Robotic Handling of Gamma-Ray Sources in Site Radiography of Steel Storage Tanks.

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This work has been funded by the Health and Safety Executive (HSE) under Research Project 3262/R5925

ABSTRACT

There are many possible causes of the radiation exposure hazard in on-site gamma radiography. Through poor safety procedures, for example, operators are in danger of rapidly acquiring radiation dosage by proximity to the radioactive source. In such circumstances a dosage, which might otherwise be associated with one year of intensive radiography work, can be acquired in a few minutes. The way forward is to find the means for reducing the risk of exposure to as little as practically possible. By contrast, the concept of a 'safe dosage level' is unacceptable. Through an integrated approach, involving remote robot handling of the radiographic equipment, safety can be better managed and higher productivity achieved. A particular benefit of this approach is the extremely fast source projection and retraction time compared with best current methods.

1. INTRODUCTION

This paper gives an account of a study [1] aimed at determining the most effective method for remote deployment of radio-active sources in on-site gamma-radiography of storage tanks. This covers the means for delivering and positioning the guide tube and the projection of the radio-active source to the collimator. The intention is to reduce the risk of exposure to radiation to as little as practically possible.

There is currently estimated to be 102,085,000 m^3 capacity in independent land based storage tanks, mainly in the USA, Europe and the Middle/Far East. This is equivalent to 16,467 tanks of 23m diameter. Refinery storage is estimated to add a further 709,588,600 m^3, equivalent to 56,767 tanks of 28m diameter. These figures do not include in excess of one million tanks in the petrochemical industry. The oldest tanks in service are understood to be more than 40 years old. The total length of pipework with diameter greater than 200 mm is understood to run into 10's of millions of miles. Whilst requirements vary with use and country, in-service inspection of tanks and pipes is typically required on a 5 - 10 year cycle.

Radiographic inspection is used extensively in the construction of new storage tanks and pipework as well as in their repair, alteration and reconstruction. This is an important provision as the potential failure in many cases represents a major industrial hazard. In view of the developing provisions for risk assessment of these based on NDT and the implementation of revised inspection strategies designed to control the incidence of catastrophes, the whole life monitoring requirement will inevitably increase demands for site radiographic survey. The impetus for this has arisen from improved understanding of the effects of varying internal pressure, mechanical vibration, settlement, wind loading, environmental loading, corrosion, and weld deterioration, which can lead to fracture and rupture.

The paper commences with a description of the radiography equipment and its use. Causes of the radiation exposure hazard and the current controls in the UK are then covered, followed by a definition of the automation task. The automation solution is then described in terms of access, delivery, handling, location, safety devices, control and system integration. Accounts of the safety system and performance precede the conclusions.

2. SITE RADIOGRAPHY

Gamma radiography equipment comprises a source projector, guide tubes, winding system, collimator, gamma source, dose rate meter and warning alarms. Figure 1a shows a source projector and figure 1b a selection of collimators. The projector, which also servers as a source container, has a depleted uranium core within a titanium casing. Other than when performing a radiographic exposure, the source is shielded in the projector-container. To use the projector, it is necessary to connect both the 'drive' and 'delivery' guide tubes. This arrangement enables the source, which is trapped in a 'pigtail' holder, to be sent along the 'delivery' guide tube towards the collimator. The means of driving out the pigtail is the winding system to which the other end of the 'drive' guide tube is attached. Winding systems can be manual or motor powered with automatic functions, such as the unit shown in figure 1c. With the latter, a delay timer enables the operator to escape well before the source starts to leave the projector. At the end of the timed exposure, the source is automatically retracted to the projector. With the more commonly employed manual winder, the operator's distance from the source during the winding in and winding out operation depends on the lengths and layout of the guide tubes.

To set up the system for a radiograph, film is secured by tape to one side of the weld plate and the collimator clamped in place on the other. An Image Quality Indicator IQI is also tapped down adjacent to the radiographic film and its location marked on the collimator side. With the guide tubes and winding system connected, the equipment is ready for use. Warning alarms are given both prior and during exposure of the source. For hazard awareness, a dose rate meter is referenced continuously throughout the work. Though not always employed, intruder alarm systems are available which guard against unauthorized entry. Formal training and certification is essential for all those involved in site radiography.

3. RADIATION EXPOSURE

Some of the common causes of the radiation exposure hazard [2] in site radiography are:

1. Misuse or malfunctioning of dose rate meters.
2. Lack of inspection and maintenance of source containers and winding equipment.
3. Inability to recognize equipment malfunction
4. Failure of winding mechanisms with sources becoming jammed in the guide tube or remaining out after the planned exposure.

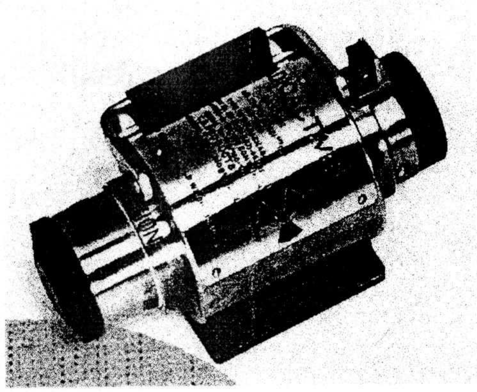

Figure 1a. Source Container-Projector

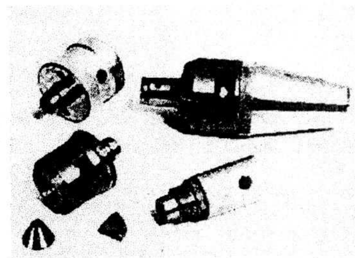

Figure 1b. Sample Collimators

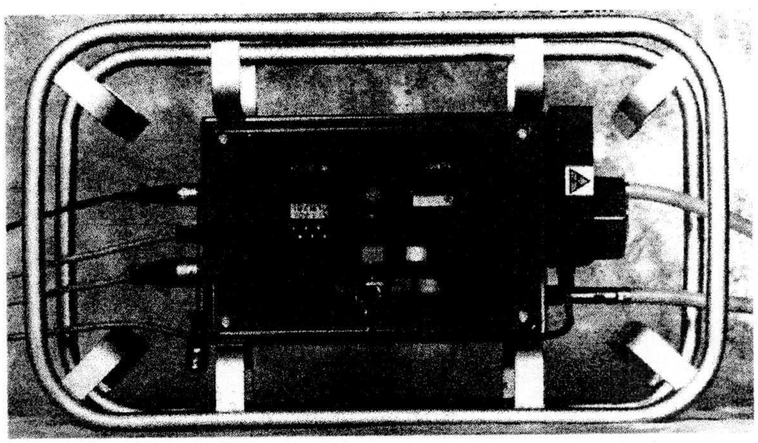

Figure 1c. Automatic Drive Unit

5. Sources becoming lost through detachment from the wind-out mechanism.
6. Failure of warning systems to detect the source exposed status and these being obscured form view, particularly on a noisy site when the audible warning is ineffective.
7. Back scatter of radiation due to surrounding air or reflection from structures.
8. Lack of confinement of the useful beam i.e. too wide a beam.
9. Containers incorrectly transported, being stolen or becoming damaged.
10. Lack of electrical protection, including earth bonding, with generators, transformers and equipment powered by them, however this is normally related to x-rays.
11. Too much time spent too near source containers (depleted uranium in titanium case).
12. Lack of care in use of designed control areas in a series of exposures at different locations i.e. wrong safety zone associated with a particular exposure (i.e. barrier too near to source).
13. Lack of security in protecting against unauthorized operation of radiographic equipment.
14. Poor safety procedures, including key lockout left in source container.
15. Poor communication between personnel, lack of training and hazard assessment

Currently in the UK, employers are required to investigate instances of 15 mSv (3/10 of the annual whole body limit) being exceeding during any calendar year. All those involved in the work wear a radiation sensitive dosemeter, such as film badge, which enables this to be monitored. Instances of 75 mSv being exceeded in five calendar years are similarly to be investigated, and a dose of 30 mSv being exceeded in any calendar quarter necessitates a report to the HSE. To give the reader some understanding of the implications of these dosage level for radiographic work, table 1. relates approximate distance (from source) to dose rate and exposure time necessary to acquire a personal dosage of 10mSv. These estimates are based on continuous exposure to an ^{192}Ir (Iridium-192) source of 0.7TBq (20Ci.) activity.

Distance (m)	Dose rate (μSvh^{-1})	Exposure time	Observation
1	100,000	6 mins	Extremely hazardous
32	100	100 hrs	Hazardous
At barrier	Less than 7.5	1330 hrs^{+}	Current practice

($^{+}$equivalent to 318 working days with 10 x 5mins exposure/day)

Table 1. Approximate Exposure Times

The basis of table 1. is that the radiation dose rate, for a point source to a point detector with negligible absorption between source and detector, obeys an inverse square law. Distance is not given for the last entry in table 1. because it is the position of source collimator which affects the barrier positioning. In the consideration of automation we strive towards zero dosage practice i.e. achieve a threshold in what is practically possible. Concepts such as 'safe dosage' or allowable dosage' are not acceptable.

4. AUTOMATION TASK

With automation, four different handling tasks can be identified in the preparation for and operation of the gamma-radiography NDT. These are (i) placement of radiographic film, (ii) placement of Image Quality Indicators (IQI), (iii) marking the film location on the source side and (iv) delivering, positioning and directing the collimator. The latter could be tackled by manual placement of small-gamma sources on the film side, which are then detected using a G-M tube on the collimator side. However, handling these sources does contribute to the exposure hazard for the operator and use of a Global Positioning System (GPS) is proposed. Film placement, whilst not an impossible automation task, is beyond the scope of this study. Furthermore, from enquires with practitioners, it is apparent that the quality of the film exposure is generally unaffected by placement of the IQI's on the source side. For the purposes of this study, therefore, the film, and IQI's are manually positioned on the same side. Regarding marking on the source side, the need for this is overcome by mapping and the use of GPS and information technology. What remains is the key safety issue, the delivery, positioning and directing of the collimator, the main target of the automation solution.

5. DELIVERY PLATFORMS

Table 2 gives the nominal specification which has been used to evaluate delivery methods under the headings of conventional and robotic. The key factors influencing choice are taken to be safety, range and reach, payload, reliability, productivity, cost, ease of use, training and evacuation. The last factor, evacuation, refers to the ease and speed with which personnel can escape to the safety zone beyond a designated barrier.

Target Structures	Circular ground storage tanks 15m max. height & 10m min.dia.
Construction	25mm-40mm stiffened steel plate
Prime task objective	Radiographic NDT survey of welds on flat plat and stiffeners.
Source	Iridium 192 Isotope (Max. activity: 0.7 TBq (20 Ci)) projected to collimator. Typical exposure time 1 min - 5 min.
Positioning requirement	5 kg. collimator assembly positioned at 200mm - 400mm offset from target surface
Accuracy	+/- 2 mm offset & +/- 1 degree direction
Location	GPS
Payload: radiography equipment	Nominal 100 kg at 200mm - 300mm offset allowed for source projector, automatic drive, dose rate meter, power packs & umbilical.
Secondary objectives	Magnetic particle, dye penetration & ultrasound. NDT for thickness, corrosion and paint condition.
Tertiary objectives	Coatings removal, welding and painting

Table 2. Nominal Specification for Radiographic NDT

A simplified classification has been adopted, the conventional comprising scaffolding, booms and cranes, lifts and suspended cradles. Scaffolding covers all static access equipment. Booms comprises all types of self powered telescopic booms and articulated arms. Suspended cradles cover both permanent or temporary systems. Lifts cover mobile plant such as mast climbers, scissors lifts and vertical telescopics. The robotic systems [e.g. 3,4], which are mostly experimental prototypes rather than commercially available systems, are grouped as climbing and non-climbing.

With climbing robots, the pull-off and shear forces achievable at the attached points must provide a factor of safety against the gravitational and motor induced forces, collision and wind loading. Equilibrium for the normal forces, shear forces and turning out moment resultants need to be guaranteed at all times. This is a difficult requirement because the shear capacity i.e. vertical hold, depends on the nature of the target surface, the residual normal force (attachment less pull), and the design of the magnet or cup interface. Furthermore, considering the overall safety issues, the operation of large payload climbing robots on vertical surfaces, whether relying on vacuum of magnetic adhesion, must be considered extremely hazardous. This observation inevitably leads to the addition of an independent cable support system, which continuously pays out or gathers cable according to the robot's motion. Seeing that this cable system is more complicated than a conventional suspended hoist system, the main benefit with the climbing type robot is largely lost.

The non-climbing robots are those which do not depend on surface contact for motion over the work surface. Where site conditions make access possible, vehicle mounted booms and arms [5] represent realistic options for positioning the radiographic package. Unfortunately, in tank work, site access conditions will frequently not accommodate the large and heavy vehicle necessary to carry the robotic boom or arm. Other problems are high cost and the risk of impact damage to the radiographic equipment or the storage tank. The use of suspended access equipment for gross positioning of a robot is an attractive option, particularly for tanks having permanent suspension equipment. Where this is not the case, a number of easy to install track systems are available. Using two suspension cables, both of which have anti-slip backup cables, loads of up to 350kg can be safely carried on the track. The vertical lift and motion along the track can be enabled by electric motors or manually operated by pull wires. For stability during source exposure, it is important that the platform is held firmly against the tank surface. Realistic solutions for this are attachment by vacuum suckers or magnets and thrusting by electric fans. Use of permanent magnets with sliding keepers is attractive because they eliminate the risk of pump or generator induced vibration during the source exposure.

Table 3. sets out our estimate of the relative performance of conventional and robotic platform systems. The scores are given on the basis of 0,3,6,9 in order of increasing merit.

					ROBOTIC						
	CONVENTIONAL				CLIMBING				NON-CLIMBING		
FACTOR	Scaff-olding	Boom	Lift	Cradle	Wheel	Leg	Frame	Clamp	On Boom	Susp-ended	Flying
Safety	9	3	6	6	6	6	6	6	6	9	0
Range-Reach	9	9	9	9	3	6	3	0	9	9	9
Payload	9	9	9	9	3	3	3	0	9	9	0
Reliability	9	9	9	9	3	3	3	3	6	9	3
Productivity	0+	9	6	6	3	3	3	0	6	6	3
Costs	3	3	3	9	3	3	3	3	3	6	3
Ease-of-use	9	3	6	6	3	3	3	0	3	6	0
Training	9	6	6	6	0	0	0	0	3	3	0
Evacuation	3	6	6	6	9	9	9	9	9	9	3
TOTALS	60	57	60	66	33	36	33	21	54	66	21

+ 0 includes erection time

Table 3.Assessment of Platforms for Radiographic NDT on Tanks

The assessment of conventional platforms, which is based on the opinions of field workers, is somewhat speculative on account of their lack of experience with methods other than scaffolding. Considering safety with booms, there is concern that the personnel and equipment carrier might collide with the tank. Difficulty of use, mainly on account of the frequency of restricted site access, and high ownership and operating costs are also problematic. Poor productivity and high costs are accepted to be a major problems with scaffolding, these due to the considerable erection time and labour involvement. However, this is not a clear cut matter in cases where the scaffolding also serves for repair and restoration works. Both booms and powered lifts are seen as difficult to use and, as with suspended cradles, requiring more training than scaffolding use. Depending on the vertical and horizontal extent of scaffolding, it is not always easy to move quickly away from the source location, thus its low evacuation score compared with other methods.

Concerning robotic platforms, clamp type climbing robots [4,5] and flying robots [3], achieve low scores on most counts and are not considered further. The remote operation, which is implied with robots, leads to good safety performance, particularly for the suspended, non-climbing robot. For the same reason, evacuation is also very good. Limited payload, un-reliability associated with lack of fitness for task, poor productivity on account of low surface speeds, and the substantial training and experience in use necessary, all contribute to low totals for the climbing robots. Whilst use of the robotic element of the suspended robot would require some training, the operation of the suspension system represents familiar activity to many NDT operators. Of the robotic solutions, a suspended robot appears to be the best robotic option.

6. REMOTE HANDLING

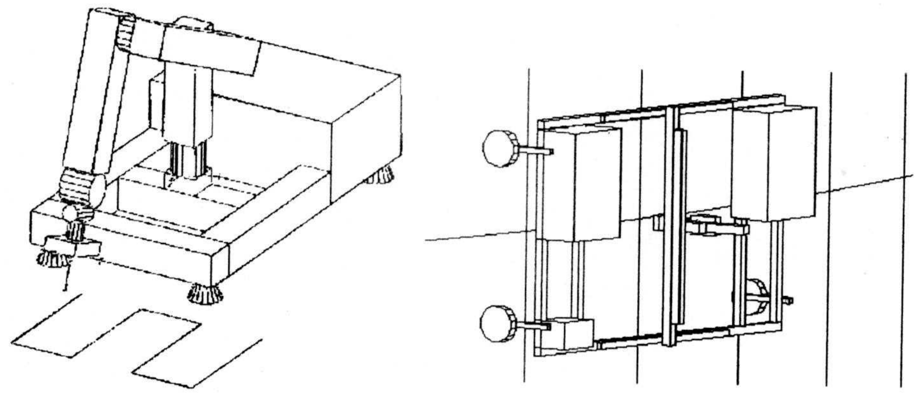

Figure 2. Robot Arm and Cartesian Robot

Factor	Cartesian Robot	Arm Robot
DoF's	5 (XYZ + pitch +yaw)	6 (3 Rev+roll+pitch+yaw wrist)
Max. Velocity	500 mm/s	500 mm/s
Max. Acceleration	250 mm/s^2	250 mm/s^2
Weight	40 kgs (assumed)	30 kgs
Max. Reach	1.5 m (diag. from corner)	1.3 m (as used)
Approx. Cost	£20k	£30k

Table 4. Overall Specifications: Cartesian Robot and Robot Arm

For the handling task, computer simulation has been used to investigate the performances of robot arm and a comparable, purpose built cartesian robot. Figures 2 shows the idealised robots and table 4 gives their overall specifications. There are two considerations in defining NDT tasks for the automation study, the geometry at the location and the tool (collimator or other probe) procedure. Holding at a point and close proximity motion over the surface are typical procedures. A generic approach has been adopted in the work, one of the procedures being continuous motion of a normal to surface probe at close proximity over three parallel lines within a 250mm x 500mm surface patch. A further example, which relates closely to collimator handling, involves normal to surface motion.

Focusing on the main findings of this investigation, it is apparent that task completion times depend largely on the maximum achievable acceleration i.e. motor power. Furthermore, where intensive scanning and multiple positioning is required, it is clear that, whilst both robots have similar performance, attention needs to be given to move design. Assuming maximum accelerations and taking account the effect of patch size on performance, it is reasonable to allow 200 secs. location time, less if GPS is used. 100 secs. would be sufficient to position and direct the collimator, following the location sequence. On average, the cartesian robot is about 8% faster than the robot arm. Of greater significance, however, is the need for careful positioning of the robot arm compared with the cartesian robot.

Following the shape of the robot arm with joint motion, it was observed that the significant displacements of the effective center of gravity would occur, even during the location task. During collimator positioning with the robot arm, the turning out moments about the lower attachment point (applied moments i.e. ignoring suspension cables) were found to be more than double those with the cartesian robot. Careful positioning of the suspension cables would only partially over come this problem. A particular hazard risk with the robot arm is that it can direct the collimator parallel to, if not outwards, from the target surface. In a cartesian robot this movement is prevented and therefore a configuration similar to that shown in figure 3. is the preferred solution.

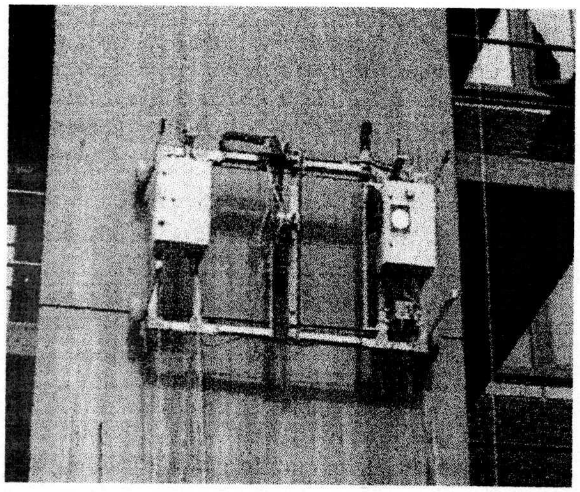

Figure 3 Suspended Cartesian Robot

7. SAFETY SYSTEM

In the automation solution the projector (figure 1a) is mounted on the robot, enabling a source projection distance to the collimator of between 100mm - 150mm. This is important as the source is unshielded during its travel. Whereas in current practice the guide tube would be about 20m long, giving a time of 3.27 seconds, the projection time in the automated solution is theoretically less than 25 milliseconds. This is an important safety feature. However, this arrangement makes remote arming of the projector necessary, and a bolt-on solenoid pulling device, with switch status sensing, is introduced. As a backup, a manual winding is also provided.

Integration of the systems safety functions builds on a zero voltage safety interlock provided with automatic drive unit (figure 1c). If this interlock is made open, the source is automatically retracted or prevented for projection. Excessive inclination, failure in surface attachment, unwarranted vibration or impact, close proximity of the collimator to the surface, unauthorized entry into the control zone and robot malfunction are events which act on the interlock. Each adapted item of radiography equipment has its own battery power supply and retains its originally functionality. Local warnings with this equipment are relayed and duplicated at the remote operator console.

Watch dog processors for the robot and the radiography system are provided, which also monitor each other. The latter checks for faults in sensors, switches, displays and as part of its start up routine and also monitors the status of all buttons and switches in the sequence to arming and projecting the source. By default, arming is prevented where the correct sequence is not followed, such as failing to issue a pre-warning alarm.

The effects of gamma radiation on the electronic circuitry[6] has been examined for the robot. Whilst the high dose rate is of no consequence, the accumulated dosage effect is. Rather than employ expensive radiation hardened circuitry, the adopted solution is to replace elements of the circuitry as part of a planned maintenance strategy.

8. DESIGN AND RISK ANALYSIS

Fault Tree Analysis (FTA) and Failure Modes Effects Analysis (FMEA) have been used to determine possible system faults and solutions to them. Another tool, known as the Activity Channels and Pools method (ACP) [7], was also employed to ascertain the links within the system and hence determine the hierarchy through which faults occur and the subsystems they affect. An advantage of this method is that rule based logic can be extracted from it. These tools were used to make a qualitative risk assessment of the radiography system and, where appropriate, outcomes were taken on and fed back into the design. The solution has been worked out in the light of current and developing legislation [8-13]

In an assessment of the system and its operation, the worst case potential hazard was identified as failure to detect the exposed source condition. To ensure the reliability of the system, therefore, three independent detections are employed as (i) a dose rate meter located near the source, (ii) encoder counts monitored for the winder and (iii) the projected/retracted status by two Hall effect sensors mounted on the source guide tube.

9 PERFORMANCE, ECONOMICS AND EXPLOITATION

Based on site trials and allowances for the radiographic equipment but excluding installation of the tracks and suspension equipment, the additional initial setting up time incurred through adoption of the system is estimated to be 2 hours. With powered access, elevating and circumferential speeds of 9 m/mins or 18 m/mins are realistic, depending on the motor capacity. For manual operation, the corresponding speeds are 5m/mins. With the aid of a GPS system, it is estimated that setting up would take less than 5 mins. In current practice, the average setting up time is typically 60 mins, thus the break even point on time could be expected at 6-8 individual settings for a large tank survey. Savings on this are, however, anticipated through substantial reductions in the instances of poor quality and abortive work, mainly on account of the precision with the automated system. The estimated additional costs with a production version of the robot system over current operation with the corresponding radiography equipment is £30,000. However, such a system would have high value, wide applicability in general NDT operations on storage tanks, tall buildings, chimneys and other extensive structures. For tanks, this could include mapping metal thickness, corrosion assessment, paint condition and thickness. The most probable exploitation scenario is with a specialist operating contractor engaging in a variety of NDT Investigations with a single

London housing authority, for example, indicate a growing requirement for NDT work, with a current demand equivalent to full time operation of several robotic systems of the type proposed. Their existence could contribute substantially to improved safety in site radiography on storage tanks.

10. CONCLUSIONS

A robotic handling system has been worked out for on-site gamma-ray radiography of circular storage tanks. It is concluded that a suspended cartesian robot gives the preferred handling solution. The large payload of this allows the heavy radiography equipment to be mounted on the robot and a short projection distance achieved. Through use of a zero voltage interlock, which is provided with the drive unit for the source projector, detected unsafe events can be used to retract the source or prevent its projection. Events such as collision or detachment from the surface of the structure are covered by this. Using the system, the total exposure time for a given number of film exposures can be substantially reduced. Further work would be necessary to quantify the contribution the system might make to reducing the radiation exposure risk for those using it.

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