AIAA 2004-0289

STRUCTURE OF FLAME BALLS AT LOW LEWIS-NUMBER (SOFBALL): NEW RESULTS FROM STS-107

Mohamed Abid, Jianbang Liu, Paul D. Ronney*
University of Southern California, Los Angeles, CA 90089

Oh-Chae Kwon
Sungkyunkwan University, Seoul, Republic of Korea

Peter Struk and Karen J. Weiland
NASA Glenn Research Center, Cleveland, OH 44135

Abstract

Experiments on steady, spherically-symmetric premixed-gas flames ("flame balls") performed on STS-107 are described. These experiments were motivated by results obtained on earlier Space Shuttle missions. The motivation and objectives for the STS-107 experiments are described, along with the results obtained. Among the highlights of STS-107 were the weakest flames ever burned either on earth or in space (about 0.5 Watt of heat release), the leanest flames ever burned either on earth or in space, and the longest-lived flame ever burned in space. While many of the questions left unresolved from the earlier space flights were answered, some new and as yet unexplained phenomena were found, for example flame balls migrating in spiral patterns. Nonetheless, flame ball experiments have provided an insight into the interactions of the two most important phenomena in combusting materials, namely chemical reaction and transport processes, in the unequivocally simplest possible configuration.

Introduction

It has been known for many years that most near-limit phenomena are influenced by gravity through the effects of buoyant convection on the transport rates of thermal energy and reactants to/from the chemical reaction zones. This has motivated a number of recent experiments on flame propagation in a μg environment[1,2]. It has been found that in a μg environment the absence of buoyant convection emphasizes other transport mechanisms, including the unequal rates of diffusion of thermal energy and diffusion of molecular reactants (the Lewis number effect) and the spectral radiation emitted from the gaseous combustion products. As a consequence of the change in the relative magnitudes of various transport mechanisms at μg, a number of new near-limit phenomena have been observed. One of the most unusual of these are "flame balls," which are the subject of the Structure Of Flame Balls At Low Lewis-number (SOFBALL) space flight experiment.

A flame ball is a steady, stationary, spherical flame, not supported by any source of reactants or sink of products at its center, that evolves from an ignition source in a chamber filled with an initially quiescent combustible gas. In a flame ball structure, fuel and oxygen diffuse from the surrounding gases inward to the reaction zone while heat and combustion products diffuse outward (Fig. 1). The continuity equation in a steady spherically symmetric system with no sources or sinks, $\nabla \cdot \rho \mathbf{u} \tilde{\square}$, where ρ is the density and **u** the fluid velocity vector, requires that **u** be identically zero everywhere. The solution to the steady diffusion equations with constant transport coefficients $\nabla^2 T = 0$ and $\nabla^2 Y = 0$ for the temperature T and limiting reactant mass fraction Y in spherical geometry are of the form $c_1 + c_2/r$, where r is the radial coordinate and c_1 and c_2 are constants. This form satisfies the requirement that T and Y be bounded as $r \rightarrow \infty$. The flame front temperature is $T^* = T_\infty + (T_{ad} - T_\infty)/Le$, where T_{ad} is the conventional adiabatic flame temperature for the homogeneous mixture and T_∞ the ambient temperature. Note that for $Le < 1$, $T^* > T_{ad}$ and thus for $Le < 1$ flame balls can exist in mixtures whose exothermicity is too low to support plane flames. For cylindrical and planar geometry the corresponding solutions to the diffusion equations are $c_1 + c_2\ln(r)$ and $c_1 + c_2 r$, respectively, which are obviously unbounded as $r \rightarrow \infty$. For this reason theory admits steady flame ball solutions, but not "flame cylinder" or "flame slab" solutions.

---

*Professor. Senior member AIAA.

Flame balls were first predicted by Zeldovich in 1944[3], but were predicted to be unstable (*i.e.*, they would either expand beyond their equilibrium radius or collapse and extinguish) and thus not physically observable. Forty years later, seemingly stable flame balls were accidentally discovered in drop-tower experiments in lean hydrogen-air mixtures[4]. The μg environment of the drop tower was needed to obtain spherical symmetry (which would otherwise be destroyed by buoyancy) and to avoid buoyant-convection-induced extinction of the flame balls. Based on μg experiments in drop towers[4] and aircraft[5], it was concluded that flame balls would probably occur in all combustible mixtures with a low Lewis number for highly diluted mixtures sufficiently close to the extinction limits. However, the short duration of drop tower experiments and the substantial g-jitter in aircraft experiments precluded definitive conclusions.

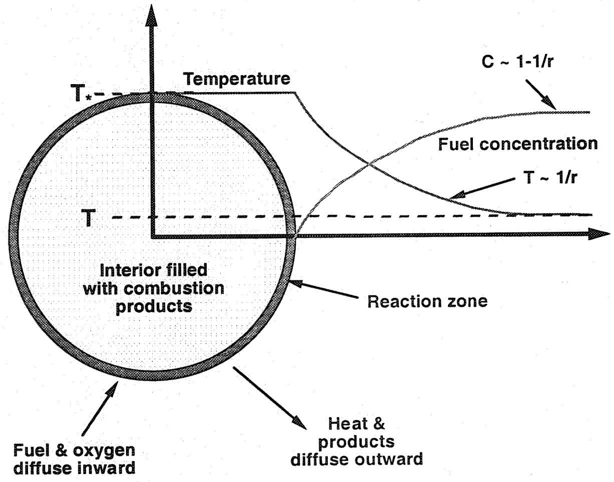

Figure 1. Schematic diagram of a flame ball.

The apparent discovery of stable flame balls in near-limit mixtures motivated further theoretical study. Buckmaster and collaborators[6,7] analyzed the effects of heat losses on the structure and stability of flame balls. A range of stable flame balls was theoretically predicted for mixtures close to the extinction limits when radiant heat losses from the combustion products were included in the model. This factor was not considered in Zeldovich's or other earlier theories (though Zeldovich noted the possibility of heat losses stabilizing flame balls), which could explain the discrepancy between the early theories and experimental observations concerning flame ball stability. Moreover, it has also been predicted[8] that stable flame balls can only exist for mixtures having Le less than a critical value which is less than unity, which may explain why they are not observed for mixtures with Le close to unity (e.g. CH_4-air) or larger than unity (e.g. C_3H_8-air), even for near-limit mixtures at μg.

Flame balls have a number of unique and interesting properties. Since they are one-dimensional, steady and convection-free at μg, they are the simplest possible type of premixed flame structure and therefore provide a useful testbed for theoretical and numerical models of the interaction between chemical and transport processes in flames, especially near flammability limits. Some of these interactions are not predicted well even by the best currently available models. For example, different chemical models of hydrogen-oxygen oxidation predict widely varying flame ball characteristics[9], even though all of these models can accurately predict the burning velocities of flames in hydrogen-air mixtures farther away from the extinction limits. This is particularly significant because models of hydrocarbon combustion chemistry must have an accurate H_2-O_2 sub-mechanism if they are to be able to model hydrocarbons accurately. Because flame balls are steady, convection-free, spherically symmetric and occur in fuels with simple chemistry, they represent the simplest possible interaction of chemistry and transport in flames. In this sense flame balls bear a similar relationship to combustion research that the fruit fly does to genetics research. Also, since flame balls can be observed in mixtures that are well outside the conventionally defined extinction limits, microgravity can be a more hazardous environment from the point of view of fire safety. Flame balls warrant particular concern because they do not propagate; this makes fire detection and suppression more difficult. This potential problem is compounded because hydrogen burns without visible radiation or smoke and sources of hydrogen abound on spacecraft (*e.g.*, in propulsion and fuel cell systems). Flame balls may also be relevant to the turbulent combustion of mixtures with low Lewis number because flame balls are more robust than plane flames (the computed radiation-induced extinction limit of flame balls in lean H_2-air mixtures is 3.43% H_2, whereas for plane flames it is 11.1%.) Consequently, sufficiently strong turbulence may extinguish planar flames, whereas flame balls could persist under the same conditions. Hence, structures reminiscent of flame balls could be the prevalent ones in near-limit turbulent combustion of lean hydrogen-air mixtures in engines.

In summary, the overall objectives of the SOFBALL experiment are as follows:

- Determine whether steady, stationary flame balls can exist in an extended-duration μg environment
- Assess the influence of gaseous radiation on flame ball size and stability

- Determine whether flame ball motion (if observed) is due to the non-zero gravity level
- Determine the effect of Lewis number and radiation on flame balls through the use of mixtures employing different diluent gases

Considerations for space experiments

The drop-tower and aircraft μg experiments indicated that a very long duration and high quality μg environment is necessary to assess the steady properties and stability limits of flame balls. A theoretical estimate of the time required can be made in the following way. The response time of flame balls is on the order of the time for thermal diffusion of energy from the near-field region of the flame ball to the far-field region. The former region is characterized by radii of the order of r^* and the latter region is characterized by radii of the order of (θr^*), where θ is the non-dimensional activation energy . Consequently, the time scale is of the order $(\theta r^*)^2/\alpha$, where α is the thermal diffusivity. Since typical values of r^*, θ and α are 0.5 cm, 10 and 0.2 cm^2/s, respectively, for lean H_2-air mixtures, a representative time scale for flame ball evolution is 125 s - much longer than the time available from drop-tower or aircraft facilities. This evolution time scale has been confirmed by numerical simulations[9]. Another consideration is that the gravity level must be small enough that the flame balls are not significantly affected by convection. Since the drift velocity of flame balls based on aircraft μg data was found to be[5] $1.5(gr^*)^{1/2}$, and velocities on the order of α/r^* are sufficient to disturb flame balls[10], we require $g << 1.5 \times 10^{-4}\ g_o$, where g_o is earth gravity. To ensure that the conductive flux, represented by α/r^*, is significantly less than the convective flux, represented by the drift velocity, the g-level should be a factor of θ less than this, or $1.5 \times 10^{-5}\ g_o$. Another requirement is that the acceleration is small enough that the flame balls do not drift into the walls of the combustion chamber before at least one characteristic evolution time has elapsed. This coincidentally also requires $1.5 \times 10^{-5}\ g_o$ or lower in the combustion chamber employed, which has a diameter of 32 cm. This time and quality of μg indicate the need for space experiments.

Prior space experiments

The first set of SOFBALL experiments were performed in the Combustion Module-1 facility, developed by the NASA-Glenn Research Center. A cylindrical chamber of 32 cm inside diameter and 32 cm length was filled from one of 14 bottles containing a pre-specified weakly combustible gas mixture and ignited using electric sparks of variable deposited energy up to 700 mJ with spark gaps variable from 0.35 to 10 mm; energies of 700 mJ and gaps of 5 mm and 2 mm, respectively, were used for the H_2-O_2-CO_2 and H_2-air tests described below. The flame balls evolving from this ignition source were observed using two intensified video cameras (sensitive to visible and near-IR emissions from 400 to 900 nm) with orthogonal views, one color video camera, a set of six thermocouples to measure gas temperature, and four radiometers (two unfiltered and two with a $5\mu m$ - $7.5\mu m$ band-pass filter to detect only H_2O radiation) to measure the radiant heat flux emitted from the flames. A gas chromatograph was used to measure post-test combustion products. Additionally, the chamber pressure was recorded during the test and the on-orbit acceleration levels were measured by on-board accelerometer instruments.

The SOFBALL experiment initially flew on STS-83 and STS-94 in April and July 1997. The results of these experiments have been summarized in a series of papers[2,9,10,11,12]. A total of two test points were conducted on STS-83 and both tests were successful. A total of seventeen test points were performed on STS-94, compared to the pre-mission plan of fifteen tests. Sixteen of these mixtures ignited. These mixtures produced from one to nine flame balls, with the mixtures having more fuel producing multiple flame balls. Most of the tests burned for 500 seconds, until the experiment timeout extinguished the flames. Ten of the initial burns were sparked again and eight of them burned for an additional 500 seconds. A total of 8 flame balls were produced on STS-83 and 52 on STS-94. Over 3 hours of test data were collected. All mixtures in the pre-flight test matrix were successfully burned at least once. The data obtained during the test runs resulted in the following conclusions:

1) Steady, nearly stationary flame balls exist in an extended-duration microgravity environment. During free drift periods, the flame balls were nearly motionless for many minutes (though longer duration tests on STS-107, described below, show that there is still some drift).
2) The extended length of the burns verifies the theoretical predictions that these flames evolve on a very slow time scale, on the order of hundreds of seconds.
3) The flame ball drift velocities due to the Orbiter accelerations were lower than expected pre-flight, most likely because the drift prediction used pre-flight was based on aircraft μg experiments, where much higher g levels are present. At the higher g levels, the Grashof numbers indicate the flow can be characterized as inviscid, whereas at the much

lower accelerations in the space experiments, the flow is highly viscous.

4) When multiple flame balls were formed, the flame balls were always found to drift apart from each other. This led to the post-flight development of a theoretical model of flame ball drift due to mutual heating and mutual fuel depletion by adjacent balls. This model was found to be in good agreement with the experimental observations.
5) In contrast to item 3. above, the flame balls were much more sensitive to Orbiter vernier thruster firings than expected pre-flight. Impulses above about 50 μg-sec (e.g., 50 μg for a period of 1 sec) produced a noticeable change in the flame ball position, drift speed, and especially radiant emissive power. Preliminary inspection of the flight data suggest that the flame balls respond ballistically to the impulses, that is, the impulse (change in velocity) imparted to the ball is the same as the acceleration impulse (as measured by onboard accelerometers). This change in velocity then decays on a time scale of tens to hundreds of seconds, which is consistent with the viscous time scale associated with the flame ball and its surrounding hot gas field. The strong effect of microgravity disturbances on radiation is probably due to the fact that the visible flame ball is like the proverbial "tip of the iceberg" in that it is surrounded by a much larger mass of hot but non-reacting gas. Most of the radiation is emitted from this large gas volume rather than the flame ball itself. This large ball of gas is extremely susceptible to buoyancy-induced motion resulting from any small impulse. When free drift could be maintained for the entire test period, excellent quality low-gravity environments were obtained.
6) Data analysis suggests that under steady-state conditions, all flame balls tested radiated from 1 to 2 Watts of infrared emission. Since at steady state, the radiative emission is nearly equal to the heat generated by chemical reaction, these results indicate that all flame balls tested generate heat at nearly the same rate. This finding was quite surprising and is not predicted by theoretical and computational models.

Some but not all of the SOFBALL science issues have been resolved by the STS-83 and STS-94 experiments. Specifically it has been concluded that

1) Flame balls do exist until a substantial amount of the fuel in the chamber is depleted.
2) Flame ball motion observed in aircraft μg experiments was almost certainly due to the acceleration levels present in those tests.
3) The "flame strings" observed in the aircraft μg experiments were almost certainly due to the acceleration levels present in those tests.
4) Lewis number does not qualitatively affect flame ball properties over the range $0.06 < Le < 0.3$.

The following SOFBALL science issues have not been resolved by the STS-83 and STS-94 experiments:

1) Because of the limited test durations, acceleration environment and the inability to ignite mixtures very close to the extinction limit, it has not been concluded whether flame balls with oscillating radii exist.
2) Because of the acceleration environment and its influence on the radiometer readings, it was not possible to conclude whether radiation is the dominant stabilizing mechanism of flame balls.
3) Because of the inability to ignite mixtures very close to the extinction limit, especially for H_2-air mixtures, the effect of mixture composition has not been determined in that the flammability limits have not been established.
4) Because fuels other than hydrogen were not tested on STS-83 or STS-94, the effects of the chemical mechanism on flame balls has not been established.

Changes to SOFBALL for STS-107

It was consistently found on STS-94 that the flame balls would drift 1 - 4 cm toward the center electrode within 20 sec following the discharge. This drift could not be attributed to the gravity level on Spacelab. KC135 data also showed some initial drift, but these results were not as consistent or convincing because of the substantial g-jitter. This initial drift compromises the value of the science data because this causes the initial thermal field to exhibit asymmetry. This is particularly problematic for radiometer data. The reason that the spark may induce drift is as follows. During the discharge, electrons are stripped off of neutral atoms and molecules creating positive ions, thus electrons are attracted to the + electrode and positive ions to the - electrode. Since the positive ions are more massive by several orders of magnitude, more momentum is imparted by the electric field to the positive ions. This momentum is distributed to the other molecules in the gas by collisions. Consequently, a net "electric wind" is generated in the direction of the - electrode. Through viscous effects, a toroidal vortex is generated with the core fluid along the centerline of the electrodes moving toward the - electrode and the surrounding fluid moving toward the + electrode. In principle, the flame balls could drift in either direction depending on their location relative to the toroidal vortex, but inevitably the balls chose to drift toward the + electrode, probably because they are not exactly on the centerline of the electrodes. A means to reduce the impulse is extremely desirable. A spark generator producing longer duration discharges was employed because the momentum imparted to the gas increases with the square of the induced electric wind velocity. Furthermore, as mentioned above with the longer discharges, the efficiency of the ignition process may improve. This would lead to the possibility that lower energy sparks may be employed that would induce less drift.

In most cases, flame balls did not extinguish before the 500 second experiment timeout, thus the tests ended while flame balls were still burning - a disappointing experience. Since the buoyancy-induced drift rates were much lower than previously expected, the additional test time can be used to obtain steady-state conditions and observe the mutual interactions of flame balls (whose separation distance increases approximately with the cube root of time[10]). The additional time can also be used to search for growing oscillatory behavior near extinction which has been theoretically predicted but not yet observed experimentally, in part due to the limited test time and acceleration disturbances (due to VRCS firings) on STS-83 and STS-94. Thus, much longer experiment durations are required for SOFBALL-2. It is highly desirable that the maximum experiment duration be not less than 3 characteristic time constants for flame ball evolution in order to obtain steady-state conditions, observe the mutual interactions of flame balls and to search for growing oscillatory behavior near extinction. The evolution time is longest for the 3 atm H_2-O_2-SF_6 mixtures. As previously mentioned, the evolution time scale is estimated as $(\theta r^*)^2/\alpha$, where r^* is about 0.5 cm and α is about 0.011 cm^2/sec for the 3 atm H_2-O_2-SF_6 mixtures. Thus the characteristic time scale is on the order of 3300 sec for the 3 atm H_2-O_2-SF_6 mixtures. Thus, a test duration of 10000 seconds was specified for the 3 atm H_2-O_2-SF_6 mixtures. In the same way, test durations for the other mixtures was determined.

The STS-94 experiments conclusively demonstrated that the flame ball motion and radiometer and thermocouple response are drastically affected by VRCS firings. In particular, the VRCS firings distort the hot gas surrounding the flame ball itself, destroying the spherical symmetry of the hot gas and compromising the resulting science data. In practically every case the Orbiter VRCS firings produced impulses exceeding 100 μg-sec, and these impulses invariably affected the radiometer data in a substantial way. Therefore, in no tests can VRCS firings be tolerated without compromising science data. Even in free drift mode, during STS-94 there was a noticeable acceleration induced by the tendency of the Orbiter to rotate from the nominal bay-to-earth, 55 degree roll bias towards the gravity-gradient orientation. This acceleration did cause a slow but noticeable drift in the flame balls. To avoid significant flame ball drift required accelerations of less than 1 μg (value averaged over the 500 second tests). Thus, based on the results from STS-94, the acceleration requirements for STS-107 were 1 μg steady state on each axis and no individual impulses from VRCS firings, water dumps, etc., of greater than 50 μg-sec. The preliminary indication that flame balls respond ballistically to the impulses with viscous decay on a time scale of tens of seconds indicate that very little drift will occur without VRCS firings, and indeed this was found to be the case.

The field of view for the two Xybion intensified video cameras is 30 cm x 22 cm at the center of the chamber. This large field of view is necessary to be able to follow the flame balls over long periods of time as they drift due to mutual repulsion and acceleration effects. At this large field of view, the resolution of the flame balls themselves was less than desired, thus the flame ball radii could not be determined as accurately as desired. In order to rectify this situation a third intensified video camera with a smaller field of view (about 5 cm at the chamber center) was added. Of course, the flame balls would sometimes drift out of the field of view of this camera.

Fuel type	Inert type	% fuel	% O_2	% inert	Press (atm)	# of balls	Burn time (sec)
H_2	CO_2	4.4	9.8	86.8	1	3	750
H_2	CO_2	4.4	9.8	86.8	1	2	425
H_2	CO_2	4.4	9.8	86.8	1	2	210
H_2	CO_2/ He	7.75	15.5	7.68 / 69.08	3	2	705
H_2	CO_2/ He	7.75	15.5	7.68 / 69.08	3	1	500
H_2	CO_2/ He	8.0	16.0	7.6 / 68.4	3	2	660
H_2	CO_2/ He	8.0	16.0	7.6 / 68.4	3	2	370
H_2	CO_2/ He	8.0	16.0	7.6 / 68.4	3	1	405
H_2	N_2	3.32	20.3	76.37	0.7	2	205
H_2	N_2	3.32	20.3	76.37	0.7	1	180
H_2	N_2	3.32	20.3	76.37	0.7	1	110
H_2	N_2	3.2	20.3	76.46	1	1	300
H_2	N_2	3.45	20.3	76.27	1	2	320
H_2	N_2	3.45	20.3	76.27	1	1	340

H_2	N_2	3.32	20.3	76.37	1	1	470
H_2	N_2	3.32	20.3	76.37	1	1	210
H_2	N_2	3.32	20.3	76.37	1.75	1	960
H_2	N_2	3.32	20.3	76.37	1.75	1	410
H_2	N_2	3.45	20.3	76.27	1.75	2	795
H_2	N_2	3.45	20.3	76.27	1.75	1	600
H_2	N_2	3.45	20.3	76.27	3	1	1200
H_2	N_2	3.45	20.3	76.27	3	0	5
H_2	N_2	3.32	20.3	76.37	3	0	4
H_2	SF_6	6.2	12.4	81.4	1	1	1260
H_2	SF_6	6.2	12.4	81.4	1	1	990
H_2	SF_6	6.2	12.4	81.4	1	1	530
H_2	SF_6	6.2	12.4	81.4	3	1	500
H_2	SF_6	6.2	12.4	81.4	3	1	1000
H_2	SF_6	6.2	12.4	81.4	3	1	1500
H_2	SF_6	6.2	12.4	81.4	3	1	585
H_2	SF_6	7.5	15	77.5	3	9	4860
CH_4	SF_6	9.9	19.8	70.3	1	1	350
CH_4	SF_6	9.9	19.8	70.3	1	1	480
CH_4	SF_6	9.9	19.8	70.3	1	1	30
CH_4	SF_6	10.2	20.4	69.4	1	1	60
CH_4	SF_6	10.2	20.4	69.4	1	1	40
CH_4	SF_6	10.2	20.4	69.4	1	1	90
CH_4	SF_6	10.2	20.4	69.4	1	1	120
CH_4	SF_6	10.2	20.4	69.4	1	1	10

Table 1. SOFBALL-2/STS-107 test matrix

Test Matrix

Table 1 shows the test matrix for SOFBALL-2 on STS-107, along with results in terms of the number of flame balls produced and the total burn duration until the last flame ball extinguished. There are five mixture families, namely H_2-O_2-CO_2, H_2-O_2-He-CO_2, H_2-air, H_2-O_2-SF_6, and CH_4-O_2-SF_6. The H_2-O_2-He-CO_2 and CH_4-O_2-SF_6 families are new for SOFBALL-2. The H_2-O_2-He-CO_2 mixtures are basically H_2-O_2-He with 10% CO_2 (that is, 10% of the He content) added. These were chosen to obtain mixtures with higher Lewis number (but still less than unity). CO_2 was added because H_2-O_2-He mixtures without CO_2 were found to produce very large flame balls (several cm) that did not survive long because of fuel depletion; adding CO_2 increased the radiative loss substantially and thus decreased the flame ball size. The CH_4-O_2-SF_6 mixtures were chosen to example flame balls in a fuel other than H_2. For the H_2-O_2-CO_2, H_2-air and H_2-O_2-SF_6 families, weaker mixtures than those flown on STS-83 and STS-94 were flown on STS-107. Also, for H_2-air mixtures, higher pressure tests were performed. The H_2-air tests on STS-94 suggest that the chamber size may be somewhat smaller than that required to completely eliminate wall effects, especially when more than one ball is present. Evidence of this is that steady radiation readings are not reached - there is a continual rise in the reading as the far-field fills up with radiating water vapor, but then wall effects come into play and the radiation starts to decrease (due to fuel depletion, which is confirmed by the decreasing size of the ball(s)). This was less of a factor for H_2-O_2-CO_2 or H_2-O_2-SF_6 mixtures, which is expected since the flame balls are much smaller and the diffusion rates are slower. Since is it not practical to increase the size of the chamber, increasing the pressure increases the time scale for fuel depletion (the number of molecules of fuel in the chamber increases, but the rate of fuel consumption per ball is not significantly affected). Increasing pressure also increases the emission intensity, which reduces the video image noise and improves the quality of the video images for H_2-air mixtures (the other mixture families have ample emission even at 1 atm). Finally, these tests provide useful information on the effect of pressure on H_2-O_2 chemistry.

Results from STS-107

On STS-107 a total of 39 tests were performed in 15 different mixtures, resulting in a total of 55 flame balls, of which 33 were named by the crew. The CM-2 /SOFBALL hardware performed almost flawlessly. Most tests (by design) produced only 1 flame ball (see Table 1), though one test intentionally designed to produce a large number of flame balls resulted in 9 balls. The total burn time for all flames was 6 $^1/_4$ hours. Since flame balls are extremely sensitive to gravitational acceleration, all tests were conducted during orbiter free drift periods. The quality of the microgravity was found to be excellent, averaging less than 1 micro-g for most tests. Much of the science data was downlinked during the mission, resulting in minimal loss of science despite the loss of Columbia and its crew. In particular, 90% of thermocouple, radiometer & chamber pressure and 90% of the gas chromatograph data was downlinked during the mission. The main science data loss was videotapes from the four cameras. However, on about 65% of the tests (24 of 37 tests that produced at least 1 flame ball), some digital video frames were downlinked from the two wide field-of-view cameras. These, however, were not always a complete record to the end of the test. This is the most key science loss because the flame ball positions (which are determined from these two wide field-of-view cameras) are needed to locate flame balls in 3D for interpretation of thermocouple and radiometer data.

Among the accomplishments of the experiment were

- The weakest flames ever burned, either in space or on the ground. The weakest flame balls produced about 0.5 watts of thermal power. By comparison a birthday candle produces about 50 watts of thermal power.
- The leanest flames ever burned, either in space or on the ground. The leanest hydrogen-air test points contained 3.2 mole percent H_2 in air (equivalence ratio < 0.079).
- The longest-lived flame ever burned in space (81 minutes)

Several issues not resolved during the previous space flight experiments on STS-83 and STS-94 in 1997 were addressed by experiments on STS-107:

- *Can flame balls last much longer than the 500 sec maximum test time on STS-83 and STS-94 if free drift (no thruster firings) can be maintained for the entire test*? Answer: not usually - some type of flame ball motion, not related to microgravity disturbances, causes flame balls to drift to walls within ≈ 1500 seconds. The only exception to this was the very last test in which 9 flame balls formed initially (Fig. 2) and extinguished one by one until only one (name "Kelly" by the crew) remained. Unexpectedly, Kelly survived 81 minutes, seemingly immune to drift, until it was intentionally extinguished due to operational limitations (it was still burning at the time). The mechanism responsible for the drift of isolated flame balls has not yet been identified, though some mechanisms have been proposed[13]. The shorter-than-expected test times on most tests meant enough time for multiple reburns of each mixture within the flight timeline.
- *Can oscillating flame balls be observed in long-duration, free-drift conditions*? Answer: Probably, but it is still necessary to determine if flame ball motion rather than inherent oscillations of stationary flame balls may have caused the observed oscillations).
- *Are higher Lewis number flame balls (e.g. H_2-O_2-He-CO_2, Le ≈ 0.8) more likely to oscillate, as predicted theoretically*[7]? Answer: No. These flames were extremely stable (Fig. 3).
- Do the flame balls using methane (CH_4-O_2-SF_6 mixtures) behave differently from those in hydrogen fuel (*e.g.* H_2-O_2-SF_6 mixtures)? Answer: Yes. They frequently drifted in corkscrew patterns, though again the mechanism responsible for this drift is not clear.

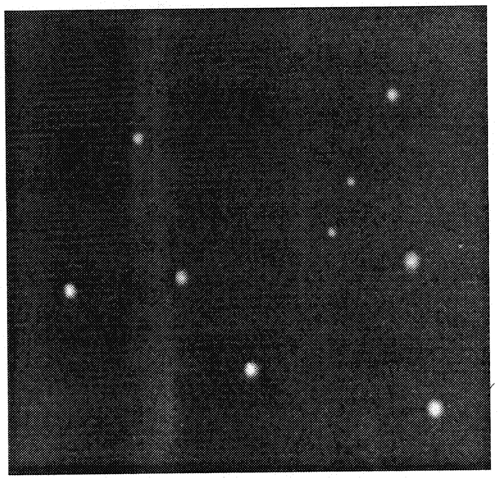

Figure 2. Image of flame balls in a 7.5% CH_4 – 15% O_2 – 77.5% SF_6 mixture at 3 atm.

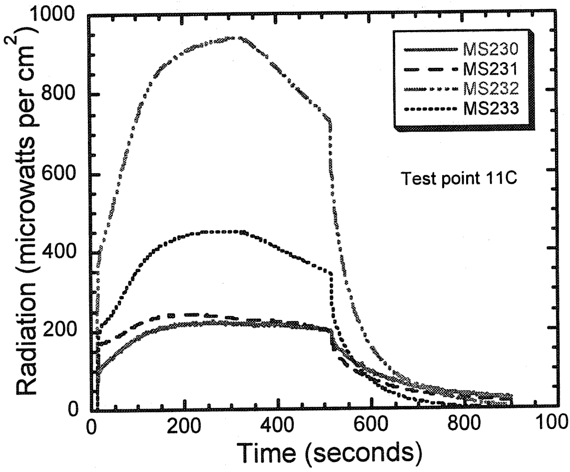

Figure 3. Signals from four different radiometers showing lack of flame ball oscillations. Mixture: 7.75% H_2 – 15.5% O_2 – 7.68% CO_2 – 69.08% He at 3 atm. This test produced 1 flame ball.

The following mechanism is proposed for the flame ball drift. Reabsorption of emitted radiation is a significant factor for all flame balls. For most gases, opacity decreases as T increases. A small increase in T in some radial direction will lead to more radiative transfer (longer absorption length) in that direction. Previous work[10] shows that flame balls will drift up temperature gradients. This drift will decrease/increase the convection-diffusion zone thickness in the upstream/downstream direction, thereby amplifying this gradient and encouraging drift. In contrast, Mineav *et al.*[13] propose a mechanism for self-drift of flame balls but their predictions suggest it exists only for flame balls larger than 3D stability limit, and thus would not be physically observable.

Several totally new results were found, including

- Oscillating flame balls that were predicted theoretically[7] but heretofore never observed experimentally (Fig. 4). It is not been established whether the mechanism outlined in this work responsible for the observed oscillations.
- For some tests, particularly in methane-oxygen-sulfur hexafluoride mixtures, flame ball drift not related to gravitational disturbances nor interactions with other balls or walls. This was a completely unexpected and as yet unexplained result.

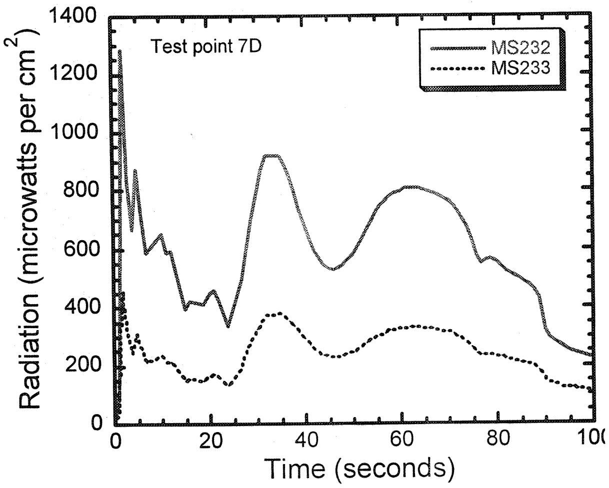

Figure 4. Signals from two different radiometers showing flame ball oscillations. Mixture: 9.9% CH_4 *–* *19.8%* O_2 *– 70.3%* SF_6 *at 1 atm. This test produced 1 flame ball.*

Acknowledgments

A large number of individuals contribute to a successful space flight experiment; only a few can be named here. The authors wish to thank the CM-2 Project Manager, Ms. Ann Over, and the entire CM-2 engineering and operations team for their effort in designing, constructing, testing and operating the CM-2 facility. Thanks also goes to Mr. Youngjin Son and Dr. Lars Sitzki for their help with the data analysis during and after the missions. Of course, a very special thanks is owed to the STS-107 crew. This paper is dedicated to their memory. This work was supported by NASA under grants NAG3-1523 and NAG3-2124.

References

---

[1] Ronney, P. D., "Understanding Combustion Processes Through Microgravity Research," *Twenty-Seventh International Symposium on Combustion*, Combustion Institute, Pittsburgh, 1998, pp. 2485-2506

[2] Ronney, P. D., Wu, M. S., Pearlman, H. G. and Weiland, K. J., AIAA Journal, Vol. 36, 1998, pp. 1361-1368.

[3] Zeldovich, Ya. B., Theory of Combustion and Detonation of Gases, Academy of Sciences (USSR), Moscow, 1944.

[4] Ronney, P. D. "Near-Limit Flame Structures at Low Lewis Number," Combustion and Flame, Vol. 82, 1990, pp. 1-14.

[5] Ronney, P. D., Whaling, K. N., Abbud-Madrid, A., Gatto, J. L., Pisowicz, V. L., "Stationary Premixed Flames in Spherical and Cylindrical Geometries," AIAA Journal., Vol. 32, 1994, pp. 569-577.

[6] Buckmaster, J. D., Joulin, G. and Ronney, P. D., "Effects of Heat Loss on the Structure and Stability of Flame Balls," Combustion and Flame, Vol. 79, 1990, pp. 381-392.

[7] Buckmaster, J. D., Joulin, G. and Ronney, P. D., "Effects of Heat Loss on the Structure and Stability of Flame Balls. II. Effects of Far-Field Losses," Combustion and Flame, Vol. 84, 1991, pp. 411-422.

[8] Lee, C. and Buckmaster, J. D., "The Structure and Stability of Flame Balls: a Near-Equidiffusional Flame Analysis," SIAM Journal on Applied Mathematics, Vol. 51, 1991, pp. 1315-1326.

[9] Wu, M. S., Ronney, P. D., Colantonio, R., VanZandt, D., "Detailed Numerical Simulation of Flame Ball Structure and Dynamics," Combustion and Flame Vol. 116, pp. 387-397 (1999).

[10] Buckmaster, J. D. and Ronney, P. D., "Flame Ball Drift in the Presence of a Total Diffusive Heat Flux," *Twenty-Seventh International Symposium on Combustion*, Combustion Institute, Pittsburgh, 1998, pp. 2603-2610.

[11] Wu, M.-S., Liu, J. B. and Ronney, P. D., "Numerical Simulation of Diluent Effects on Flame Ball Structure and Dynamics," *Twenty-Seventh International Symposium on Combustion*, Combustion Institute, Pittsburgh, 1998, pp. 2543-2550.

[12] Abid, M., Wu, M. S., Liu, J. B., Ronney, P. D., Ueki, M., K. Maruta, K., Kobayashi, H., Niioka, T. and VanZandt, D. M., "Experimental and Numerical Study of Flame Ball IR and UV Emissions," *Combustion and Flame*, Vol. 116, pp. 348-359 (1999).

[13] S. Minaev, L. Kagan, G. Joulin and G. I. Sivashinsky, "On self-drifting flame balls," Combust. Theory Modelling, Vol. 5, 609–622 (2001).