CHAPTER II
HISTORY OF TREMES AND THEIR PARENT STORMS
OBSERVATIONS AND MEASUREMENTS

II.1. The history of TREMEs: The phenomena which are the subject of this report have been reported in the scientific literature for over 100 years, based upon the earliest known report in the literature (Mackenzie and Toynbee, 1886). Other eyewitness observations include those of Everett (1903), Boys (1926) and Fisher (1990). Until a decade ago, they were not recognized by the scientific community as a whole, nor did they even possess proper names. Many atmospheric scientists were familiar with reports of phenomena variously called "cloud-to-stratosphere lightning" or “upward lightning”, as they were summarized in the *Handbook of Unusual Natural Phenomena* (Corliss, 1977). This book is replete with reports of meteorological esoterica such as turtles encased in hailstones, half meter wide snowflakes and toads falling during rain showers. The "freak lightning” event therefore tended to be viewed as an interesting meteorological conversation piece, but of little consequence. A physical mechanism allowing for the possibility of such events was proposed by Nobel Laureate C.T.R. Wilson (1925). Wilson (1956) even observed one himself, commenting, “It is quite possible that a discharge between the top of the cloud and the ionosphere is a normal accompaniment of a lightning discharge to earth...but one which is only likely to be visible under very special conditions...a diffuse discharge between the top of the cloud and the upper atmosphere...many years ago I observed what appeared to be discharges of this kind from a thundercloud below the horizon. They were diffuse, fan-shaped flashes of greenish color extending up into a clear sky.” Many descriptive accounts of these events are in a vein similar to the following: “The lightning phenomenon...appears to be the rare type of discharge known as *flachenblitz*. It is not peculiar to the tropics; in fact most of the recorded accounts refer to temperate latitudes. In its most typical form it consists of flames appearing to shoot up from the top of the cloud or, if the cloud is out of sight, the flames seem to rise from the horizon” (Ashmore, 1951).

Summaries of these intriguing but subjective and qualitative accounts from credible witnesses were prepared by (Vonnegut, 1980) and Vaughan and Vonnegut (1982, 1989). The reports were widely dispersed geographically, with a broad distribution from equatorial regions to above 50° latitude. The large majority of the sightings (>88%) were made at night. About 75% of the reported sitings occurred over land. The eyewitness visual observations share at least one common characteristic - they are perceived as highly unusual and atypical of "normal lightning" (Lyons and Williams, 1993).

The “mystery” surrounding these phenomena began to dissolve at 0414.22 UTC on 6 July 1989. Scientists, from the University of Minnesota, lead by Prof. Jack Winckler, were testing a low-light imager for an upcoming flight onboard a sounding rocket when they, quite serendipitously, obtained the first concrete evidence that such phenomena were indeed real (Franz et al., 1990). While directing the camera to the northern horizon, they recorded a twin flash originating above distant cloud tops and apparently extending into the stratosphere. The flash lasted for two 16.67 ms TV fields with the greatest intensity occurring in the first field. GOES cloud top images revealed the event occurred above a mesoscale convective complex (MCC) located just north of the Minnesota-Ontario border. Radar summary charts showed radar echo tops up to 14.8 km.

The National Lightning Detection Network (NLDN) cloud-to-ground flash data showed a relatively low flash rate storm, although it did produce a rather large number of positive flashes.

From this singular observation has stemmed a decade of research in the electrodynamics of the middle atmosphere. Today the various phenomena have been given names: red sprites, blue jets, elves, haloes, and trolls. Undoubtedly more varieties are yet to be discovered. Collectively they were originally termed Transient Luminous Events (TLEs). But as research has progressed, even this appellation appears somewhat inadequate. In additional to their various optical manifestations, the events affect a wide portion of the electromagnetic a spectrum (from possible gamma rays through much of the RF (Eack et al., 1996; Lyons, 1996; Armstrong et al., 2000; Boccippio et al., 1995; Reising et al., 1996). Thus we have begun using the term transient electromagnetic events (TREMEs), implying the presence of energetic processes across a broad range of the electromagnetic spectrum. Recently, we have found increasing evidence that infrasound signatures may also be generated (Bedard et al., 1999 – see chapter on infrasound later in this report), along with chemical signatures (Lyons et al, 1997). These events, and their parent thunderstorms are proving to be very complex and are a potential source of system-confusing signatures in a number of applications.

In the early 1990s, NASA’s Marshall Space Flight Center began searching their archives of images from the Space Shuttle payload bay low-light TV camera system in search of confirmation of the “Winckler plume” as some were then calling it. This work has been summarized in a series of papers by Vaughan et al. (1992), Boeck et al. (1991, 1992, 1995) and Lyons and Williams (1993). At least 17 cases of luminous events in the stratosphere and mesosphere were identified. This orbital perspective also made it clear that there was a relationship between TREMEs and the thunderstorm lightning discharge process. The TREME occurred after the onset of cloud illumination, presumably from intra-cloud (IC) or cloud-to-ground (CG) flashes (Lyons and Williams, 1993).

In every case, the maximum cloud luminosity occurred during or just a few video fields before the TREME event. This implied that the TREME was triggered by some event within the cloud, presumably a high energy phenomenon that peaks with the cloud illumination. In the Space Shuttle imagery, the number of illuminated fields before the TREME begins ranges from 0 to 50 fields, with an average of 20.4 fields (340 ms). After the TREME itself (4 to 14 fields), the cloud illumination continued anywhere from 7 to 226 fields, with an average of 50.2 fields (837 ms). One unusually long cloud discharge lasted over 4 seconds. In the Space Shuttle video one notes the electrical activity in the general vicinity of the TREME was moderately vigorous. Yet the lightning flash rate within the portion of the storm that launched the TREME was generally quite low, only 1.8 per minute. This supported the contention of Boeck et al. (1995) that the TREME’s parent cells often have a low flash rate. Although the cloud flashing rate was low, the specific cloud flash associated with the TREME often was among the brightest, if not the brightest, flash in the entire region. This suggested that the TREME may occur after an especially energetic discharge within a storm cell otherwise exhibiting low flash rates.

In 1993, FMA Research was contracted by NASA KSC (under an SBIR Phase I) to assess whether this newly discovered “cloud-to-space lightning” might pose a potential threat to Space Shuttle missions, especially during launch or recovery phases. Needed was a determination of how to routinely detect such phenomena, where and when they might occur, their frequency and their energetics. Based upon the experience in Minnesota and analysis of the Space Shuttle cases, it appeared reasonable to assume that these events might be found above the stratiform regions of large mesoscale convective systems (MCSs), regions known to generate relative few lightning strikes but often very energetic discharges. On the night of 7 July 1993, a Xybion model 255 low-light imager (identical to the unit first employed by Winckler) located at the Yucca Ridge Field Station (104 deg 40 min N; 104 deg, 56 min W) was trained above a large nocturnal MCS in Kansas, some 400 km distant. After several hours of recording nothing but lightning, a display of 248 events occurred over the next four hours (Lyons, 1994a). It was immediately clear the events were almost certainly the same phenomenon as observed by Franz et al. (1990), in the Space Shuttle imagery and the "plume" type discharges described by Ashmore (1950), Wilson (1956), Fisher (1990), Malan (1937) and others. Many of the events occurred simultaneously with in-cloud flashes, although the great range of the storm system made many cloud flashes difficult or impossible to observe. Subsequent analysis revealed that all of the sprites identified were associated with CG flashes of positive polarity (+CGs). A few of the very brightest (as seen on video tape replay) could be seen with the dark-adapted naked eye. Figure 1 (left) is a representative image of how these appear to the naked eye under ideal conditions.

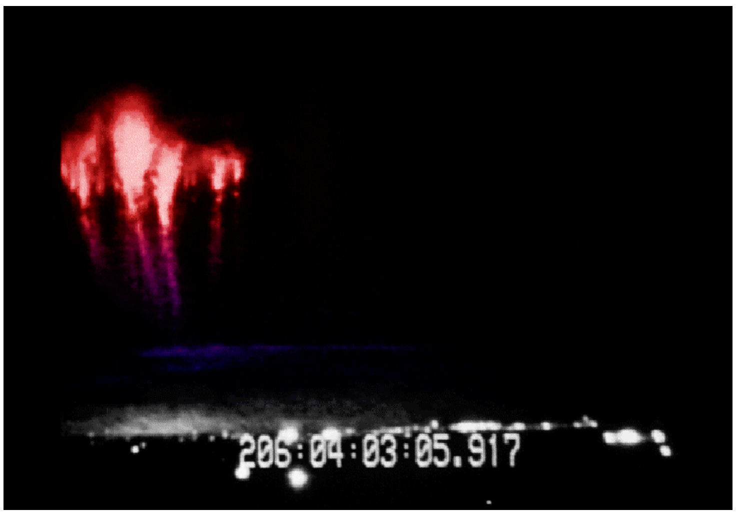

Figure 1. a typical sprite imaged on a Xybion LLTV system with flash color added.

Within 48 hours, in totally independent research effort, sprites were recorded from a high flying aircraft over Iowa (Sentman et al., 1993). Shortly thereafter came the first video records of blue jets (Wescott et al., 1995). The first evidence of what are now called elves were reported in 1994 from Yucca Ridge (Lyons et al., 1994). These were confirmed the following year (Fukunishi et al., 1995). Figure 2 (right) summarizes the basic morphology of the key TREME components as we understand

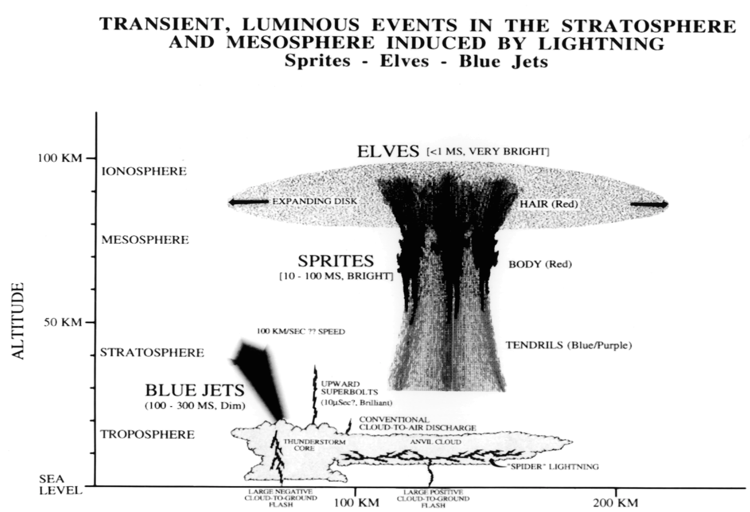

Figure 2. The general morphology of TREME events.

them today. In 1999, some new phenomena were also identified, such as the "haloes" which appear to precede bright sprites and the upward propagating trolls, reminiscent of a return stroke up the previously formed channel of a sprite tendril (Lyons et al., 1999). Since 1993, there has been an annual SPRITE campaign conducted at the Yucca Ridge Field Station (YRFS) to gather information on these events and to form the basis of understanding them.

<u>II.2. Descriptions of the summer sprites campaigns and representative observations:</u> The summer campaigns have steadily grown in complexity and size with each summer since 1993. To-date over 40 scientists from over 20 organizations representing four nations have participated in coordinate observation programs with YRFS (Table 1). Over twenty students have either been in residence at YRFS or used data collected during the SPRITES campaigns in their own research efforts. At least eight MS and Ph.D. dissertations have resulted from these investigations. Over three dozen technical papers and peer-reviewed articles have employed data obtained at YRFS. The summer field programs at YRFS are a result of the combined support of a number of agencies, including the U.S. Department of Energy, Defense Special Weapons Agency (now Defense Threat Reduction Agency), USAF Philips Laboratory (now the Air Force Research Laboratory, NASA Kennedy Space Center, NASA Office of Space Sciences, and the National Science Foundation Physical Meteorology Program.

The primary goal of each summer's campaign was to obtain coordinated RF, video, and photometric measurements of specific TREME events in order to investigate the fundamental physical mechanism involved (Figure 3). The scope of these experiments quickly focussed onto obtaining information on the specific lightning events which are the parent source of the TREMEs, as well as the meteorological regimes which give rise to these unique discharges. The efforts also evolved into coordinated activities with relevant satellite measurements as well as closely coordinated measurements from other participating sites.

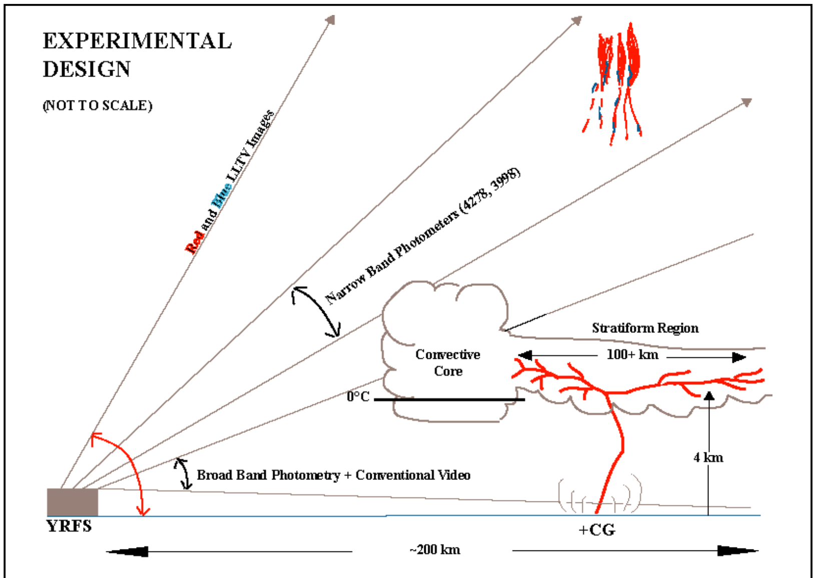

Figure 3. Schematic representation of the data gathering approach at YRFS.

Beginning with the 1996 campaign, the YRFS laboratory space was significantly expanded. A 440 sq ft observation deck allowed the deployment of numerous cameras and tracking units (Figure 4). A command and control center for monitoring both meteorological conditions and system performance was established (Figure 5).

By collocating low-light television cameras on tracking units with multiple broad- and narrowband photomultipliers (PMTs), information on both the morphology and radiometric

Table 1. Institutions Participating in Recent SPRITES Campaigns at Yucca Ridge

Onsite	*Sensors/Experiment*
FMA Research	Xybions, VLF, PMTs, high-speed video
Mission Research Corporation	Multi-color PMTs, data loggers
Tohoku University	PMT arrays, spectrometers, ULF, low-light imagers
Los Alamos National Laboratory	Low-light imagers, narrow band PMTs, tracker
Utah State University	Low-light, filtered imagers (ISIT, ISOCONS)
Stanford University	Fly's Eye, Video, VLF/ELF receivers
SRI International	24 MHz Radar; High resolution low-light imager
University of Otago	VHF receivers, PMTs, ULF
Pennsylvania State University	VHF sferics monitoring
NASA Goddard	ULF sferics
UC – Berkeley	Spectrometers
University of Minnesota	Low-light video, broad band PMT, VLF
University of Arizona	Telescopic monitoring
Offsite	*Sensors/Experiment*
Massachusetts Institute of Technology	ELF transients
New Mexico Tech	High speed cameras, low-light video, VLF
University of Alaska	EXL aircraft campaign, low-light imagers
Tel Aviv University	ELF background and transients
Hungarian Academy of Sciences	ELF background
Global Atmospherics, Inc.	NLDN, wave form recording
Sandia Laboratory	Satellite optical measurements
University of Oklahoma	Balloon x-ray experiments
University of Houston	Stratospheric sprite balloon mission
National Severe Storms Laboratory	Mobile vans, electric field balloons

properties of TREMEs could be obtained (Figure 6). YRFS is located on the locally highest terrain in the region (1654 m MSL). This, combined with the unobstructed horizon and relative lack of local light sources and clean air, permitted observations of sprites to distances approaching 1000 km under ideal conditions. Optical sprite detection was primarily attained using Xybion Model ISS-255 low light camera systems. These red-sensitive GEN II sensors have sufficient response into the near infrared to easily detect most sprites and elves. The cameras were strapped to record individual fields at 16.67 ms of a second duration. GPS time stamping to the nearest millisecond was employed. Audio tracks included VLF audio signals as well as observer commentary.

Figure 4. Picture of the Yucca Ridge Field Station, looking to the west.

Meteorological conditions were observed using a variety of techniques. Local cloud systems were monitored using time lapse video. Video was used to record CG lightning strikes, sometimes to ranges of 200 km, and IC flashes to 400 km. Real-time NLDN lightning ground flash data were received by satellite downlink and displayed via an interactive computer system. Broad band Internet access allowed retrieving and archiving onto CD a myriad of satellite and radar images plus other supporting weather data.

Figure 5. Picture of the command center for the Yucca Ridge Field Station.


Figure 6. Picture of one of the instrument clusters used at Yucca Ridge Field Station, also showing the observational view to the southeast.

The SPRITES’97 campaign focused on obtaining improved narrow-band PMT measurements of TREMEs in conjunction with lightning characteristics (from video, photodiodes, and ELF transient monitoring [Huang et al., 1999]).

During the course of the 1998 summer, two intensive observation periods were conducted. During the 15 May through 15 June period, we supported the MEaPRS (MCS Electrification and Polarization Radar Study) program conducted by NOAA's National Severe Storms Laboratory. Coordination with Los Alamos balloon launch crews was maintained in an effort to place balloon-borne X-ray detectors into a sprite-bearing storm. Unfortunately near drought conditions precluded meeting this objective. During the second half of the SPRITES'98 campaign, we coordinated observations with the University of Alaska staff during their measurements aboard the EXL98 aircraft.

The SPRITES'99 campaign was primarily planned to support the University of Houston’s balloon missions scheduled for 2-21 August 1999. During the early phases of the program, we contributed to the design specifications of the payload package and assisted in developing flight strategies based upon our knowledge of the High Plains nocturnal mesoscale convective systems (MCSs) which generate TREMEs. A concerted effort was made to enhance the YRFS baseline ground observation system (low-light imagers and VLF receivers) with a range of complementary sensors operated by cooperating science teams. In this we were successful, mounting an intensive program featuring a variety of RF, photometric and imaging sensors.

During 1997 and 1998, a Kodak high speed image intensified camera (1000 fps) was available for three weeks of each campaign. We obtained dozens of spectacular sprite images on several nights. In addition, hundreds of high-speed images of lightning cloud-to-ground and in-cloud events were logged on tape, invaluable for increasing our understanding of the characteristics of High Plains lightning events. During each summer, we coordinated activities with mission personnel for several space borne sensors including the DOE/LANL FORTE lightning mission, NASA's OTD, and several DOD assets.

Table 2 summarizes the observational programs conducted during the three most recent SPRITES campaigns. YRFS was on stand-by for a total of 166 nights. On 107 nights systems tests and/or active data logging was conducted. One or more sprites and/or elves were observed on 70 nights. Almost 3000 TREMEs were logged during these campaigns. More complete summary sheets of activities are included in the appendix materials.

Table 2. Summary of the 1997, 1998, and 1999 SPRITES Campaigns.

Activity	Units	1997	1998	1999
LLTV Video Tape Monitoring	hours	252	408	210
Sprites and Elves Recorded	events	504+	854+	1568+
Digital PMT and RF samples obtained	files	1097	994	1000
GOES satellite and NEXRAD radar images	images	2928	1664	1250
NLDN real-time lightning data plots	maps	412	274	224
NLDN raw lightning data records	CD	1	1	1
Length of program	nights	61	66	39
Operations or tests	nights	39	45	23
Sprites or elves recorded	nights	28	27	15

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APPENDICES

1997-1998-1999 Field Program Logs from Yucca Ridge Field Station

SPRITES'97 SUMMARY OF EVENTS

J Date	UTC Date	Total TLEs	SPRITES	%	ELVES		%
177	26JUN97	1	1	*100*	0		*0*
182	01JUL97	25	20	*80*	5		*20*
188	07JUL97	1	1	*100*	0		*0*
190	09JUL97	22	21	*95*	1		*5*
192	11JUL97	38	35	*92*	3		*8*
193	12JUL97	8	7	*88*	1		*12*
194	13JUL97	57	55	*96*	2		*4*
197	16JUL97	14	13	*93*	1		*7*
199	18JUL97	1	1	*100*	0		*0*
200	19JUL97	40+	30	*75*	10	*est*	*25*
201	20JUL97	10	10	*100*	0		*0*
202	21JUL97	34	31	*91*	3		*9*
206	25JUL97	1	1	*100*	0		*0*
207	26JUL97	2	2	*100*	0		*0*
208	27JUL97	4	4	*100*	0		*0*
212	31JUL97	4	4	*100*	0		*0*
213	01AUG97	20	17	*85*	3		*15*
214	02AUG97	31	26	*84*	5		*16*
215	03AUG97	21	16	*76*	5		*24*
221	09AUG97	4	1	*25*	3		*75*
224	12AUG97	36	21	*58*	15		*42*
229	17AUG97	24	23	*96*	1		*4*
231	19AUG97	12+	11+	*92*	1		*8*
234	22AUG97	28	26	*93*	2		*7*
239	27AUG97	9+	8+	*89*	1		*11*
240	28AUG97	5	5	*100*	0		*0*
241	29AUG97	16	15	*94*	1		*6*
242	30AUG97	5	5	*100*	0		*0*
285	12OCT97	31	30	*97*	1		*3*
TOTALS		504+	440+	*87%*	64		*13%*

SPRITES'98 SUMMARY OF EVENTS

J Date	UTC Date	Total TLEs	SPRITES	%	ELVES	%
139	**19MAY98**	**21**	**20**	*100*	**1**	*0*
140	**20MAY98**	**400**	**395**	*99*	**5**	*1*
145	**25MAY98**	**28**	**23**	*82*	**5**	*18*
147	**27MAY98**	**17**	**17**	*100*	**0**	*0*
149	**29MAY98**	**115**	**112**	*97*	**3**	*3*
150	**30MAY98**	**2**	**2**	*100*	**0**	*0*
159	**08JUN98**	**11**	**11**	*100*	**0**	*0*
174	**23JUN98**	**80**	**80**	*100*	**0**	*0*
196	**15JUL98**	**10**	**10**	*100*	**0**	*0*
197	**16JUL98**	**5**	**5**	*100*	**0**	*0*
198	**17JUL98**	**1**	**1**	*100*	**0**	*0*
200	**19JUL98**	**9**	**8**	*89*	**1**	*0*
201	**20JUL98**	**39**	**38**	*97*	**1**	*3*
203	**22JUL98**	**3**	**3**	*100*	**0**	*0*
205	**24JUL98**	**3**	**3**	*100*	**0**	*0*
207	**26JUL98**	**17**	**17**	*100*	**0**	*0*
208	**27JUL98**	**29**	**27**	*93*	**2**	*7*
209	**28JUL98**	**6**	**6**	*100*	**0**	*0*
210	**29JUL98**	**3**	**3**	*100*	**0**	*0*
211	**30JUL98**	**8**	**7**	*88*	**1**	*12*
213	**01AUG98**	**2**	**2**	*100*	**0**	*0*
214	**02AUG98**	**18**	**15**	*83*	**3**	*17*
221	**09AUG98**	**5**	**5**	*100*	**0**	*0*
222	**10AUG98**	**4**	**1**	*25*	**3**	*75*
224	**12AUG98**	**4**	**3**	*75*	**0**	*25*
237	**25AUG98**	**12**	**12**	*100*	**0**	*0*
238	**26AUG98**	**2**	**2**	*100*	**0**	*0*
TOTALS (1998)		**854+**	**828**	*97%*	**26**	*3%*

SPRITES'99 SUMMARY OF EVENTS

J Date	UTC Date	Total TLEs	SPRITES	%	ELVES	%
156	**05JUN99**	**776**	**n/a**	*100*	**n/a**	**n/a**
161	**11JUN99**	**50**	**n/a**	**n/a**	**n/a**	**n/a**
184	**03JUL99**	**500+**	**n/a**	*n/a*	**n/a**	**n/a**
219	**07AUG99**	**3**	**0**	*0*	**3**	*100*
221	**09AUG99**	**12**	**1**	*8*	**11**	*92*
223	**11AUG99**	**28**	**28**	*100*	**0**	*0*
224	**12AUG99**	**35**	**25**	*71*	**10**	*29*
226	**14AUG99**	**23**	**23**	*100*	**0**	*0*
230	**18AUG99**	**120**	**108**	*90*	**10**	*10*
231	**19AUG99**	**6**	**0**	*0*	**6**	*100*
233	**21AUG99**	**8+**	**4**	*50*	**5**	*50*
234	**22AUG99**	**2**	**2**	*100*	**0**	*0*
235	**23AUG99**	**1**	**1**	*100*	**0**	*0*
246	**03SEP99**	**5**	**5**	*100*	**0**	*0*
247	**04SEP99**	**5**	**5**	*100*	**0**	*0*
TOTALS (1999)		**1574**			**45+**	***3+%***

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