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Incineration of municipal and assimilated wastes in France: Assessment of latest energy and material recovery performances

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Abstract

Incineration has an important place in waste management in France. In 2003, around 130 incineration plants have treated 12.6 Mt of non-dangerous waste, mainly composed of household waste (10.8 Mt), non-dangerous waste from industry, business, services (1.0 Mt), sewage sludge (0.2 Mt) or clinical waste (0.1 Mt). The incineration of these wastes generated 3.0 Mt of bottom ash of which 2.3 Mt were used for roads construction and 0.2 Mt of ferrous and non-ferrous metal were recycled. It also produced 2 900 000 MWh of electricity, of which 2 200 000 MWh were sold to Electricité de France (EDF) and 9 100 000 MWh of heat, of which 7 200 000 MWh were sold to private or public users. These French incinerators of non-hazardous waste are currently being thoroughly modernized, thus making possible the consolidation and the enhancement of their environmental and energy performance. This process is related to the implementation of the European Directive 2000/76/CE whose expiration date is 28 December 2005. Upon request of ADEME, the engineering company GIRUS has realised the first technical and economical evaluation of works necessary to bring incinerators into compliance. The financial estimations, carried out in 30 June 2003, show that the investments to be devoted could reach 750 million euros. This assessment shed new light on the situation of non-hazardous waste incinerators, including an identification and a rank ordering for each incinerator of the most frequent and the most complex non-conformities to be solved in term of cost and delay. At last, this assessment gives the solutions for each non-compliance.

Keywords: Incineration; Municipal wastes; Energy recovery; Material recovery

1. Introduction

In France, the field of waste incineration has known drastic changes over the past decade driven by specific European legislations. Four European Directives (89/369/EC, 89/429/EC, 94/67/EC and 2000/76/EC) have been implemented and have significantly changed this field in terms of facility number, treatment capacities, environmental impacts, costs, and energy and material recovery performances. Previous studies [1,2] are no longer up-to-date due to the drastic changes and the latest French incineration assessment [3] was only based on 42 incineration plants built since 1992. The purpose of this paper is to present the latest available and complete information regarding energy and material recovery performances of French municipal and assimilated waste incinerators. If the latest Directive (2000/76/EC) already applies to new incineration plants since 28th December 2002, it shall apply to existing plant as from 28th December 2005. This paper also points out the main legal requirements to be solved before the end of 2005 and gives a perspective view of future performances.

2. 1993–2003: a decade of rapid technological developments

In France, the incineration sector has undergone drastic technological developments over the past decade. Most of the changes have been driven by legislation specific to this sector and this has, in particular, reduced air emissions from individual installation and encouraged energy and material recovery.

2.1. Purpose of incineration

Basically, incineration is the chemical reaction of oxygen (oxidation) with a combustible material. Waste is generally a highly heterogeneous material, consisting essentially of

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organics, minerals, metals and water. During incineration, the flue gases created contain the majority of the available fuel energy as heat. The organics in the waste will burn in gas phases when they have reached their necessary ignition temperatures and come into contact with oxygen. The actual combustion process takes place in gas phase in fractions of seconds and simultaneously releases energy. This leads to a thermal chain reaction and self-supporting combustion, i.e. there is no need for the addition of other fuels.

Incineration of municipal and assimilated wastes also generates a solid slag, called "bottom ash", which takes the form of a grey-coloured chunks, a mixture of metals, glass, silica, alumina, limestone, lime, unburned matter and water. Since 1992, bottom ash must be separated from other combustion residues, such as air pollution control residues. As stipulated by a government circular issue 9 May 1994, bottom ash must be subjected to leaching tests for purposes of establishing a classification and determining potential use in road building. Generally, three materials are obtained after treatment of the bottom ash: construction materials, ferrous metals and non-ferrous metals.

2.2. Incineration is one of the available treatment tools of integrated waste management systems

The choice of a waste management system, which must be economically sustainable for a municipality, is a challenging task. Key factors need to be considered simultaneously such as accurate knowledge of the composition of the different types of wastes, use of the best available techniques to the relevant waste types, optimisation of qualitative and quantitative waste variations and minimisation of environmental impacts and human health risks.

Integrated waste management systems include prevention, sorting, recovery, reuse, mechanical, biological and thermal treatments and landfill disposal; such systems allow energy and material recoveries. If prevention, sorting and recycling allow major environmental benefits, mainly due to resource savings, our lifestyle together with technical and economical constraints strongly limit the performances of this system. As a result and despite all potential efforts, additional treatment is required for a certain proportion of wastes, which is estimated in France to more than 50% of municipal and assimilated wastes.

Incineration, which can treat large varieties of heterogeneous wastes, is one of the available treatment tools that can be used within integrated waste management systems. Incinerators, designed and constructed under the latest European standards and especially the 2000/76/EC incineration European Directive, fully respect the environment and human health at an acceptable price.

2.3. Seven major changes occurred during the 1993–2003 period

In France, seven major changes occurred during the 1993–2003 period:

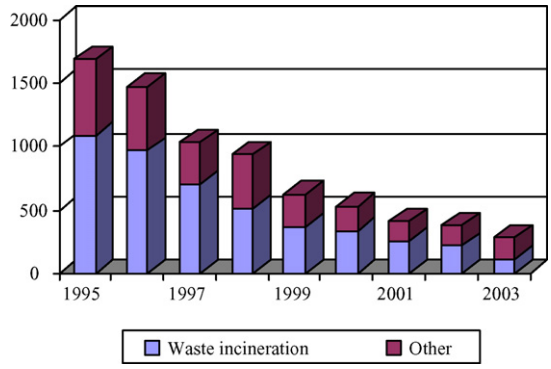

Fig. 1. Evolution of dioxin atmospheric emissions in France (g I-TEQ/yr) [5–7].

1. The number of incinerators has dropped significantly, from over 300 incinerators in 1998, 210 in 2000 to only 123 in 2003.
2. The average plant capacity has increased to reach 110 kt/yr in 2003. Most small incinerators, i.e. with a capacity less than 3 t/h, have closed due to economical difficulties to apply new regulations.
3. In 2003, most of the incinerators accepts two or three different kinds of wastes, in addition to household wastes which still represent approximately 80% of processed wastes. Additional wastes are sewage sludge, non-hazardous industrial wastes and packaging, clinical wastes, bulky wastes, rejects from sorting centres and biological treatment facilities.
4. Bottom ashes are better recovered, both in terms of quality and quantity. Since 1993, more than 50 treatment and stabilisation bottom ash facilities were created. They handle approximately two thirds of bottom ashes generated in France. Also, numerous research and development studies have been carried out. Partnerships have been signed between ash producers, potential users and public administration. Information has been made available to the public for better transparency [4].
5. Energy is more efficiently recovered. Nearly 200 small and old incinerators without energy recovery were closed and no incinerator without energy recovery was constructed since 1993. In addition, energy recovery efficiency per tonne of treated wastes has increased.
6. Pollutant emissions to air and water (dioxins and furans, acid gases, dust, heavy metals, organic compounds, etc.) have decreased. As shown in Fig. 1 for example, dioxin emissions from the incineration of municipal and assimilated wastes have decreased by 90% between 1995 (1085 g I-TEQ/yr) and 2003 (115 g I-TEQ/yr) and will decrease by another 90% between 2003 and 2006 (<15 g I-TEQ/yr) when the European Directive 2000/76/EC is implemented in all facilities.
7. As a result of the above, investment, operational and treatment costs have increased. Investment cost for instance rose from €2.6 m per t/h capacity in 1993 to approximately €4.0 m per t/h capacity in 2003. Global incineration cost,

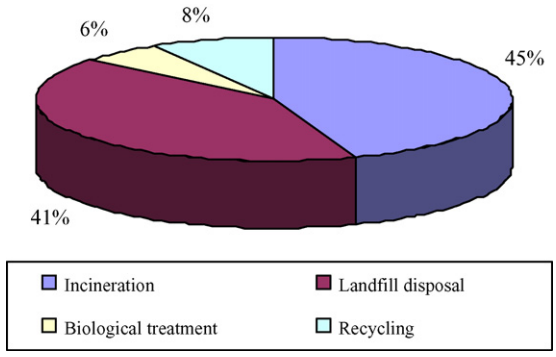

Fig. 2. Destination of the 24.2 million tonnes of household wastes produced in France in 2002 [8].

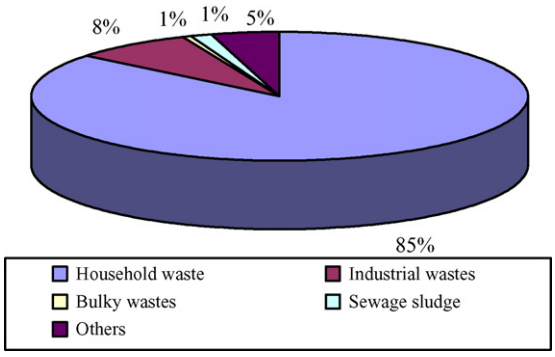

Fig. 3. Origins of the 12.6 million tonnes of municipal and assimilated wastes incinerated in France in 2002 [8].

which takes into account the amount of the investments[1] and the global operating cost,[2] is now estimated between €70 and €90 per tonne of waste treated [3].

3. Review of energy and material recoveries from waste incineration in 2002 and 2003

Since 1992, ADEME, the French Agency for Environment and Energy Management, carried out nationwide annual surveys of all waste sorting and treatment facilities. Following figures are extracted from the latest 2002 survey [8]. This article also presents the results of a technical and economical assessment, carried out in 2004 for ADEME by the consulting firm GIRUS, on incinerators in operation as of June 2003 [9].

3.1. Key facts and figures

3.1.1. Destinations and origins of wastes

In 2002, France produced 45.6 million tonnes of municipal and assimilated wastes, including 24.2 million tonnes of household wastes. Municipal and assimilated wastes not only include household wastes but also non-hazardous industrials, commercial, school, administration (etc.) wastes collected in the same conditions as household wastes, bulky wastes, sewage sludge, rejects from sorting centres and biological treatment centres.

As shown in Fig. 2, incineration was in 2002 the first destination of household wastes (45% or 10.8 million tonnes of household wastes) before landfill disposal (41%), recycling (11%) and biological treatment (6%).

French incinerators received a total of 12.6 million tonnes of municipal and assimilated wastes, which were mainly household wastes as shown in Fig. 3 (85% or 10.8 million tonnes of household wastes) but also a fraction of industrial wastes (8%).

3.1.2. Applied incineration techniques

Grate incinerators are widely applied for the incineration of municipal wastes. Different grate systems can be distinguished by the way the waste is conveyed through the different zones in the combustion chamber. Each has to fulfil requirements regarding primary air feeding, conveying velocity and raking, combustion of solid residues, as well as mixing of the waste.

Rotary kilns are more widely applied for the incineration of hazardous wastes than for municipal wastes. It consists of a cylindrical vessel slightly inclined on its horizontal axis. The vessel is usually located on rollers, allowing the kiln to rotate or oscillate around its axis. The waste is conveyed through the kiln by gravity as it rotates.

Finally, fluidised bed incinerators are applied only to the incineration of finely divided and pre-treated wastes and sewage sludge. Used for decades for the combustion of homogeneous fuels, such as coal, raw lignite and biomass, its application to treat municipal solid waste is recent and still limited.

In 2003, the grate furnace was the most widely used incineration technique in France: 93% of wastes were incinerated in a grate furnace and 84% of French incinerators had a grate furnace. In second position was the rotary kiln technique, which equipped rather small facilities (only 3% of the national capacity treated in 10% of incinerators). Finally, only 3% of wastes were incinerated in fluidised bed facilities.

3.1.3. Incinerator capacities

In France, average plant capacity in 2003 was equal to 14 tonnes per hour (t/h). This average value may vary according to the age of the installation, the number of lines and whether it recovers energy. Incinerators without energy recovery are older, with an average age equal to 25 years, and an average plant capacity of only 5 t/h. On the other hand, the average age of incinerators with energy recovery is 14 years with an average plant capacity of 16 t/h.

3.2. Energy recovery assessment

Waste incinerators both produce and consume energy. In a large majority of cases, the energetic value of the waste exceeds the process requirements and this results in the net export of

[1] The investment cost is based on a pay-off time of 15 years, an investment paid off at 100% by a bank loan at 6% interest rate and a plant operating 8000 h per year.

[2] Operational cost may be derived as follows: fixed costs (personnel, insurance, etc.), costs for by-products elimination (fly ash, bottom ash) and revenues from energy or by-products sales.

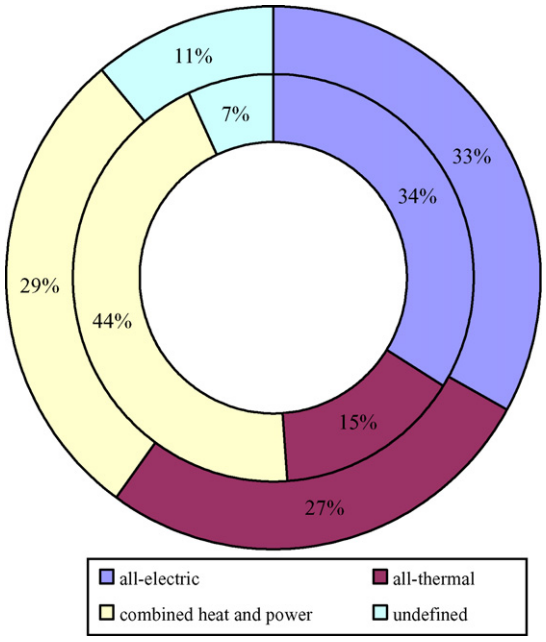

Fig. 4. Breakdown of energy recovery systems per tonne of wastes treated (inner circle) and per the number of incinerators (outer circle) [9].

energy. There are three ways of recovering energy: all-electric, all-thermal and combined heat and power.

In 2003, as shown in Fig. 4, incinerators with energy recovery were equally divided between electricity recovery (33%), thermal recovery (27%) and combined heat and power recovery (29%). This breakdown slightly differs in terms of capacity treated: combined heat and power recovery system was more widely applied (44% of tonnes of wastes treated) whereas all-thermal recovery system represented only 15% of capacity treated.

In 2002, as shown in Table 1, total energy recovered from waste incinerators (11 657 855 MWh) was mainly sold (9 400 501 MWh), the other part (2 557 354 MWh) being used on-site for process requirements. The origin of electricity sale (2 185 717 MWh) came nearly equally from all-electric facilities (1 034 437 MWh) and combined heat and power ones (1 151 280 MWh). On the other hand, most of the sales of heat (7 214 784 MWh) came from combined heat and power facilities (5 383 920 MWh) that treated much more waste quantities than all-thermal ones.

Table 1
Energy recovery of French incinerators [8]

	Plant consumption	Sales	Total recovered
All-electric incinerators			
Electricity (MWh_{elec})	182629	1034437	1217066
All-thermal incinerators			
Heat (MWh_{th})	381150	1830864	2210902
Combined heat and power incinerators			
Electricity (MWh_{elec})	532334	1151280	1683614
Heat (MWh_{th})	1462353	5383920	6846273
Total electricity + heat (MWh)	1994687	6535200	8529887
Total			
Electricity (MWh_{elec})	714963	2185717	2900680
Thermal (MWh_{th})	1842391	7214784	9057175
Total electricity + heat (MWh)	2557354	9400501	11957855

Another recent study [3] revealed that a significant overall improvement in energy recovery was observed for new incinerators operated since 2001; this improvement was confirmed by performance forecasts of facilities under construction. For all-electric incinerators for instance, the energy recovery ratio was evaluated to 360, 418, and 528 kWh/t, respectively for an "average" incinerator, for new incinerators in operation and for incinerators under construction. Also, for heat and combined power incinerators, the total energy recovery ratio was evaluated to 767, 992, and 1326 kWh/t, respectively for an "average" incinerator, for new incinerators in operation and for incinerators under construction.

Finally, wastes such as municipal and assimilated ones contain biomass. In such cases, the energy derived from the biomass fraction may be considered to substitute for fossil fuel and therefore the recovery of energy from that fraction be considered to contribute to a reduction in the overall carbon dioxide emission from energy production. Based on the hypothesis that 50% of municipal wastes are biodegradable, the French production of renewable energy from waste incineration is evaluated to 1 280 000 MWh of electricity and 4 700 000 MWh of heat. In France in 2002, based on the above figures and assuming that the energy that has been recovered was substituting a fossil fuel made of 50% natural gas and 50% oil, municipal and assimilated waste incineration allowed a 0.15 million tonnes CO_2 reduction for electricity production and a 2.5 million tonnes CO_2 reduction for thermal production.

3.3. Material recovery assessment

One tonne of municipal and assimilated wastes generates between 230 and 270 kg of bottom ash. This value varies according to the type and quality of wastes. In 2002, based on the above figure of 12.6 million tonnes incinerated and given a national bottom ash production of 3.2 million tonnes, one tonne of municipal and assimilated wastes generated 250 kg of bottom ash. This value includes metals that are extracted either on the incineration site or on a bottom ash management facility.

Some of French incinerators extract ferrous metals directly on site. In that case, the amount of ferrous metals was evaluated to 206 000 tonnes in 2002. In other cases, ferrous metals are extracted on the site of a bottom ash management facility, which gave another 95 400 tonnes in 2002. The total French production of recovered ferrous metals from waste incineration was therefore evaluated to 301 400 tonnes in 2002.

The destination of bottom ash is as follows: 15% landfill disposal, 20% straight resource savings as road works and 65% bottom ash management facilities. There are in France over 50 bottom ash management facilities for treatment and maturing.

Performances of the facilities rely on the level of the mechanical treatment process. Several operations can occur during the mechanical preparation of the bottom ash: granulometric separation by screening, size reduction by crushing large elements or

otherwise breaking them up, airstream separation to eliminate light unburned fractions, magnetic sorting to recover ferrous metals and induction sorting to recover aluminium and other non-ferrous metals.

After maturation, results of year 2002 show an excellent mass balance with a reject rate of only 2.5% and a resource saving rate of 97.5%, which takes into account 91.7% of matured and treated bottom ash, 5.3% of ferrous metals and 0.5% of non-ferrous metals.

4. 2003–2006: last period of massive investment works

By 28th December 2005, all incinerators must fulfil the 2000/76/EC Directive requirements. The technological developments initiated in the mid 1990s, mainly for new incinerators, now concern approximately 100 existing facilities that need revamping works before the end of 2005.

As of June 2003, all operators had to provide the French administration a feasibility study analysing technical choices and costs of works required by the 2000/76/EC Directive application. This article presents the results of an assessment of all these feasibility studies produced in France [9].

Ninety percent of the studies have been collected, which makes the following results representative of the actual situation. The Directive has been divided into 190 individual legal requirements in order to assess the position of each incinerator on the same basis. The incinerators have then been qualified for each individual legal requirement as follows: Directive requirement achieved, not achieved or not concerned. Statistical computations that have been performed allow presenting, as of June 2003, whether each individual legal requirement is achieved or not. The following list ranks the individual legal requirements that are not achieved by French incinerators as of June 2003:

- 95% incineration plants are concerned by Article 6.3: plants shall have and operate an automatic system to prevent waste feed;
- 70% incineration plants are concerned by Article 10: controls and monitoring of NO_x, conditions and mass concentrations of emissions of NO_x into air;
- 70% incineration plants are concerned by Article 8.7: storage capacity shall be provided for contaminated water arising from spillage or fire-fighting operations;
- 50–60% incineration plants are concerned by Article 6: each line of the incineration plan shall be equipped with at least one auxiliary burner;
- 42% incineration plants are concerned by Article 7: incineration plants shall be designed, equipped, built and operated in such a way that the emission limit value of dioxins is not exceeded in the exhaust gas.

However, a legal requirement qualified as "not achieved" may be simply achieved without significant investment and delay. Therefore, another analysis has been carried out to take into account the amount of works to be done both in terms of delay and investment costs. As it could be expected, the most difficult requirement to solve is air pollution prevention.

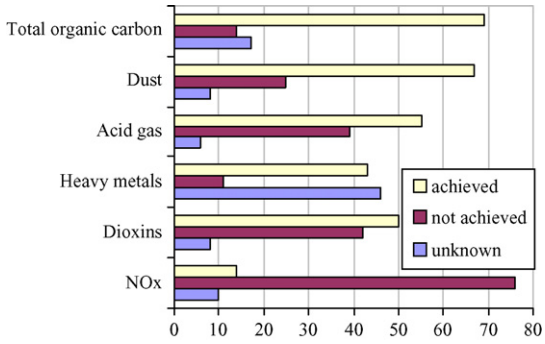

Fig. 5. Breakdown of the number of French incinerators (%) achieving or not the 2000/76/EC Directive requirements regarding limit values of atmospheric pollutant emissions.

Fig. 5 shows the breakdown of the number of French incinerators achieving the 2000/76/EC Directive requirements regarding limit values of atmospheric pollutant emissions. Emission limit values (ELV) of acid gas are not achieved by 39% of French incinerators, dioxin ELV by 42% and NO_x ELV by nearly 80%. These figures strongly suggest that comprehensive flue gas treatment works need to be done.

In terms of investment, operational and treatment costs, available forecast data concern a panel of 100 facilities, as of June 2003. In other words, these figures are the first estimates which will have to be confirmed by true costs once works are completed. Total national investment cost is estimated between €580 and €730 m depending on the technical choices. Investment costs, per facility, vary between €0.04 and €25 m or between €0.01 and €2.3 m per t/h. The average investment cost, per facility, is estimated between €5.2 and €6.7 m.

Additional operational costs, as well as investment costs, vary significantly from one facility to another due to specific local constraints, existing characteristics of the incinerators and technical choices. Additional operational costs vary from 0.4 to 25.4 €/t, with an average value estimated between 6 and 8.5 €/t.

As a result, additional treatment cost vary significantly between 1.7 and 50.8 €/t and the average additional treatment cost, per facility, is estimated between 15 and 21 €/t.

5. Conclusion

Driven by specific European legislation on incineration, comprehensive technological developments occurred over the past decade. Major investment works are still carried out in order to fulfil, by the end of December 2005, the 2000/76/EC Directive requirements. As of June 2003, as shown in this article, it is obvious that French incinerators have nothing left in common with what existed in the early 1990s even if investment works are not completed yet. Together with new technical, environmental and human protection standards, the French incineration sector has even increased its treatment capacity to reach in 2002 12.6 million tonnes. Incineration thus allows significant energy and material recoveries, by producing renewable heat and electricity as well as alternative materials for road works and recovered ferrous and non-ferrous metals.

References

[1] ADEME, French Agency for Environment and Energy Management, Evaluation des coûts induits par le projet de Directive Européenne sur l'incinération des déchets, ADEME, 2000.
[2] ADEME, French Agency for Environment and Energy Management, Incinération des dechets ménagers en France – Situation en 2000 – Evolutions et perspectives au 31.12.2002, ADEME, 2003. http://www.ademe.fr/htdocs/publications/publipdf/rap_aghtm.pdf, http://www.ademe.fr/htdocs/publications/publipdf/an_aghtm.pdf.
[3] E. Autret, French treatment – a comprehensive assessment of 42 recent MSW incinerators, Waste Management World, 2004, pp. 45–54.
[4] ADEME, French Agency for Environment and Energy Management, Ash Management Facilities for Treatment and Stabilisation of MSW Incineration Bottom Ash – Assessment of 32 Facilities in France Funded by ADEME, ADEME, 2002.
[5] MEDD, Ministère de l'Ecologie et du Développement Durable, L'évolution récente des émissions de dioxines dans l'atmosphère, 2003, http://www.ecologie.gouv.fr/article.php3?id_article=842.
[6] MEDD, Ministère de l'Ecologie et du Développement Durable, La réduction des émissions de dioxines des usines d'incinération d'ordures ménagères, 2003, http://www.ecologie.gouv.fr/article.php3?id_article=841.
[7] CITEPA, Centre Interprofessionnel Technique d'Etudes de la Pollution Atmosphérique, Inventaire des émissions de polluants atmosphériques en France – format SECTEN, 2004, http://www.citepa.org/publications/secten-2003.pdf.
[8] ADEME, French Agency for Environment and Energy Management, Enquête sur les installations de traitement des dechets ménagers et assimilés en 2002. ITOM 2002, le Traitement Thermique, ADEME, 2004. http://www.ademe.fr/Collectivites/Dechets-new/Mots-chiffres/ITOM2002.asp.
[9] ADEME, French Agency for Environment and Energy Management, Bilan technico-économique des études de mise en conformité des UIOM réalisées en application de l'arrêté du 20 septembre 2002, ADEME, 2004. http://www.ademe.fr/htdocs/publications/publipdf/uiom.htm.