity is included in all vertical accelerations so the figure quoted is the net acceleration separating the package from the vehicle, resisted by the tie-downs.
3. Bounding mass for a package is not given in the standard and so an assumption has been made based upon a typical upper limit for a loaded ISO freight container.
4. ‘Maximum expected’ figures are quoted.
5. Use of design stresses is instructed to allow a working margin below yield.
6. Fatigue is excluded from this study.

3. CONVENTIONAL APPROACHES TO TIE-DOWN

Examples of conventional approaches to the provision of a tie down system are reproduced from TCSC 1006[1] as Figure 1 below:

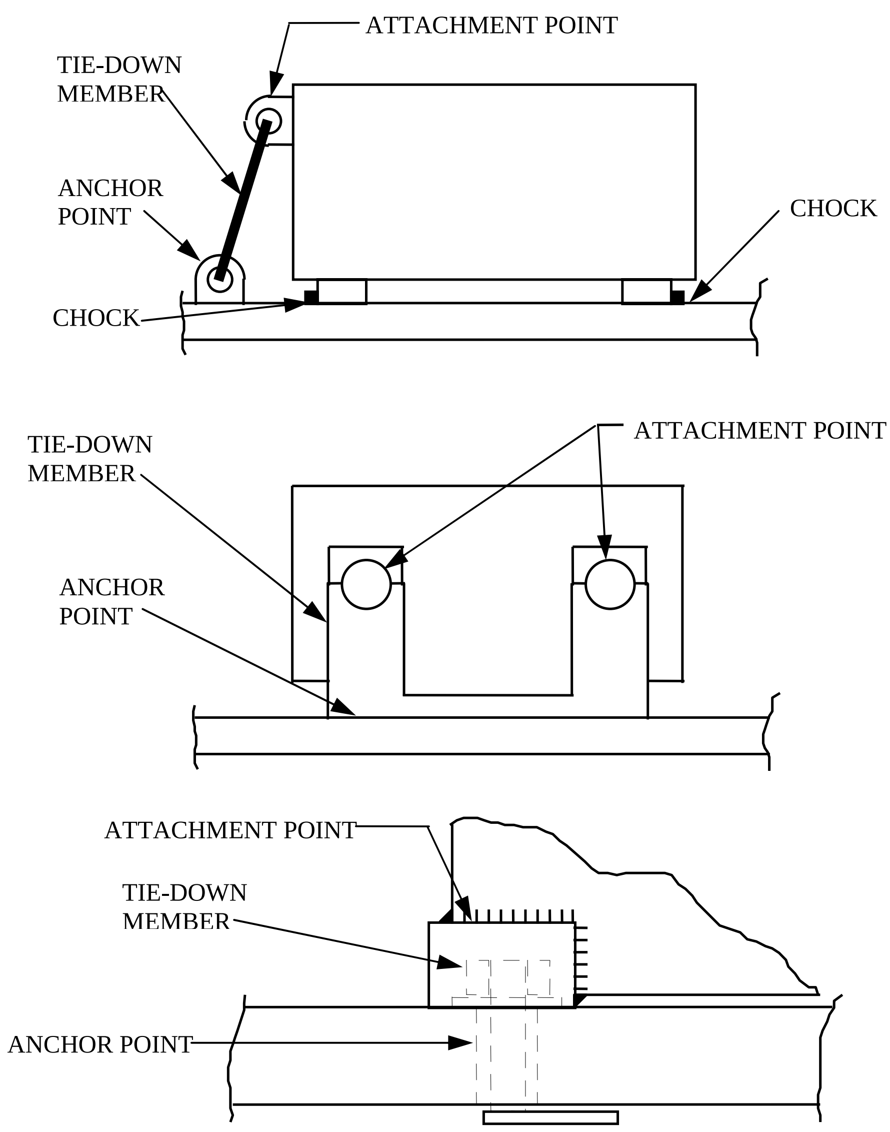

Figure 1 – Examples and Definitions of Tie-Down Systems from TCSC 1006

This standard uses definitions for Tie Member, Anchor Point and Attachment Point as illustrated above, for consistency with the IAEA definitions. A transport frame is not specifically depicted in these illustrations, but can be considered as a development of the 'Tie-Down Member' that connects the package to the vehicle in the second illustration above.

4. THE WEAK-LINK PRINCIPLE

For 'Accident' conditions, IAEA[2] suggests that *"..the package is permitted, and may be required as part of the design, to separate from the conveyance by the breakage or designed release of its restraint in order to preserve the package integrity."* This approach is commonly known as 'weak-link' and is referred to as such in both IAEA[6] and TCSC 1006[1]. The positioning of this 'weak link' is such that the package separates from its tie members, leaving the bulk of the tie-down system remaining attached to the vehicle. By this means the safety of a package can be shown not to be prejudiced: *"Any features added at the time of transport that are not part of the package shall not reduce its safety"* to satisfy IAEA[6] 612.

Within Table 1 are listed the acceleration load factors recommended for road shipments by various standards, including TCSC 1006. These factors are necessarily applied to the weakest connection between package and vehicle such that complete retention is assured, generally with a working margin or application of design stresses rather than yield. In order to apply the 'weak-link' principle, clearly there is a threshold above the Table 1 factors at which the weak-link system should fail and thereby release the package; and a correspondingly higher threshold at which the tie-down system could become detached from the vehicle.

For the designer it is not always a straightforward task to ensure that the 'weak-link' connections remain intact and undamaged at the Table 1 factors, but *must* fail before the vehicle anchorage does. Where a 'self retaining' system is adopted, such that the package rests in a shaped pocket or stillage, this weak link approach is readily determinable such that the package topples and leaves the pocket at a known acceleration. When considering positive retention systems, however, design for failure is generally an alien principle to engineers, is subject to much uncertainty, and needs removal of all of the normally applied conservatisms. In practice it is achieved by ensuring a very significant margin exists between the worst case weak-link failure force and the onset of damage at the vehicle connection. For packages of small or moderate mass this is not generally an onerous design task, as adequately large sectional areas can be applied for fastening the tie-down system to the vehicle.

5. PROBLEMS WITH HEAVIER PACKAGES

Whilst tie down arrangements that satisfy the required load factors of Table 1 and the weak link principle may be practical for small to medium packages, such as up to a mass of 30 tonne, they may not be practical for the larger and heavier packages without invoking unnecessary mass and complexity in the securing arrangements.

For the heavier package designs examined in this paper, a dedicated transport frame is conventionally used as the interface with the carrying vehicle. The package may be secured to the frame by directly bolted feet, shear pins, trunnions, or yokes with overstrapping. A potential alternative is to use the 'self retaining' principle discussed above and described in TCSC[1]. An example of the latter is the transport of A2 flasks by EDF, where the flask weight is typically double that of the conveyance. Attachment of the frame to the vehicle anchor points is typically by direct bolting or discrete tie members such as chains and links. In combination with any of these methods, chocks may be employed to directly resist shear forces and relative sliding.

A tie-down system to meet any of the above standards would invoke forces within tie members, attachment points and anchors, which increase in proportion to package mass. A further factor to consider is the generally large bulk of these heavier packages, resulting in high centres of gravity and enhanced loads in tie-members to prevent tipping.

Achievement of the significant margin needed between the worst case weak-link failure force and the onset of damage at the vehicle connection, described above in the 'weak link' section, relies on creating an 'overstrong' connection to the vehicle to overcome uncertainties. This approach may not be achievable for the much higher forces incurred by very heavy packages for several reasons. There may be insufficient space available for bolting at the vehicle interface; or the vehicle may not offer enough or adequately strong anchor points. If it can be shown that the load factors of Table 1 may be excessive when applied to very heavy packages, then a tie down system, exhibiting both the weak link approach and satisfactory retention to the vehicle, becomes more of a practical possibility.

6. RELEVANCE OF LOAD FACTORS TO VERY HEAVY PACKAGES

When very heavy loads are carried by road, permissible speeds must drop to comply with local legislation. For the UK this is the Road Vehicles General Order regulations 2003[7], which apply when a gross vehicle weight exceeds 44 tonne. Category 1 (STGO1) applies up to 50 tonne, STGO2 up to 80 tonne, and STGO3 up to 150 tonne. Vehicles of greater than 150 tonne require Special Order approval. Maximum speed for the heavier two STGO categories (80 and 150 tonne) is 30 mph on single carriageway roads, and for over 150 tonne it will not exceed 20 mph on dual-carriageways or motorways, or 12 mph on other roads.

<u>Lateral load factors</u>

In practice the difficulties of manoeuvring these very large vehicles at road junctions and bends results in many of these direction changes being taken at below 10 mph. As a consequence the lateral accelerations applied to the loads are very small for routine transport. The vehicle operators are well aware of the potential for vehicle overturning when carrying heavy loads with a high centre of gravity, and precautions are often taken with such loads by a combination of low speed, and real-time adjustments to camber of the trailer to maintain the level of the load. The latter is generally achieved using hydraulic systems built into the trailers, with operator (steersman) interventions made, whilst difficult manoeuvres are often made at a walking pace or creep speed.

It is often easy to demonstrate that the application of the Table 1 load factors will cause roll-over of the vehicle, and several examples for road transport of heavy and high loads are given later. Another example of this is described in the paper 'Designing Tie-Down Systems for Heavy RAM Packages – Should Revised Design Criteria Apply?' Purcell P[8]. In that paper a particular rail transport example was addressed, in which overturning of the wagon was predicted at a lateral acceleration of 0.32 g, ie much lower than the design figure of 0.5 g applied in design of the securing arrangement.

Longitudinal load factors

Because of the very high vehicle weights, changes in speed, in particular acceleration, are very gentle. Braking, however, could have a similar performance to conventional goods vehicles because all wheels would be braked. The question arises whether the more arduous 'Normal' conditions of transport will incur higher longitudinal accelerations. Normal for road is defined as including '*minor impacts with vehicles and obstacles'*. Other road users will invariably have a much lower mass, and a proportionally small effect upon the load vehicle should they be unfortunate enough to impact it. Because of the low speeds any impacts with fixed objects under normal manoeuvring situations (kerbs, bollards, barriers etc) will be gentle and cushioned either by tyres or minor vehicle deformations. Recent trials conducted by Rolls-Royce to instrument a 16-axle hydraulic flat-top trailer of mass 85 tonne under emergency braking have indicated that decelerations were generally lower than 0.5 g, other than for very short period low-energy spikes. More test work is required to understand the influence of a heavier load on trailer braking performance. Such empirical data will potentially be very useful in understanding the longitudinal acceleration factors required to retain the package. In summary with additional test work relevant to the vehicle and package under consideration, it may be possible to apply a lower load factor than the TCSC[1] 1 g figure to accommodate braking loads. For rearward acceleration of the load, under the very leisurely vehicle acceleration achievable, there may already be a sufficiently sound argument to use less than 1 g.

Vertical load factors

Several of the standards listed in Table 1 recognise that vertical restraint is not necessary. In particular TCSC[1] states that a large mass package "…*provides sufficient inertia so that a vertical component of acceleration sufficient to dislodge the package* (in the context of a self-retaining system) *cannot occur under Normal Conditions of Transport."* Again the low speed of the vehicle will prevent uplifts occurring over humped structures, and the hydraulic suspension systems in typical heavy load trailers accommodate local road profiles without gross effects of significance to the whole trailer. Figure 2 illustrates the latter point.

Figure 2 – Trailer Performance Over Humps

In summary it should often be possible to make a reasoned argument to the package Competent Authority why the load factors of Table 1 can be revised for particular instances of a very heavy package by road.

7. EXAMPLES OF ROLLOVER SITUATIONS

The following examples of real packages are used to illustrate that very heavy designs would encounter stability problems well before the recommended design lateral load factor is reached.

Medium Fuel Flask on Road Transporter

This flask under development by Rolls-Royce is destined for road transport in the UK. The flask and its dedicated transport frame have a combined mass of 35 tonne (Figure 3), and a combined centre of gravity positioned approximately 1.2 m above the base of the frame.

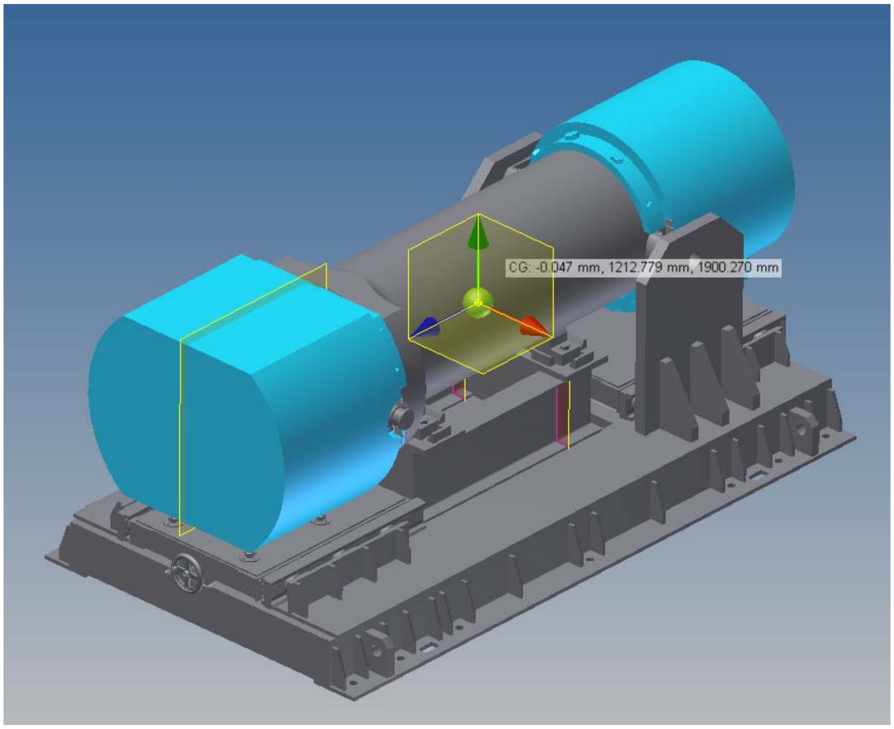

Figure 3 – Medium Fuel Flask and Transport Frame

There are several optional trailer designs for this weight but it is assumed for this example that a hydraulic modular flat-top full trailer could be used, having four rows (axles) each of eight wheels, with a drawbar connection to a tractor unit (Figures 4 and 5). This arrangement is compact, manoeuvrable and very effectively spreads the load over the road surface. It is accordingly very suitable for the minor roads, weak bridges and tight radius bends that can sometimes be experienced when accessing UK coastal facilities. Trailer empty weight would be approximately 13.5 tonne, resulting in a laden axle load of around 12 tonnes, which should permit either STGO2 or STGO3 controls for UK road transport.

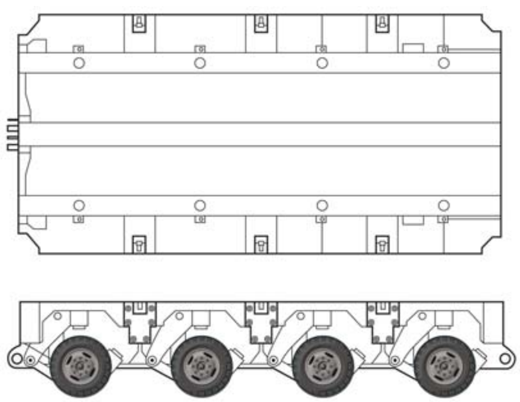

Figure 4 – Typical Four-Row Trailer

Figure 5 - Flat-Top Hydraulic Trailer Illustrating Manoeuvrability

Geometry of the trailer (normal bed height, C of G position, and positions of axle articulation points) permits an assessment to be made of toppling when carrying the load. For a given lateral acceleration, such as under severe cornering or evasive action, it is readily predictable when marginal stability or toppling will result. Figure 6 illustrates a typical behaviour of the hydraulic flat-top trailer under toppling. Of most significance is the height of the combined C of G above the axle articulation point. For this example instability is predicted to occur at a lateral acceleration of 0.52 g. This falls very close to the TCSC 1006 [1] design figures for lateral acceleration, namely ±0.5 g to design stress or ±1 g to yield.

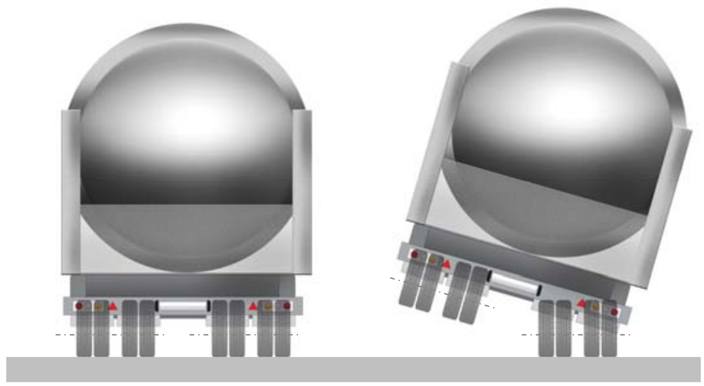

Figure 6 – Typical Toppling Behaviour under Lateral Loading

<u>Large Fuel Flask on Road Transporter</u>
A further flask being developed by RR for multi-modal transport has a greater mass and size and could potentially be carried on either a 'low-loader' style of trailer (as depicted in Figure 7), or a longer version of the hydraulic flat-top trailer depicted in Figures 4 and 5. The combined flask and transport frame mass is approximately 80 tonne, and it has a centre of gravity height of approximately 1.45 m.

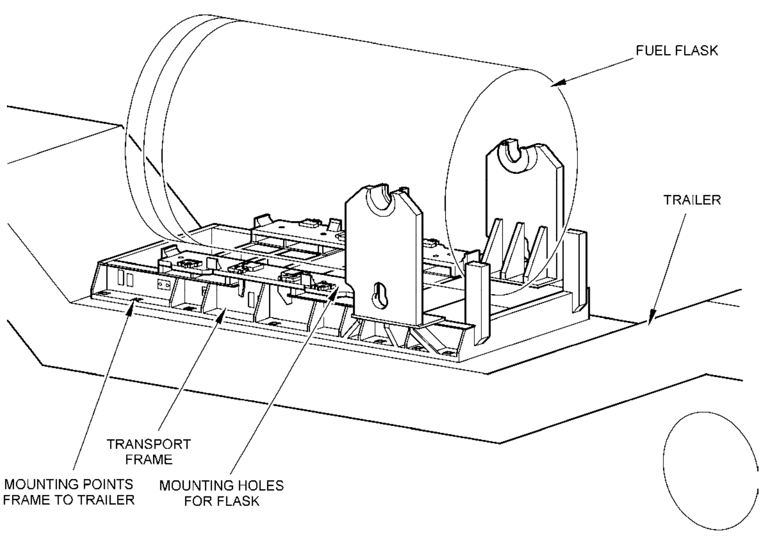

Figure 7 – Large Fuel Flask and Transport Frame on Low-Loader Trailer

If extreme manoeuvrability and compactness of the arrangement were to be of great importance, the hydraulic flat-top trailer would be used. Because of the potentially higher centre of gravity, the example given below cites the use of a hydraulic flat-top trailer.

Adopting the modular type of trailer depicted in Figure 4, nine lines of axle would be recommended, giving an empty trailer mass of approximately 31 tonne, a bed height in normal service of 1.2 m, and an axle loading of around 12 tonne. This would be transported under STGO3. Conducting a simple toppling analysis as per Figure 6 would suggest that instability occurs at around 0.5 g lateral acceleration.

Tie-down studies for this flask have not yet commenced, but it would appear that application of the TCSC 1006[1] design figures would be adequate to restrain the flask to the vehicle in the so-called ‘Normal’ circumstances of IAEA SSR-6[6].

Potential Decommissioned Item on Road Transporter

A conceptual RAM load for road transport is notionally depicted in Figure 8, which would cover all but the largest decommissioning items (discussed later). The item and its tie-down cradles are assumed to have a combined mass of around 200 tonne, and a centre of gravity height for the load is assumed at 2.5 m from the road. With a gross vehicle mass of around 300 tonne, this would need to be transported under Special Order controls in the UK.

Figure 8 – Potential Decommissioned Item for Road Transport

Conducting a simple toppling analysis as per Figure 6 would suggest that instability would occur at around 0.42 g lateral acceleration. Clearly the transport operators would need to ensure that lateral accelerations are maintained well below this figure by active load levelling during camber changes and use of crawl speeds during tight manoeuvring.

It would appear that application of the TCSC 1006[1] design figure of 0.5g for lateral acceleration in such an example may be unnecessarily restrictive.

Decommissioned Extreme-Sized Boiler on Road Transporter

Over recent years the complement of boilers from the UK Berkeley nuclear power station have been prepared and consigned by Magnox Ltd to Sweden for size reduction and extraction of radioactive material at the Studsvik site. These boilers have been categorised as SCO-I and as such have no drop testing requirements and consequently no need for any 'weak-link' system to allow release under accident conditions. Figure 9 illustrates the arrangement for road transport to the UK docks for Boiler No. 1, which had a gross mass of 310 tonne, and was carried on a hydraulic flat-top trailer of mass approximately 60 tonne.

Figure 9 – Road Transport of Decommissioned Boiler

Conducting a simple toppling analysis as per Figure 6 would suggest that instability occurs at around 0.25 g lateral acceleration. Clearly these operations had to ensure that lateral accelerations were maintained well below this figure, and real-time control of the load level over camber changes was adopted throughout the short (~4 mile) road journeys. The design figure adopted for attachment to the trailers was 0.3 g in any direction.

8. INFLUENCE OF FLASK TO TRAILER RELATIVE MASS CONSIDERATIONS

It is evident from the above examples that the heavier flasks and their transport frames combined will normally exceed the mass of a road trailer. When this ratio is above unity the question arises as to which part of the complete system controls the forces transmitted. That is whether for a given acceleration applied by the trailer, whether it is the mass of the package, the package and frame combination, or that of the trailer alone that generates the transmitted forces. Ignoring overturning moments, a simplistic assessment is conducted below.

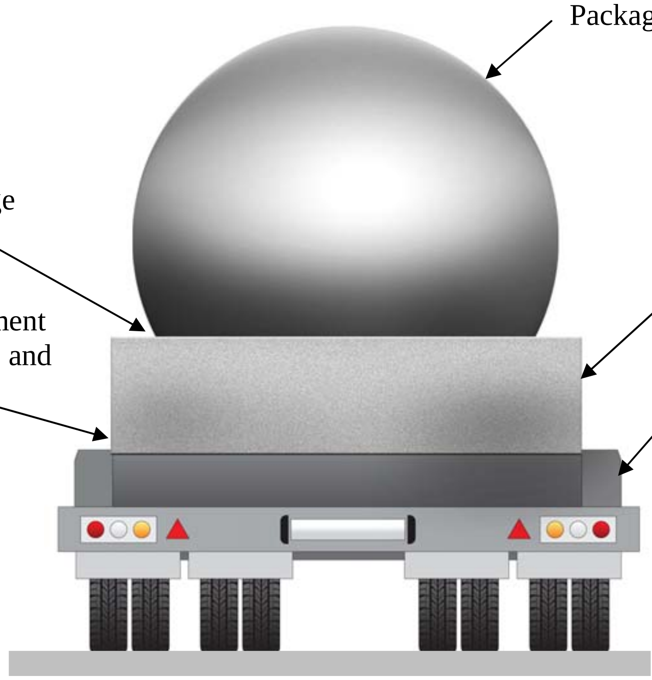

Figure 10 Schematic for Masses and Connections

Referring to Figure 10, for a lateral acceleration a_y applied by the trailer, such as caused by a turning of the vehicle, then:

Weak link connection is exposed to force $A.a_y$
Frame to trailer connection is exposed to force $(A + B).a_y$

Similarly for a longitudinal acceleration a_x applied by the trailer, such as under braking, force relationships will be as above. For lateral and longitudinal directions therefore, conventional approaches to force transfer in the tie-down system should continue, irrespective of package and conveyance relative masses.

Were a downward acceleration to be applied by the trailer, however, (ie package tending to separate from vehicle), such as by breasting a rise in the road profile, the trailer will be held up by the package and the limiting forces at the connections will be dictated by the lowest mass component.

When the package is significantly heavier than the frame and trailer combination, this results in a reduction in the applied vertical forces through the weak link when compared with the traditional simplistic manner of applying the acceleration through the whole tie-down arrangement. Were a 'self-retaining' method to be adopted then the package may momentarily part company with the transport frame, and sufficient depth of engagement must be maintained to prevent disconnection. The frame to trailer attachment in this case would be subjected to loads dominated by the lower of the two masses, normally the frame.

9. SUMMARY AND ALTERNATIVE APPROACHES

Weak links

When carrying packages that require drop test justification, that is from IP-2 upwards, the designer of the tie-down system needs to consider the inclusion of a 'weak-link' system, to assist in satisfying IAEA[6] Para 612. If employed, the weak-link system needs to retain the package on the conveyance at a set of design load factors used as the basis of the tie-down design. These load factors may be from existing codes of practice, eg TCSC[1], or other figures as may be agreed with the Competent Authority for heavy packages (discussed below). Retention of the major components of the tie-down system to the vehicle must then be demonstrated at a bounding set of accelerations greater than the 'weak-link' design figures, to ensure the correct hierarchy of failure.

Lateral acceleration factors

It is clear from the examples given that when package masses become great enough to exceed the capability of normal Heavy Goods Vehicles, instability of the vehicle in roll-over can occur even under relatively low levels of lateral acceleration. From these examples of packages weighing from 35 tonne upwards to 310 tonne, all will be very close to or beyond rollover if a sustained lateral acceleration factor of 0.5 g is applied.

The TCSC code of practice [1] for what might be termed 'conventional' packages, that is up to approximately 30 tonnes gross mass, recommends a lateral acceleration factor of 0.5 g be applied to the design of a tie-down system. This recommendation is rational and based on a great deal of experience with designers, consignors, operators and modal authorities. When masses and dimensions are significantly greater, however, the rationale breaks down, and for such abnormal loads the engineering to achieve a tie-down system of the recommended strength becomes more challenging. For loads significantly greater than 30 tonne it is recommended that road vehicle stability is assessed and an appropriate lateral acceleration factor is proposed for prior agreement with the Competent Authority. This approach will avoid unnecessary over-design of the tie-down system, and may in some situations allow the as-fitted anchor points on commercial trailers to be used without modification.

Longitudinal acceleration factors

Vehicles will not generally suffer from toppling instabilities when under longitudinal accelerations because of their proportions, and because braked axles must be adopted on trailers, further evidence will be required from heavy loads before permitting design accelerations to be reduced in this axis. Some research has already been conducted by RR into braking performance of these heavy vehicles and early results indicate some scope for reduction below the 1 g figure recommended by TCSC[1]. In the direction of accelerating the load, for very heavy vehicles even the circumstances of 'Normal' transport are not expected to approach the 1g figure given in TCSC 1006. In the absence of any specific data for the vehicle combination proposed, however, the longitudinal figures contained in TCSC[1] are recommended to be used.

Vertical acceleration factors

Where vertical accelerations are specified that tend to cause separation of the package from the trailer, it is apparent that the relative masses of the principal components, package, transport frame and trailer, need to be considered in detail to avoid over-design of attachments. However the general case recommended is that little or no vertical restraint is necessary for heavy packages. A self-retaining system is offered as a general solution, provided that sufficient analysis is conducted as recommended in TCSC 1006[1] to confirm that depth of engagement within the transport frame, or other engagement feature, is adequate. In consequence only a downward applied acceleration should be considered, but the factor of 2 g in TCSC 1006 may be excessive and open to discussion with the Competent Authority, when the operational limitations (such as speed) are considered.

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