SUB-COMMITTEE ON SHIP SYSTEMS AND EQUIPMENT
7th session
Agenda item 6

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REVIEW OF SOLAS CHAPTER II-2 AND ASSOCIATED CODES TO MINIMIZE THE INCIDENCE AND CONSEQUENCES OF FIRES ON RO-RO SPACES AND SPECIAL CATEGORY SPACES OF NEW AND EXISTING RO-RO PASSENGER SHIPS

Fire test research on ships carrying lithium-ion battery vehicles

Submitted by China

SUMMARY

Executive summary:	This document provides the report of a fire test research as a background information to supplement document SSE 7/6/6 (China). China carried out a series of fire and fire protection system verification tests for ships carrying lithium-ion battery vehicles by building an open/closed simulation test vehicle cabin and a lithium-ion battery vehicle mock-up
Strategic direction, if applicable:	Other work
Output:	OW 36
Action to be taken:	Paragraph 6
Related document:	SSE 7/6/6

Introduction

1 This document provides the report of a fire test research as a background information to supplement document SSE 7/6/6 (China).

2 Protection requirements of a vehicle, special category and ro-ro spaces of SOLAS regulation II-2/20, such as ventilation, electrical explosion protection, fire detection and fire extinction, are mostly developed based on the characteristics of volatile, flammable and explosive oil fuel contained in conventional oil fuel vehicles. Paragraphs 7 to 11 of document SSE 7/6/6 identify the special risks of ships carrying lithium-ion battery vehicles different from those carrying conventional fuel vehicles and the shortcomings of the existing fire protection measures of the SOLAS Convention through accident and risk analysis.

3 Due to the complex thermal runaway chain reaction mechanism and the characteristics of easy re-ignition even after extinguishing a fire involving lithium-ion batteries, ships carrying lithium-ion battery vehicles are subject to higher fire risks than those carrying conventional fuel vehicles. In addition, the effectiveness of the fire-extinguishing systems commonly used on ships to suppress lithium-ion battery vehicle fires, remains to be verified.

Fire test research

4 The China Classification Society and Chinese industrial units conducted a research on fire test, the report of which is set out in the annex. The report contains a series of fire and fire protection system verification tests specifically for ships carrying lithium-ion battery vehicles. By building an open/closed simulation test vehicle cabin and a lithium-ion battery vehicle mock-up, the fire detection and fire-extinguishing tests were carried out, which verified the effectiveness of different types of fire detectors and fire-extinguishing systems.

5 China is of the opinion that the conclusions of the test can provide reliable data resource for improving the fire protection measures contained in the SOLAS Convention regarding lithium-ion battery vehicles carried in vehicle spaces, special category spaces and ro-ro spaces.

Action requested of the Sub-committee

6 The Sub-Committee is invited to note the information provided when considering document SSE 7/6/6.

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ANNEX

REPORT OF FIRE TEST AND FIRE PROTECTION SYSTEM VERIFICATION ON SHIPS CARRYING LITHIUM-ION BATTERY VEHICLES

1 SUMMARY

Due to the fire characteristics of lithium-ion battery vehicles different from conventional fuel vehicles, this test takes vehicles powered by lithium iron phosphate battery (LFP) and ternary lithium battery (NCM), which have a large market share, as the research object. By building an open/closed simulation test vehicle cabin and a lithium-ion battery vehicle mock-up, a series of full-scale tests in conditions simulating lithium-ion battery pack fires in the test cabin are conducted to verify the effectiveness of the marine fire detection system and fire extinguishing systems with regard to detection and suppression of the fire in the space carrying lithium-ion battery vehicles, so as to provide support for China to put forward the modification proposal of SOLAS.

The tests are carried out at the Test and Validation Center of CATL, participating companies include Wuhan Rules and Research Institute of China Classification Society, Contemporary Amperex Technology Ltd., Zhejiang Yaning Fire Equipment Co. Ltd., Yantai Chuangwei New Energy Technology Co., Ltd., Jiangxi Samsung Qilong Fire Safety Co. Ltd. and Wuhan Modern Yangtze River Morgan Technology Co., Ltd.

The test consists of two parts: (1) Fire detection test and (2) Fire extinguishing test.

In part 1, two comparative tests were designed to verify the response of the smoke detector and the temperature detector at the same position or at the different positions. In part 2, the effectiveness of five marine types of fixed fire-extinguishing systems (carbon dioxide, heptafluoropropane, aerosol, fire-extinguishing system, pressure water mist and low-expansion foam) was verified, and each type tested at least four times in order to eliminate occasionality.

According to the test phenomena and analysis results, the following conclusions can be drawn for the space carrying lithium-ion battery vehicles:

(1) It is better to be equipped with smoke detectors or smoke and temperature combined detectors than sole temperature detectors. In addition, it is also recommended to fit a video monitoring system as an auxiliary means to achieve comprehensive detection of the space.

(2) It is recommended that the space be given priority to be equipped with a fixed water-based fire-extinguishing system. If using gas fire-extinguishing system, there is a need to put forward strengthened requirements of gas tightness of the space, vehicle isolation, and response to re-ignition.

(3) It is recommended to provide special personal protective equipment for fire-fighters entering the space.

(4) It isn't recommended that lithium-ion battery vehicles be charged on ships. If necessary, there should be corresponding protective measures. When carrying fuel vehicles and lithium-ion battery vehicles at the same time, it is recommended that these two types of vehicles be stored separately.

2 TEST SCHEME DESIGN

2.1 Simulation vehicle cabin and vehicle mock-up

In order to simulate the space carrying lithium-ion battery vehicles on ships, a simulation test cabin was modified with a 20-foot container as shown in figure 1. Several operable doors are provided on its bulkheads, which can simulate a closed space when doors are closed, and an open space when doors are open. The inner side of the cabin is covered with thermal insulation material, and a side door is provided with an observation window with fireproof and explosion-proof performance. The top of the cabin is provided with an air inlet, an outlet and a mechanical fan.

Figure 1-Test cabin

By referring to the fuel vehicle mock-up of MSC.1/Circ.1430, a lithium-ion battery vehicle mock-up was designed as shown in Figures 2 and 3. This mock-up was composed of a vehicle body frame structure and a battery pack, and the battery pack was located in the middle and rear of the body and at the chassis position.

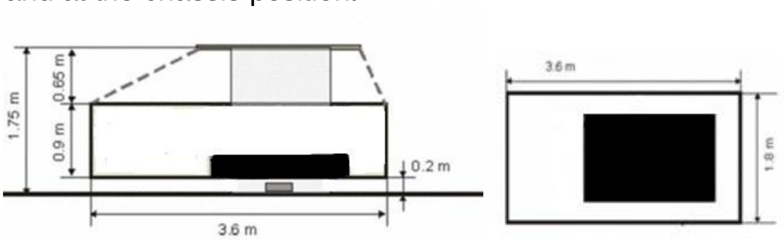


Figure 2-Design drawings of lithium-ion battery vehicle mock-up

Figure 3-Lithium-ion battery vehicle mock-up

2.2 Fire detection test scheme

2.2.1 Test method

Two comparative tests were designed:

(1) Comparative test 1 used a smoke detector and a temperature detector. The vehicle mock-up was placed in the test cabin. On the top of the test cabin at a distance of 1m away from the battery pack horizontally, 3# smoke detector and 8# temperature detector were placed at the same position. This test aims to compare the response effectiveness of the smoke detector and the temperature detector at the same position.

(2) Comparative test 2 used a smoke detector and a temperature detector. The vehicle mock-up was placed in the test cabin. On the top of the test cabin at a distance of 1 m away from the battery pack horizontally, 2# smoke detector was placed, and 9# temperature detector was placed 1m away from 2#. This test aims to compare the response effectiveness of the smoke detector and the temperature detector at the different positions.

2.2.2 Test equipment

a）marine temperature detector b）marine smoke detector

Figure 4 Fire detectors for test

2.3 Fire extinguishing test scheme

2.3.1 Test method

(1) Overcharge the battery pack in the closed test cabin with the vents and fan in operation. When the battery cell catches fire and the fire gradually increases and causes the entire battery pack to burn for about 2 minutes, start the gas fire-extinguishing system, and close the vents and fan at the same time. Measure the temperature change of the battery pack, vehicle mock-up and cabin, and observe the battery pack for re-ignition or explosion.

(2) Overcharge the battery pack in the open test cabin. When the battery cell catches fire and the fire gradually increases and causes the entire battery pack to burn for about 2 minutes, start the pressure water mist or low-expansion foam fire-extinguishing system. Measure the temperature change of the battery pack, vehicle mock-up and cabin, and observe the battery pack for re-ignition or explosion.

2.3.2 Test equipment

The following five types of fixed fire-extinguishing system pipes and nozzles are arranged in the test cabin: Carbon dioxide, heptafluoropropane, aerosol fire-extinguishing system, pressure water mist and low-expansion foam fire-extinguishing systems which comply with the Fire Safety Systems Code and related MSC Circulars.

a)Carbon dioxide b)Heptafluoropropane c)Aerosol d)Pressure water mist, low-expansion foam

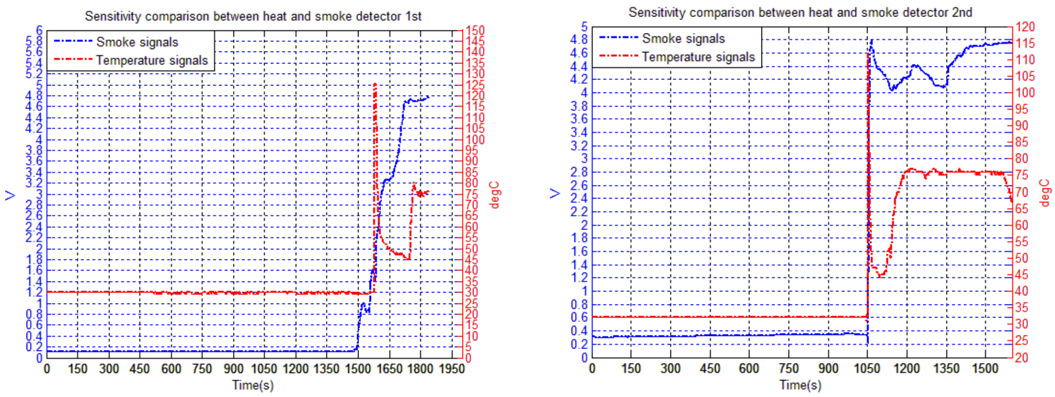
Figure 5-Fire extinguishing systems for test

3 TEST PHENOMENA AND ANALYSIS

3.1 Fire detection test

3.1.1 Test phenomena

In comparative test 1, battery cells vented for more than 1 minute, which caused the whole battery pack to explode. The response of the fire detectors was shown in figure 6a. In comparative test 2, battery cells vented and the battery pack exploded almost simultaneously, and the smoke detector and temperature detector responded simultaneously. The response of the fire detectors was shown in figure 6b.



a) Comparative test 1 **b) Comparative test 2**

Figure 6-Comparison of response of different fire detectors

3.1.2 Test analysis

The smoke detector is more sensitive than the temperature detector when cells vented and then caused the whole battery pack to explode. When cells vented and the battery pack exploded simultaneously, the temperature and smoke detectors nearly can simultaneously monitor smoke and temperature signals.

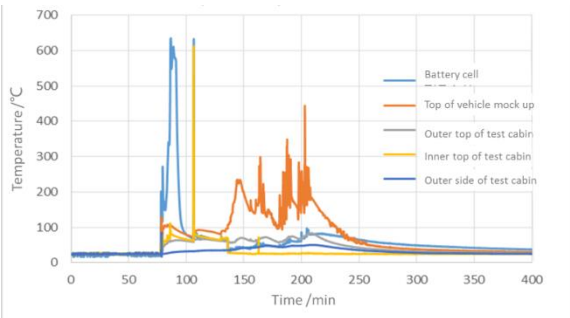
3.2 Fire extinguishing test

3.2.1 Test phenomena

(1) Carbon dioxide fire extinguishing test. Four repetitive tests were conducted totally, including two tests for NCM and two tests for LFP. In the four tests, the flame was extinguished instantly after the release of extinguishing agent, and a large amount of white smoke appeared in the cabin, the visibility was low, and the temperature of thermocouples decreased overall. However, after a period of time, the battery pack was on fire again and could not be controlled in two NCM tests and one LFP test. It could only be allowed to burn freely for a long time. The battery was checked after standing for 24 hours, and the battery pack has completely burned out(as shown in figure 7). In another test for LFP, the battery pack did not reignite, and only the overcharged module was ablated, which did not affect the rest modules (as shown in figure 8).

a) battery pack preparation b) fire-extinguishing system preparation c) pack fire

d**) released fire extinguishing agent e) fire again f) battery residues**



g) Temperature change curve

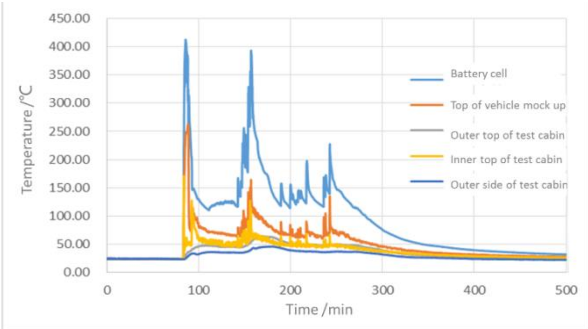
Figure 7 Phenomena of carbon dioxide fire extinguishing test （NCM vehicle mock-up）



a) **battery pack preparation b) fire-extinguishing system preparation c) pack fire**



d) released fire extinguishing agent e) no burnback f) battery residues



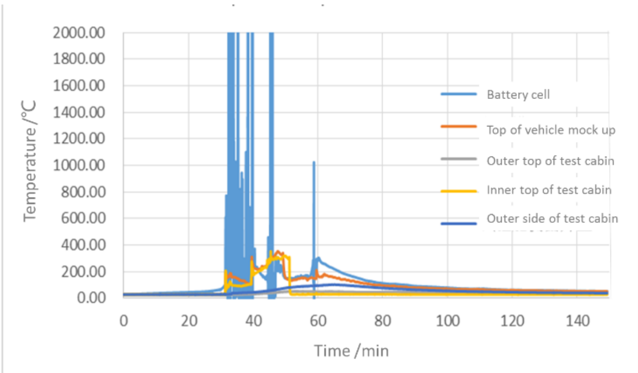
g) Temperature change curve

Figure 8-Phenomena of carbon dioxide fire extinguishing test（LFP vehicle mock-up）

(2) Heptafluoropropane fire extinguishing test. Four repetitive tests were conducted totally, including three tests for NCM and one tests for LFP. In the four tests, the flame was extinguished instantly after the release of extinguishing agent, and a large amount of white smoke appeared in the cabin, the visibility was low, and the temperature of thermocouples decreased overall. However, after a period of time, the battery pack was on fire again and could not be controlled in three NCM tests. It could only be allowed to burn freely for a long time. The battery was checked after standing for 24 hours, and the battery pack has completely burned out (as shown in figure 9). In another test for LFP, the battery pack did not reignite, and only the overcharged module was ablated, which did not affect the rest modules (as shown in figure 10).

a) battery pack preparation b) fire-extinguishing system preparation c) pack fire

d) released fire extinguishing agent e) fire again f) battery residues

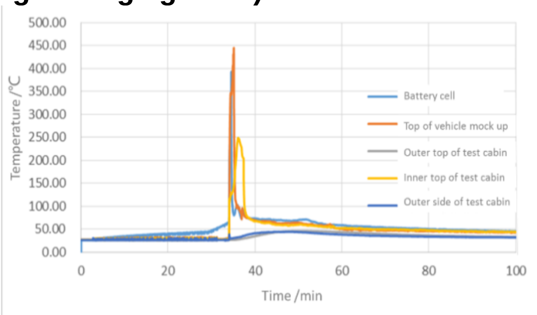


g) Temperature change curve

Figure 9-Phenomena of heptafluoropropane fire extinguishing test （NCM vehicle mock-up）

a) battery pack preparation b) fire-extinguishing system preparation c) pack fire

d) released fire extinguishing agent e) no burnback f) battery residues



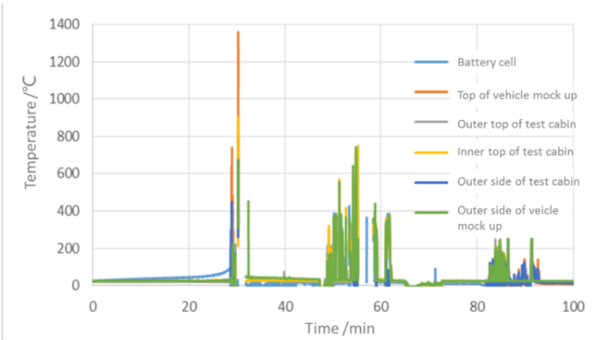
g) Temperature change curve

Figure 10-Phenomena of heptafluoropropane e fire extinguishing test （LFP vehicle mock-up）

(3) Aerosol extinguishing fire test. Three repetitive tests were conducted totally, including two tests for NCM and one test for LFP. In the three tests, the flame was extinguished immediately after the release of extinguishing agent, and a large amount of white smoke appeared in the cabin, the visibility was low, and the temperature of thermocouples decreased overall. However, after a period of time, the battery pack was on fire again and could not be controlled. It could only be allowed to burn freely for a long time. The battery was checked after standing for 24 hours, the battery pack has completely burned out (as shown in figure 11 and 12).

a) battery pack preparation b) fire-extinguishing system preparation c) pack fire

d) released fire extinguishing agent e)fire again f) battery residues



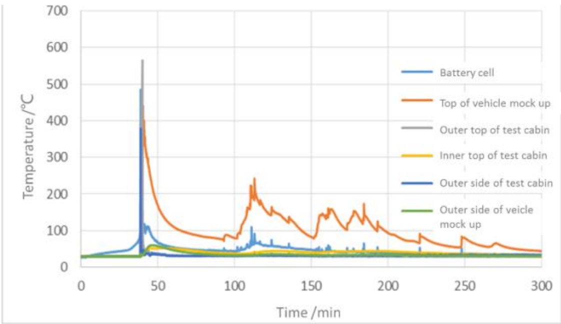
g) Temperature change curve

Figure 11-Phenomena of Aerosol fire extinguishing test（NCM vehicle mock-up）



a) battery pack preparation b) fire-extinguishing system preparation c) pack fire

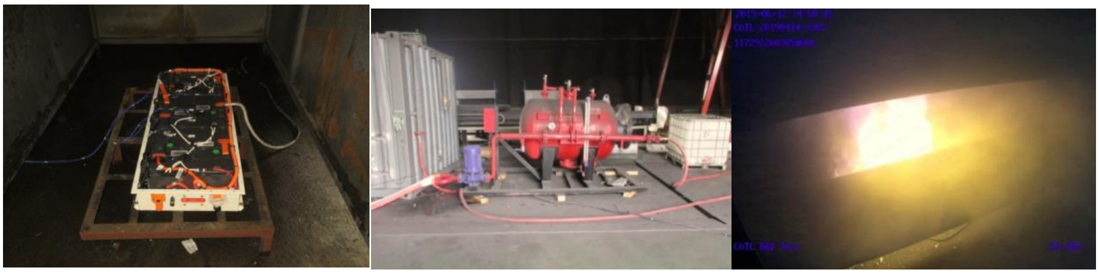
d) released fire extinguishing agent e)fire again f) battery residues



g) Temperature change curve

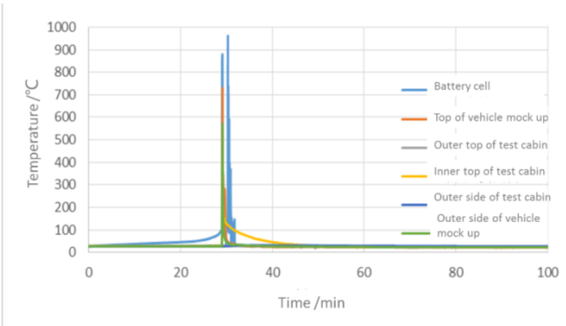
Figure 12-Phenomena of aerosol fire extinguishing test（LFP vehicle mock-up）

(4) Pressure water mist fire extinguishing test. Five repetitive tests were conducted totally, including three tests for NCM and two tests for LFP. In the five tests, the flame was extinguished immediately after the system activated, and a large amount of white smoke appeared in the cabin, the visibility was low, and the temperature of thermocouples significantly decreased overall. All the battery packs did not catch fire again. Checking was carried out after standing for 24 hours, and the battery was basically damaged by water (as shown in figures 13 and 14).



a) battery pack preparation b) fire-extinguishing system preparation c) pack fire

d) released fire extinguishing agent e) no burnback f) battery residues

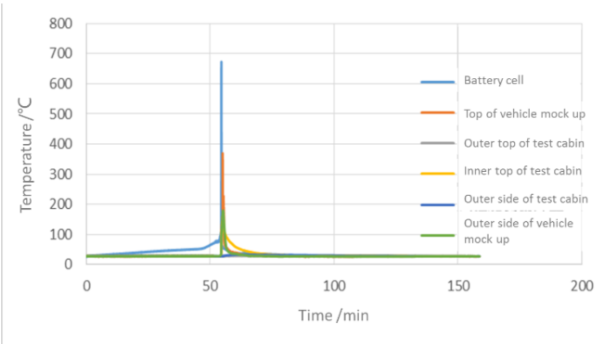


g) Temperature change curve

Figure 13-Phenomena of pressure water mist fire extinguishing test （NCM vehicle mock-up）

a) battery pack preparation b) fire-extinguishing system preparation c) pack fire

d) released fire extinguishing agent e) no burnback f) battery residues



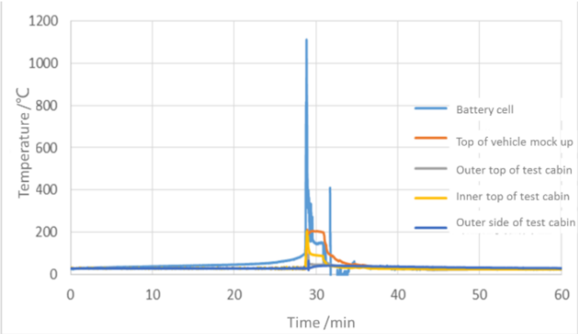
g) Temperature change curve

Figure 14 Phenomena of pressure water mist fire extinguishing test （LFP vehicle mock-up）

(5) Low-expansion foam fire extinguishing test. Four repetitive tests were conducted totally, including two tests for NCM and two tests for LFP. In the four tests, the flame wasn't extinguished immediately after the system activated because the foam could not reach the battery pack, and later gradually died out for its cooling effect accompanying a large amount of white smoke in the cabin. The temperature of thermocouples decreased overall. All the battery packs did not catch fire again. Checking was carried out after standing for 24 hours, the battery was basically damaged by water(as shown in figures 15 and 16).

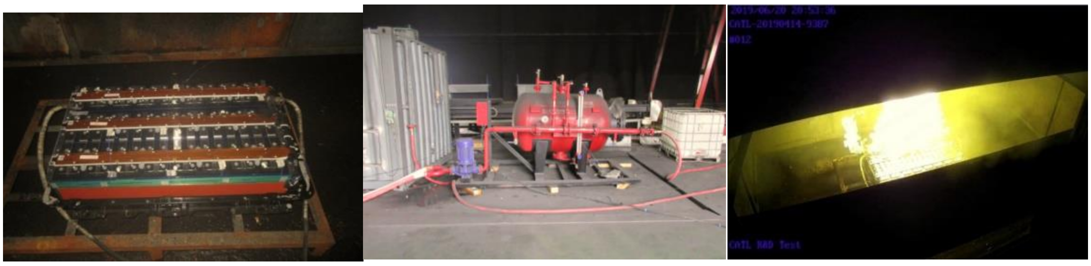
a) battery pack preparation b) fire-extinguishing system preparation c) pack fire

d) released fire extinguishing agent e) no burnback   f) battery residues



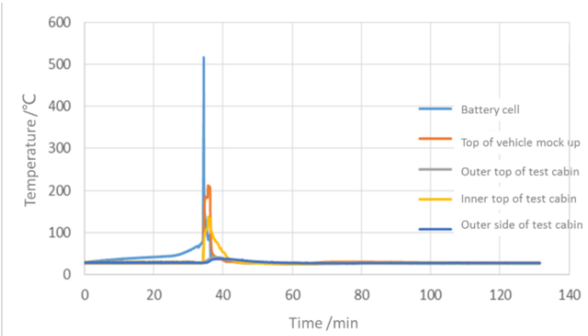
g) Temperature change curve

Figure 15-Phenomena of low-expansion foam fire extinguishing test （NCM vehicle mock-up）



a) battery pack preparation b) fire-extinguishing system preparation c) pack fire

d) released fire extinguishing agent e) no burnback f) battery residues



g) Temperature change curve

Figure 16-Phenomena of low-expansion foam fire extinguishing test (LFP vehicle mock-up)

3.2.2 Test analysis

Through the test phenomena of above fire-extinguishing systems on the fire of lithium-ion battery vehicle mock-up, it can be concluded that:

(1) Pressure water mist fire-extinguishing system is the most effective and its cooling effect is significantly better than gas fire extinguishing agents.

(2) The fire of NCM pack is more difficult to extinguish than the fire of LFP pack. In heptafluoropropane, carbon dioxide and aerosols extinguishing tests, the NCM vehicle mock-ups caught fire again after the fire was extinguished for the first time. The interval from extinguishment to re-ignition is the shortest in aerosol extinguishing tests.

(3) The use of gas fire-extinguishing systems alone in the space carrying lithium-ion battery vehicles is not effective. If used, there is a need to put forward strengthened requirements of gas tightness of the space, vehicle isolation, and response to re-ignition. In the application, such issues should be taken into consideration.

(4) The low-expansion foam fire-extinguishing system has a good cooling effect, but it cannot quickly extinguish the flame of the vehicle mock-up. Moreover, the foam increases the conductivity of the liquid agent, which may cause short circuits and electric sparks during the fire-extinguishing process. After the fire is extinguished, there are certain safety risks.

The following table shows the fire suppression effects of various fire-extinguishing systems in the space carrying lithium-ion battery vehicles:

Table 1-List of test effectiveness of fire-extinguishing systems in the space carrying lithium-ion battery vehicles

Fire extinguishing system	Test number	Battery type	Phenomena		Effect evaluation
			Whether to reignite or explode	Cooling effect	
Carbon dioxide	1	NCM	Yes (re-ignition after 29min)	ordinary	Ordinary
	2	NCM	Yes (re-ignition after 18min)	ordinary	
	3	LFP	Yes (re-ignition after 1h25min)	ordinary	
	4	LFP	no	ordinary	
Heptafluoropropane	1	NCM	Yes (re-ignition after 10min)	ordinary	Ordinary
	2	NCM	Yes (re-ignition after 25min)	ordinary	
	3	NCM	Yes (re-ignition after 16 min)	ordinary	
	4	LFP	no	good	
Aerosol	1	NCM	Yes (re-ignition after 12min)	not good	Not good
	2	NCM	Yes (re-ignition after 6min)	not good	
	3	LFP	Yes (re-ignition after 25min)	not good	
Pressure water mist	1	NCM	no	best	Best
	2	NCM	no	best	
	3	NCM	no	best	
	4	LFP	no	best	
	5	LFP	no	best	
Low-expansion foam	1	NCM	no	better	Better, but causing electric sparks
	2	NCM	no	better	
	3	LFP	no	better	
	4	LFP	no	better	

4 CONCLUSIONS

According to the above test phenomena and analysis results, the following conclusions can be drawn for the space carrying lithium-ion battery vehicles:

(1) Provision of fire detection system

In order to detect lithium-ion battery vehicle fires as soon as possible, it is recommended to fit a fixed fire detection system with smoke detectors or smoke and temperature combined detectors in the space. In addition, it is also recommended to fit a video monitoring system as an auxiliary means to achieve comprehensive detection of the space.

(2) Provision of fixed fire extinguishing system

Since it can't be judged whether the vehicles are installed with LFP battery packs or NCM battery packs, it is recommended that the space be given priority to be equipped with a fixed water-based fire-extinguishing system (Pressure water mist fire-extinguishing system was used in the test with similar extinguishing mechanism). If using gas fire-extinguishing system, the spaces shall be capable of being sealed, and the system is recommended to be designed to provide protection twice so as to deal with the battery re-ignition. Moreover, in the aspect of vehicle isolation, a fire separation water curtain system can be set up for the use of cooling and separation functions.

(3) Provision of personal protective equipment

Both the LFP battery and the NCM battery generate a large amount of toxic gases during the burning process with high temperature and long duration, and the visibility in the space is very low. Therefore, it is recommended to provide special personal protective equipment for fire-fighters entering the space.

(4) Management measures

The methods adopted in the tests are overcharging. Overcharging is one of the important reasons for thermal runaway and fire of the battery. Therefore, it isn't recommended that lithium-ion battery vehicles be charged on ships. If necessary, there should be corresponding protective measures; when carrying fuel vehicles and lithium-ion battery vehicles at the same time, in order to prevent the mutual influence of the fire of the two types of vehicles and facilitate the fire-fighters to take different fire extinguishing strategies, it is recommended that these two types of vehicles be stored separately.

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