Indian Journal of Fibre & Textile Research
Vol. 50, June 2025, pp. 137-143
DOI:10.56042/ijftr.v50i2.8286

Effect of flame retardant additive concentration on the flame spread behaviours of polypropylene knitted fabrics

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Received 24 January 2024; revised received and accepted 19 July 2024

Polypropylene (PP) is widely used in technical textiles, such as protective/safety and home textiles. However, its inherent flammability limits its performance in such contexts. This study investigates the flammability characteristics of PP raw material mixed with organophosphonate-based flame retardant additive. The FR additive was incorporated into the PP matrix at concentrations ranging from 1 % to 8 % using a laboratory-scale melt-spinning process. Pure and FR-treated PP fabrics' burning and flame spread behaviours were investigated in detail. Flame spread behaviours were further supported by digital photographs and AutoCAD drawings. Results show that the pure PP fabric exhibits double-burning peaks and burns for a long time. Burning lengths and burning time were significantly reduced by adding FR additives. Fabrics with FR treatment predominantly display single-peak and middle-ignition behaviour, indicating improved fire resistance. These findings highlight the effectiveness of organophosphonate-based additives in enhancing the flame retardancy of PP textiles, supporting their safer use in technical applications.

Keywords: Burning time, Flame retardant, Flame spread behaviour, Flammability, Polypropylene

1 Introduction

The flame retardancy properties of textile materials are mostly determined by vertical flammability test and Limited Oxygen Index (LOI). These tests provide quantitative data that allow researchers to evaluate the flammability characteristics of various textile structures. Many studies have focused on the flame retardancy of different textile materials, including knitted, woven, nonwoven, and composite fabric, in the literature[1-5]. Beyond quantitative measurements (vertical flammability, LOI test data, etc.), it is also essential to interpret burning behaviours, such as combustion and flame spread behaviours and flame-retardant patterns. These observations and results offer deeper insights into the flame-retardant performance of textile materials and are often supported by photographic evidence and schematic illustrations[6-11]. In this way, more detailed analyses can be carried out about "Flame spread behaviours" in these types of studies[12-17].

Polypropylene (PP) filament yarns are frequently used in technical textiles due to their outstanding properties, such as low density, easy processability, sufficient tenacity, high chemical resistance, low cost, etc. However, the inherent flammability of PP limits its application in areas requiring high fire safety standards. To address this issue, flame retardant (FR) additives—particularly organophosphonate-based compounds—can be incorporated into the PP matrix to enhance its fire resistance.

In the present study, FR additives were blended into PP at varying concentrations (1 % to 8 %) during the melt-spinning process to produce FR-modified filament yarns. These yarns were subsequently knitted into fabrics, which were then evaluated for their flammability and flame-spread behaviour. The burning performance of the fabrics was analysed in detail using vertical flammability tests, supported by digital photographs and technical drawings to visualise flame propagation and combustion characteristics. The novelty of this study lies in the comprehensive investigation of the flame behaviour of PP-knitted fabrics modified with a broad range of FR additive concentrations. The findings contribute valuable insights into the relationship between additive content and fire resistance, offering practical guidance for researchers and developers to enhance the flame retardancy of PP-based textile materials.

2 Materials and Methods

2.1 Materials

Sabic PP 518P polypropylene polymer chips and an organophosphonate-based flame-retardant additive

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(CESA-Flam CFR1) as raw materials were used in this study. Sabic PP 518P is an isotactic polypropylene (IPP) with key properties summarised in Table 1.

Among the five principal flame-retardant systems suitable for polypropylene — phosphorus-, halogen-, silicon-based, metal hydrate/oxide, and nanocomposite — phosphorus-based compounds, particularly organo-phosphonates, are favoured for their dual action: promoting char formation and acting as condensed-phase barriers. The selected FR additive (CESA-Flam CFR1) was chosen for its compatibility with PP and effective processability in melt spinning. Additionally, spin-finish oil (Polymast-MKL) was used as an auxiliary chemical during the production of yarns to reduce fibre-metal and fibre-fibre frictions and prevent filaments' adhesion to each other.

2.2 Methods

2.2.1 Production of PP Filament Yarns

PP filament yarns were produced using a lab-scale melt spinning machine (LabFil) based on the melt spinning principle[18-20]. PP chips and the FR additive were dry blended at concentrations ranging from 1% to 8 % by weight (Table 2) and fed into a single-screw extruder.

The extrusion zone was maintained at a temperature gradient of 220-245°C. A volumetric pump regulated the melt flow at 350 cm^3/min. PP filaments were air-cooled, treated with spin finish oil before passing into the drawing godets. Then, PP filaments were drawn using heated godets before being wound. The speeds of the two godets served to adjust the drawing ratio: the first godet speed was set at 400 rpm (41.9 rad/s), whereas the second one was set at 800 rpm (83.8 rad/s), giving a drawing ratio of 2. Finally, the PP filament yarns were wound on cheese packages. The entire process was kept constant except for the variable FR additive ratios. Filament yarns were designated as "144f918 denier" with circular cross-sections. The extruder's L/D ratio (27:1) enabled thorough mixing, ensuring homogeneous dispersion of the FR additive.

The surface morphology of filament yarns was investigated using an SEM (Jeol JSM-6390 LV) at 20 kV. Before testing, yarns were conditioned under standard atmospheric conditions (20 °C ±2, 65% ±2 RH). Different mechanical and structural properties, such as tenacity (cN/tex), breaking elongation (%), unevenness (U % and CVm %) and intermingled (number of nips per meter) tests were performed. Tenacity and breaking elongation tests were carried out with the Uster Tensorapid-3 test device (BS EN ISO 2062 standard, 1995), and unevenness tests were carried out with the Uster Unevenness Measurement device (DIN 53817-1test standard, 1983)[21,22]. The intermingling test was realized with the Rothschild Entanglement Tester R-2070 test device (internal method).

Table 1 — Properties of PP polymer chips (Sabic PP 518P)

Property	Value	Standard
Melt flow rate (MFI) (230 °C & 2.16 kg load density)	24 g/10 min 905 kg/m^3	ASTM D 1238 ASTM D 792
Tensile strength	32 MPa	ASTM D 638
Tensile elongation	12%	ASTM D 638
Flexural modulus	1550 MPa	ASTM D 790A
Notched izod impact strength (23 °C)	30 J/m	ASTM D 256
Rockwell hardness (R-scale)	100	ASTM D 785
Vicat softening point	152°C	ASTM D 1525B
Heat deflection temperature (455 KPa)	118°C	ASTM D 648

Table 2— Structural and mechanical properties of PP filaments[18]

Sample	Tenacity, cN/tex	Breaking elongation, %	Uster, U%	CVm, %	Intermingling. No. of nips/m
Pure PP	22.8	28.4	5.94	7.49	10.1
1% FR	23.6	28.4	5.29	6.63	10.2
2% FR	23.0	27.4	5.45	6.88	11.0
3% FR	22.5	26.7	5.60	6.95	8.9
4% FR	22.7	27.3	5.98	7.53	10.1
5% FR	22.8	26.2	5.95	7.41	9.7
6% FR	23.4	26.6	5.37	6.64	10.0
7% FR	23.7	28.7	5.97	7.50	12.0
8% FR	22.5	26.7	6.17	7.63	9.2

2.2.2 FR-Fabric Production and Flammability Tests

PP filament yarns were converted to a single jersey knitted fabric using a Lonati Goal-6715 brand knitting machine (3.5″ diameter, 54 needles, 160 rpm). The GSM and thickness of the knitted fabric were352 g/m^2 and 0.4 mm, respectively. Figure 1 shows the knitted structure and surfaces.

300×76 mm test samples were prepared from these knitted fabrics for vertical flammability test (ASTM D 6413 testing standard)[24] and this test was applied on Atlas Brand Fire Science Product-AGC Automic Gas Control device. Specimens were clamped to avoid buckling. Flame exposure: 19 mm flame for 12 seconds; after flame duration was measured.

Limit Oxygen Index (LOI) test was applied on 140×52 mm samples as per ASTM-D 2863 testing standard[25] using Dynisco brand device. Each test was conducted 15 times per sample type. All samples were pre-conditioned under standard conditions.

3 Results and Discussion

3.1 Flammability Test

The vertical flammability test is applied to determine whether the fabric continues to burn once the ignition source is removed. The sample is directly exposed to a flame at its lower central edge in this test. This method yields critical insights into the flame-retardant behaviour of fabrics, such as "after flame", "afterglow", after time", "dripping behaviour", "burning behaviours" and "flammability properties"[18]. In the present study, vertical flammability tests were performed on polypropylene (PP) knitted fabric samples, both untreated and treated, with varying concentrations (1–8 %) of a flame-retardant (FR) additive. The fabrics were assessed regarding char length, after-flame time, limiting oxygen index (LOI), dripping behaviour, colour change, and burning status (Table 3).

The data reveal that pure PP knitted fabric exhibits the longest char length (145.7 mm), the longest after-flame duration (46 s), and the lowest LOI (19 %). In contrast, fabrics with FR additive display markedly improved flame retardancy. A reduction in char length is particularly notable with FR concentrations of 7 % and 8 %, the latter achieving a char length of just 52.4 mm — representing a 64 % reduction compared to the control.

Table 3 indicates the effect of varying FR additive concentrations on the after-flame time of PP knitted

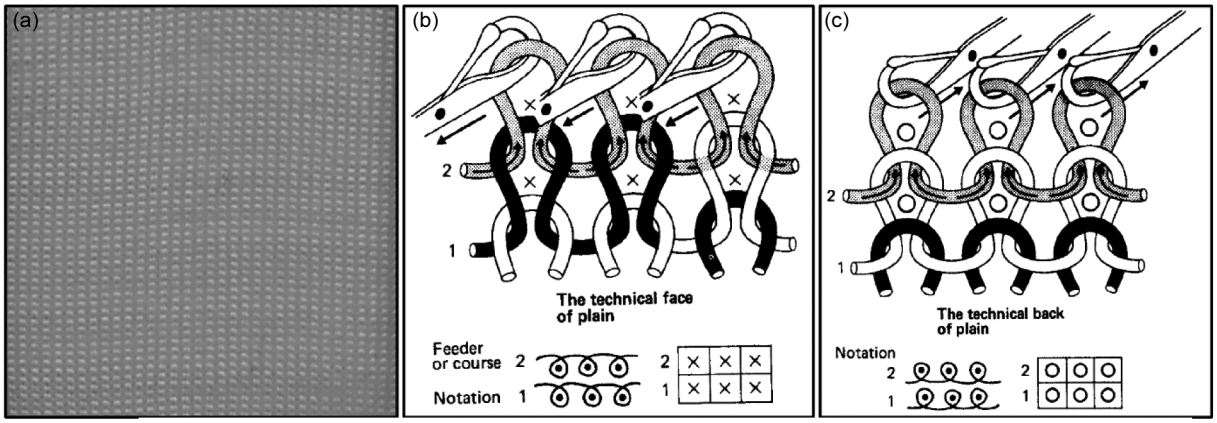

Fig. 1 — Structure and surfaces of PP single jersey knitted fabric (a) full structure, (b) technical face and (c) technical backside[23]

Table 3 — Vertical burning (UL-94) and LOI test results of pure PP and FR-treated PP knitted fabrics

Samples	Char length, mm	After flame time, s	LOI, %	Dripping/Drops	Colour changing [from white (little yellowness) to red]	Burning status of knitted fabrics
Pure PP	145.7	46	19	Few	No colour changing	Mostly Burnt
1% FR	92.3	9.7	25	Few	Little	Fire retardant
2% FR	90	3.8	26	Few	Little	Fire retardant
3% FR	83.9	2.6	27	No	Little	Fire retardant
4% FR	81.6	1.9	27	No	Little	Fire retardant
5% FR	82.6	0.7	28	No	Little	Fire retardant
6% FR	84.4	0.6	28	No	Little	Fire retardant
7% FR	69.2	1.2	30	No	A lot	Fire retardant
8% FR	52.4	1	30	No	A lot	Fire retardant

fabrics. The pure PP knitted fabrics burns for 46 s after a 12 s exposure to flame, whereas the FR-treated PP knitted fabrics exhibit significantly lower after-flame times, indicating improved flame resistance. Dripping behaviour is not observed in most FR-treated samples. However, dripping does occur in the pure PP, 1 % FR, and 2 % FR-treated PP knitted fabrics.

The LOI value of the pure PP sample is calculated as 19 %, which is slightly higher than the typical LOI range of 17-18 % reported for PP materials. The LOI value of PP sample fabric used in this study has been found to be higher[19,26]. This increase likely results from the higher linear density (918 denier) of the PP filament yarn used, as supported by previous studies[18,27].

LOI values of PP knitted fabrics rise significantly with the addition of FR additive at a rate of 1 %. According to literature, fabrics treated with 1–6 % FR fall into the "Slowly Flammable" products category, showing LOI values of 25 %, 26 %, 27 % and 28 %, respectively. Fabrics treated with 7 % and 8 % FR additive achieve LOI values of 30 %, classifying them as "Flame Retardancy-Self-Extinguishing Material"[18,28,29]. Based on their burning performance, the fabrics are categorised accordingly: pure PP fabrics are considered "Mostly Burnt", whereas FR-treated PP fabrics fall under the "Fire Retardant" category due to their reduced after-flame times, absence of dripping (in most samples), and significantly higher LOI values (Table 3).

The colour of these pure PP knitted fabrics is white. FR additive leads to yellowness on the PP knitted fabrics in this study. As a result, the colour change was observed in FR-treated knitted fabrics after the flame retardancy test. The colour of the burned area of the FR-treated PP knitted fabrics has changed from white (little yellowness) to red (Figure 2).

Dripping was observed only in pure PP and low FR-loaded samples (1 % and 2 %), indicating limited suppression of melt-drip behaviour at lower additive levels. Furthermore, colour change from white/yellowish to red is visible in FR-treated fabrics post-burning, intensifying with higher FR content. This visual change further supports the influence of the FR additive on flame propagation and degradation pathways. Overall, incorporating organophosphonate-based FR additives significantly improves the flame-retardant properties of PP knitted fabrics, reducing char length and after-flame time while increasing LOI, particularly at concentrations ≥7 %.

3.2 Flame Spread Behaviours of PP Knitted Fabrics

While vertical flammability and LOI tests provide primary metrics for assessing flame retardancy, the detailed flame spread behaviour—such as ignition point, burn patterns, number of burning peaks, and directional spread—offers further insight into material performance under fire conditions. Figure 3 presents digital photographs of all fabric samples post-flammability testing. The flame spread characteristics are visually evident, enabling the interpretation of peak types and burn pathways.

Key observations from the flame spread behaviour analysis include:

- Pure PP fabric (sample a) exhibits two distinct burning peaks, indicative of rapid horizontal flame spread and secondary ignition at the edges. In contrast, all FR-treated samples (b–i) display single burning peaks, mainly confined to the ignition point.

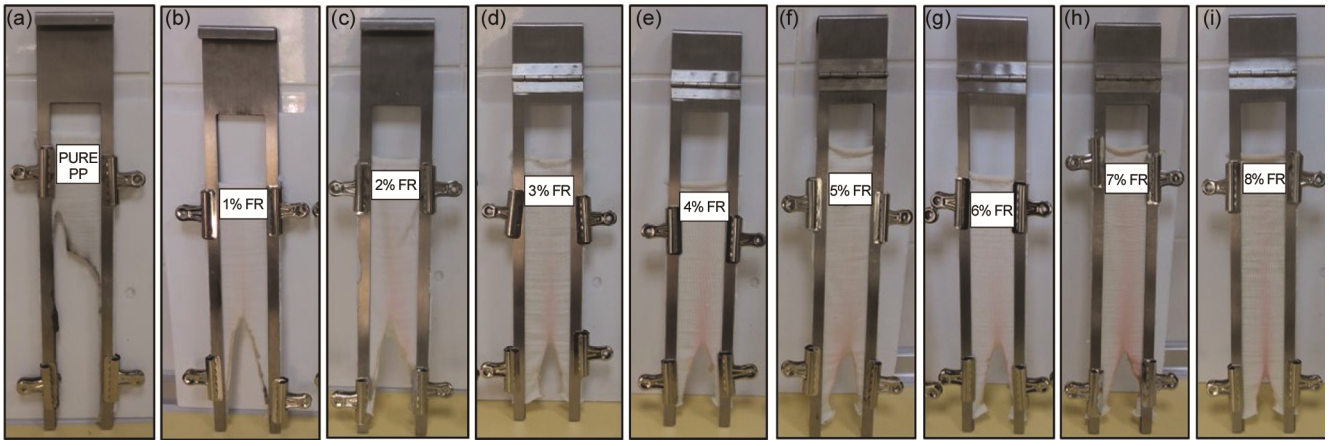

Fig. 2 — Digital pictures of pure and FR-treated PP knitted fabrics after vertical burning test-flame spread behaviours

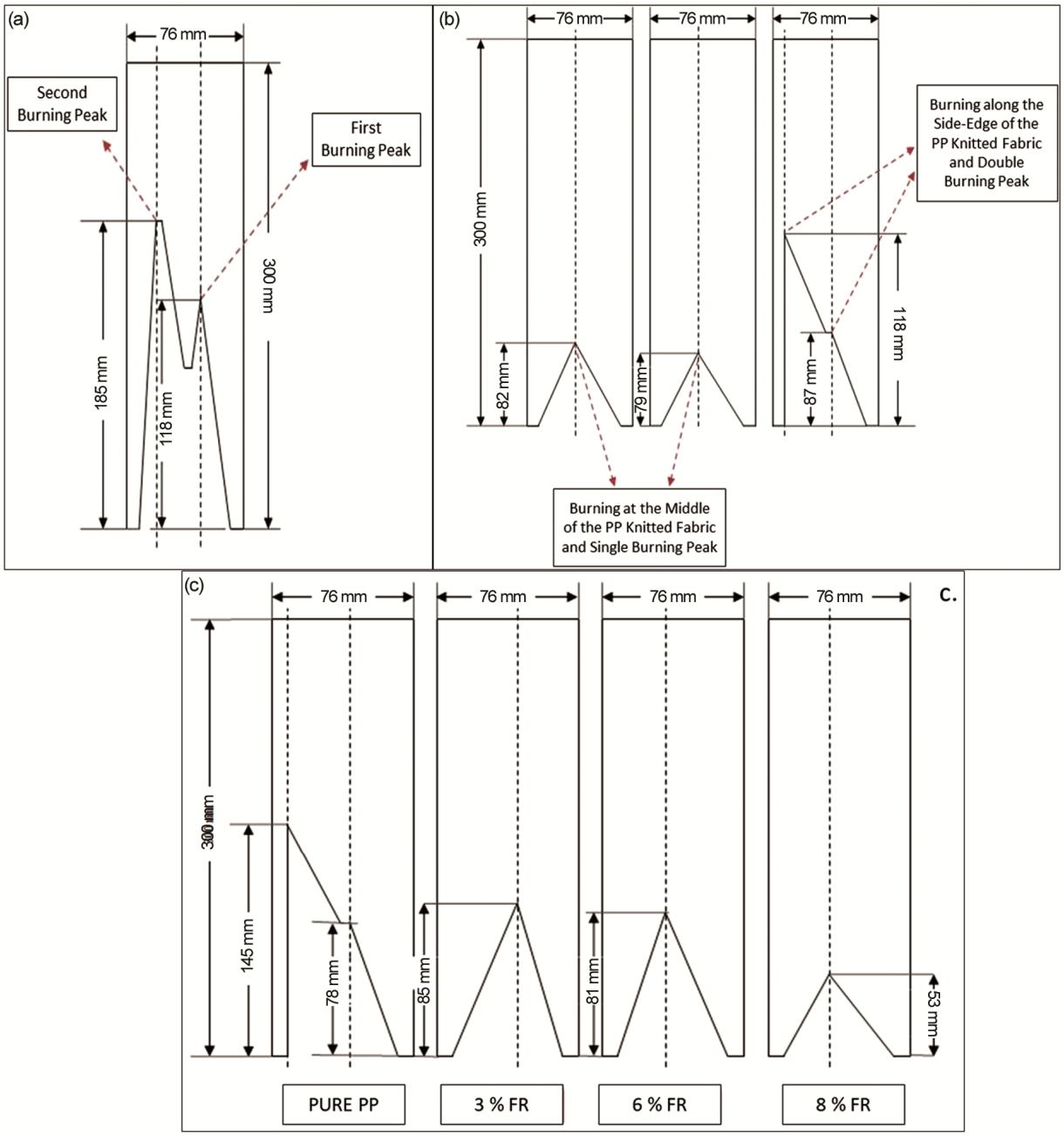

Fig. 3 — Technical drawings of flammability behaviours of PP knitted fabrics (a) burning peaks, (b) burning types and (c) burning lengths

- In pure PP fabric (sample a), the flame initiates at the central lower edge and spreads quickly towards the sides, causing dual-peak burning. This results in extensive damage and longer burning lengths. FR-treated fabrics (samples b–i) generally burn only from the ignition point with restricted spread, highlighting the effectiveness of the additive.
- Samples with 1–6 % FR (b–g) show moderate and comparable char lengths. A notable reduction is observed at 7 % (sample h) and is most pronounced at 8 % FR (sample i), where the char length is reduced by 64 % relative to the control.
- LOI values increase with FR content, with samples b–g (25–28 %) classified as "slowly flammable", and samples h and i (30 %) qualifying as "self-extinguishing" [19,28,29]
- Melting and agglomeration are commonly observed in all samples, but dripping is restricted to samples a–c. The burning time decreases drastically with FR content; for instance, after-flame time in sample

f (5 % FR) is 0.7 s, representing a ~98.5 % reduction compared to pure PP (46 s).

Technical drawings created using AutoCAD to quantify burning lengths and peak distribution are shown in Figure 3. In sample a, the first burning peak (central ignition) measures 118 mm, while the second burning peak (edge ignition) reaches 185 mm, collectively consuming the majority of the sample. In contrast, FR-treated fabrics exhibit short, single peaks. Sample i, treated with 8 % FR, displays the shortest burn length—64 % less than pure PP, 37.6 % less than sample d (3 % FR), and 35 % less than sample g (6 % FR).

The results clearly demonstrate that higher FR content correlates with reduced flame propagation, shorter char lengths, and diminished post-flame combustion.

4 Conclusion

This study evaluates the flammability behaviour and flame-retardant performance of PP-knitted fabrics treated with varying concentrations (1–8 %) of an organophosphonate-based FR additive. The results confirm that the incorporation of FR additive significantly enhances the flame-retardant properties of PP knitted fabrics. Compared to pure PP, FR-treated samples exhibit markedly reduced char lengths, shorter after-flame times, higher LOI values, and suppressed dripping behaviour. Notably, samples containing 7 % and 8 % FR additives achieve an LOI of 30 %, classifying them as "Self-Extinguishing" according to international standards. The sample with 8 % FR additive demonstrates the best performance, with a 64 % reduction in burning length and minimal after-flame time, indicating its superior thermal stability and reduced flammability. The study also reveals two distinct burning patterns: double-peak ignition in pure PP and single-peak ignition in FR-treated fabrics. The latter is indicative of more controlled combustion and effective flame suppression. Colour change and melt behaviour further support the improved flame-retardant action of the FR additive. This research establishes that organophosphonate-based FR additives can be effectively utilised to enhance the fire safety of PP knitted fabrics.

Acknowledgements

This work was financially supported by the "Turkey Ministry of Science, Industry and Technology" within the research program called SAN-TEZ, and Project Number: 00428.STZ.2009-2.

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