The Development of Thermal Models for a UF6 Transport Container in a Fully Engulfing Fire.

J. Lomas, D.G. Clayton

Engineering Technology Section, Engineering Division, British Nuclear Fuels plc,
Risley, Warrington, Cheshire, WA3 6AS, UK.

INTRODUCTION

In 1987 the IAEA, as part of its review of transport regulations for UF6 containers, recommended that further work into the response of containers to a fire test should be undertaken. The IAEA regulations concerning fires, specify that the thermal test should consist of exposure to a fully engulfing hydrocarbon fire with an average flame temperature of 800°C for a period of thirty minutes. Originally it was expected that the heat transfer processes in a UF6 container were sufficiently well-known to allow a theoretical analysis to verify that the container would pass the fire test. However, it now appears that there are several uncertainties in the physics and heat transfer parameters assumed, leading to variations in the predictions produced by several workers. These predictions are sufficient to indicate either survival of the test or failure at some time during the last 10 minutes of the fire period. It is desirable therefore to have a single thermal model that is accepted by all interested parties.

The IAEA therefore established an international collaborative programme with the object of producing an agreed thermal model of a UF6 container. At the thermal modelling review meeting and the UF6 handling conference both held at Oak Ridge in 1991, the following work programmes were discussed.

1. Small-scale tests to provide improved data on the heat transfer phenomena within the container. (*Park 1991*).

2. Near-full-scale tests on a type 48Y cylinder to examine the overall thermo-physical properties of the heating process. (*Casselman et al 1991*).

3. Refinements to the BNFL mathematical models, comparison with existing experimental results and an examination of protective thermal coatings. (*Clayton et al 1991*).

This paper describes the progress made as part of work programme 3 noted above.

Since the tests proposed by Casselman et al were not scheduled to start before 1993 no results are presently available. Similarly, at the time of writing, no results were available from the small scale tests proposed by Park either. The only progress therefore is on the comparison work with existing experimental results and the investigation of external thermal insulation. For completeness, a brief review of the BNFL lumped parameter model and its predictions is presented first.

THE BNFL LUMPED PARAMETER MODEL

The lumped parameter model was constructed with the intention of incorporating all the possible heat transfer phenomena that could occur during the transient heating of a UF6 container. The model was designed to cater for bare steel cylinders of any practical size and for a variety of heating sources. No attempt was made to model the valve or other leakage path. To simplify the calculational method, the cylinder was represented as a rectangular box of the correct volume, although this resulted in an over estimation of the heat transfer surface area. In an attempt to offset this over estimation, the base of the box was made adiabatic. In addition to conduction, convection and radiation, other physical processes such as sublimation, melting and an evaporation condensation cycle between the liquid surface and any exposed solid were also modelled. A conceptual arrangement of the model is shown in figure 1.

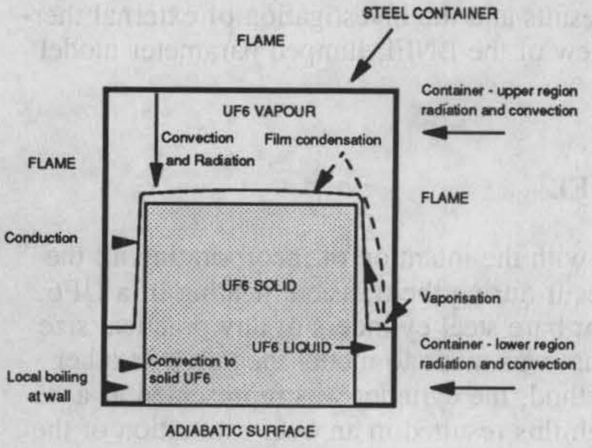
An analysis of a container in a fire produces one of three possible outcomes:

- Failure by bursting of the cylinder under excessive vapour pressure, termed a vapour burst, which can occur during the fire period or immediately afterwards.

- Failure by bursting of the cylinder under excessive liquid pressure, termed a hydraulic burst, which can occur during the fire period or even several minutes into the subsequent cool-down period, as solid continues to melt and cause sufficient expansion to remove the vapour space.

- The container survives the fire and subsequent cool-down without failure. This condition is verified by running the model throughout the cooling-down period until the UF6 liquid temperature returns to its melting point (64°C).

Using the model initialised for a type 48Y cylinder in a regulatory fire of 800°C for 30 minutes, it predicts a vapour burst at 20.2 minutes; figure 2 depicts the response of the container and contents. Further information about the original model and its predictions for a type 48Y container are given by Clayton et al 1991. In general, current predictions indicate that container survival is doubtful and that some modification to the container will be required in order to be confident of predicting survival.



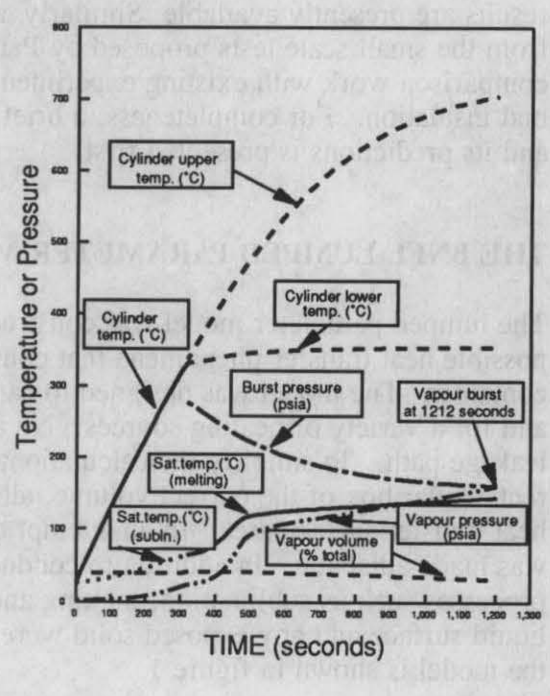


Figure 1. Conceptual arrangement of lumped parameter model

Figure 2. Model prediction for type 48Y container

COMPARISON WITH EXPERIMENTAL FIRE TESTS

In order to provide some validation of the thermal model it was agreed to compare the models predictions with experimental test results. The only experimental results on cylinders containing UF6 that have so far been located are a series of tests carried out at Oak Ridge USA in 1965 (*Mallett 1966*). In these tests, small, bare nickel or monel cylinders 3.5 to 8 inches in diameter and containing UF6 were subjected to diesel-oil fires. The tests were conducted in the open air with the cylinders secured horizontally to beams above an open topped tank of fuel. The tests were primarily a demonstration of the consequences of a fire accident engulfing a UF6 container and were not particularly concerned with the detail of the thermal processes involved. The diesel fuel produced a flame temperature of at least 1500°F (816°C) or higher and without exception all the bare cylinders suffered catastrophic failure. This was either by explosive rupture or by gross leakage from the valve fitted to the cylinder.

Although the data collected by Mallett is sparse, there being only the time to rupture for most tests, there are some internal and external temperatures reported for one 8 inch cylinder test.

For each of the cylinder sizes tested by Mallett, an attempt was made to replicate the conditions using the BNFL model. The comparison work produced the following findings.

3.5 INCH CYLINDER: - Two cylinders were tested by Mallett, resulting in failure by gross leakage from the valve in both cases after 4 and 6 minutes. The cylinder material was described as monel, but information on this size of cylinder in the ANSI standards quotes nickel as the material of manufacture. In any event the valve leakage prevents the model from correctly simulating the events, since the model has no representation of a valve. For a simple cylinder, the model predicts failure by hydraulic burst, after 4 minutes with monel or 2.5 minutes with nickel cylinders.

5 INCH CYLINDER: - Mallett conducted two tests with 5 inch monel cylinders, one with a valve cover and one without. No information except the rupture time is available for these tests. The cylinder without the valve cover failed at 8 minutes with a leaking valve. The cylinder with the valve cover, explosively ruptured at 10 minutes.

The emissivity of monel varies considerably with temperature and condition. Consequently a range of internal emissivity values were examined but a fixed external value of 0.8 was employed as recommended in the IAEA guidelines for fire tests.

Table 1 shows the results predicted using the BNFL model, initialised for a 5 inch monel cylinder.

Internal emissivity	Time to burst (minutes)
0.1	10.1
0.3	9.5
0.5	9.1
0.8	8.7
1.0	8.4

Table 1. Time to cylinder burst for various internal emissivity values

The choice of emissivities is based on setting a value of 0.5 as the best available information from the literature and then testing lower values in an attempt to reach the reported time to burst for the cylinder with a protected valve. The predicted time to burst is of the right order when reasonable estimates of thermal parameters are chosen. There is however, insufficient information in the report by Mallett to determine the effect of the valve cover on heat input and hence only minimal confidence in the models predictive capabilities can be credited. The failure mode predicted by the model was a hydraulic burst but again, there is no information available from the test report to confirm this.

8 INCH CYLINDER: - Mallett conducted two tests on 8 inch nickel cylinders, again with and without valve covers. The cylinder with a valve cover explosively ruptured at 10½ minutes and the cylinder without a valve cover explosively ruptured at 8½ minutes. For the cylinder without a valve cover, measurements of internal and external temperatures are available. The internal temperatures are measured by thermal elements placed inside 0.5 inch diameter thermowells which are inserted into the base of the test cylinder. The diagram on figure 3 indicates the position of the thermal elements. The flame temperature was estimated to be at least 1500°F (816°C) or higher.

The BNFL code predicted a hydraulic burst after 8.2 minutes when assuming an internal emissivity of 0.3 and an external emissivity of 0.8 . The value of 0.3 being chosen for the internal emissivity as the best available information based on a literature survey of nickel properties and the value of 0.8 for the external emissivity based on the IAEA guideline as before.

Figure 3 compares internal temperatures measured by Mallett, for the cylinder without valve covers, with those predicted by the BNFL model. It is difficult to interpret the temperatures measured by Mallett due to their erratic nature. Mallett comments that there are numerous dips in the thermocouple readings while the test is progressing but offers no explanation. The temperature predicted by the BNFL model nearly always marks the upper bound of measured temperatures.

The model predicts cylinder failure due to hydraulic pressure and it is reasonable to assume that, if the maximum value from the upper thermocouples in the cylinder is measuring a liquid temperature, that the burst was caused by hydraulic pressure rather than vapour pressure in the test.

As a check on the sensitivity of the problem to both internal and external emissivity, a series of runs were completed with internal and external emissivities varying between 1.0 and 0.1 . This exercise demonstrated that it is possible to predict times to burst anywhere between 28.3 and 5 minutes and clearly points to the requirement to know the true emissivity of the container wall if accurate predictions are to be made.

EXTERNAL THERMAL INSULATION

Having gained some confidence in the model and its predictions from the comparison work with small cylinders and determined from earlier work that there is some doubt that a 48 inch cylinder will survive the regulatory fire period, attention was directed to the possibility of applying insulation to the cylinder which would limit the heat input. Some recent work (*Abe et al 1989*), has indicated that the provision of protective covers on each end of the cylinder, extending as far as the stiffening ring, provided sufficient insulation to prevent either hydraulic or vapour burst within the half hour period of the fire. The BNFL lumped parameter model was modified to enable the addition of user-specified amounts of insulation coverage to be simulated. As a test of the modified model, the conditions calculated by Abe et al were replicated and a comparison of the two predictions is shown in figures 4 and 5. There are significant differences between the two predictions, most notably, the peak temperature and bursting pressure of the cylinder as well as the peak vapour pressure. Resolution of these differences should provide a greater understanding of the heat transfer problem.

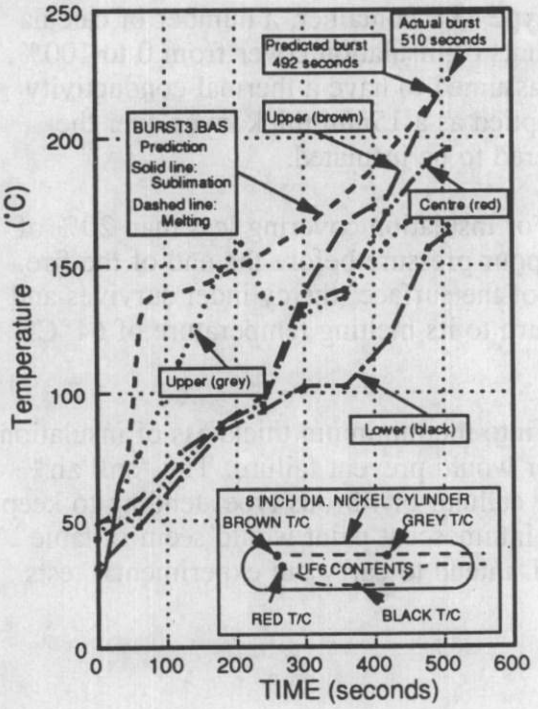


Figure 3. Internal temperatures for nickel cylinder compared with model prediction

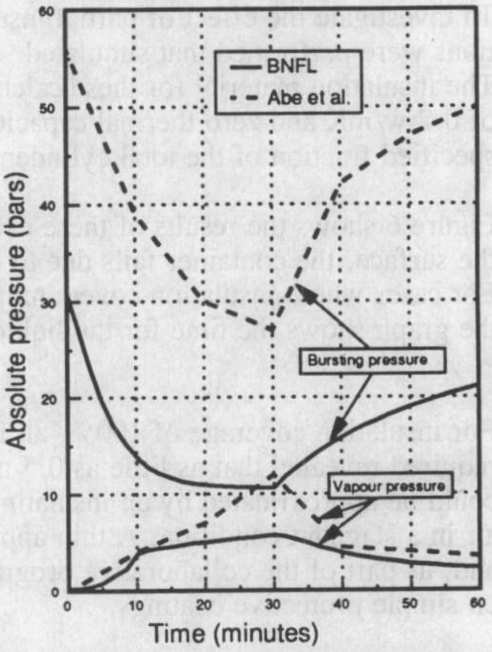


Figure 4. Comparison between Abe and BNFL predictions for a 50% insulated cylinder vapour pressure and bursting pressure

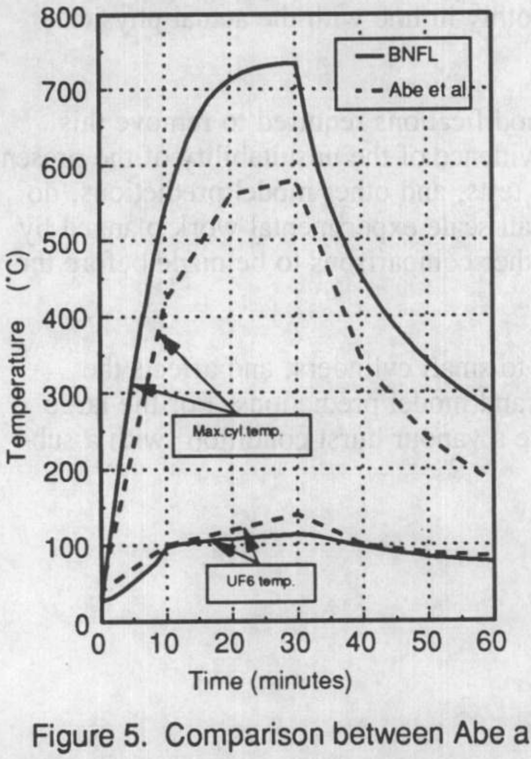


Figure 5. Comparison between Abe and BNFL predictions for a 50% insulated cylinder

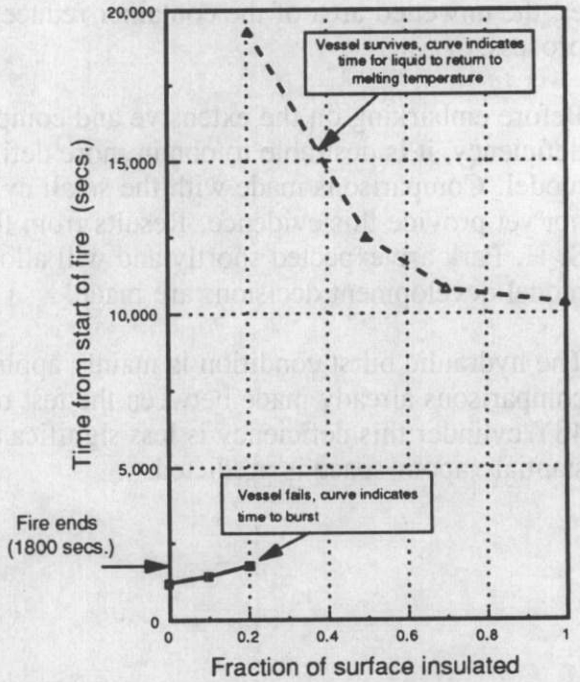


Figure 6. Effect of partial insulation

To investigate the effect of partial insulation on a type 48Y container, a number of calculations were performed that simulated varying amounts of insulation cover from 0 to 100%. The insulation material for these calculations was assumed to have a thermal conductivity of 0.2 w/mK and zero thermal capacity. It was applied as a 15mm thick layer over the specified fraction of the total cylinder area considered to be insulated.

Figure 6 shows the results of these calculations. For insulation covering less than 20% of the surface, the container fails due to excessive vapour pressure before the end of the fire. For cases where insulation covers more than 20% of the surface, the cylinder survives and the graph shows the time for the liquid UF6 to return to its melting temperature of 64°C.

For insulation coverage of 100%, an investigation into the minimum thickness of insulation required revealed that as little as 0.5 mm of still air would prevent failure. The "still air" could be approximated by an insulating material of cellular or fibrous type, tending to keep air in a stagnant condition. A thin applied layer of intumescent paint would seem suitable and, as part of the collaborative programme, BNFL intend to carry out experimental tests on simple protective coatings.

MODEL IMPROVEMENTS

A deficiency of the BNFL lumped parameter model is the geometric representation of the UF6 cylinder by a rectangular box. This geometric simplification causes the greatest uncertainty when the hydraulic burst condition is approached. This is because the flat top of the box remains unwetted until the instant of rupture and the simulation of heat transfer from the internal surface of the container is thus in error. In a cylindrical representation however, the unwetted area of the container reduces smoothly in line with the actual physical process.

Before embarking on the extensive and complex modifications required to remove this deficiency, it is desirable to obtain more definite evidence of the unsuitability of the present model. Comparisons made with the small cylinder tests, and other model predictions, do not yet provide this evidence. Results from the small scale experimental work planned by S. H. Park are expected shortly and will allow further comparisons to be made before the model development decisions are made.

The hydraulic burst condition is mainly applicable to small cylinders, and affects the comparisons already made between the test results and model predictions. For the large 48Y cylinder this deficiency is less significant since a vapour burst condition, with a substantial vapour space is predicted.

CONCLUDING REMARKS

Verification of the BNFL lumped parameter model is proving difficult to demonstrate. Comparisons with the small cylinder test results have given a certain degree of confidence inasmuch as rupture times have been underestimated by between 4% and 22% of the actual rupture times. The comparison cannot be drawn too closely because of the presence of valve leakage during the tests. The model assumes no leakage prior to a burst and is thus unable to take account of any pressure relief a leaking valve provides.

Notice must also be taken of the variation encountered in testing, such as when an eight inch cylinder exploded at 8.5 minutes without a valve cover, and 10.5 minutes with a valve cover fitted. Similarly, the effect of a valve cover on the five inch cylinder was to prevent valve leakage and increase time to rupture.

The results from the small scale cylinder tests, planned to take place at Oak Ridge this year, should provide some much-needed guidance for mathematical models in the area of internal heat transfer methods and magnitudes.

The most promising route to ensure survival seems to be the provision of a coating of thermal insulation. Calculations indicate that a minimal degree of insulation is sufficient. We recommend that one of the near-full-scale tests planned with a 48 inch cylinder should be used to prove the effectiveness of a suitable coating.

REFERENCES

ABE H., ESASHI Y., KOBAYASI S., GOMI Y., SATOH K., YAMAKAWA H., ET AL
The integrity verification tests and analyses of a 48Y cylinder for transportation of natural Uranium Hexafluoride
PATRAM '89 PROCEEDINGS VOL.3 pages 1734 TO 1741.

CASSELMAN C., DURET B., SEILER J.M., RINGOT C., WARNIEZ P.
High temperature experiments on a 4 tons UF6 container - Tenerife
2nd INT. CONF. ON UF6 HANDLING, pages 169 TO 175. OCTOBER 1991.

CLAYTON D.G., HAYES T.J., LIVESEY E., LOMAS J., PRICE M.
Modelling of the thermal behaviour of 48 inch cylinders.
2nd INT. CONF. ON UF6 HANDLING, pages 163 TO 168. OCTOBER 1991.

MALLETT A.J.
ORGDP Container test and development program: Fire tests of UF6 filled cylinders.
K-D-1894 JANUARY 1966.

PARK S.H.
UF6 Cylinder fire test.
2nd INT. CONF. ON UF6 HANDLING, page 179 - POSTER SESSION
OCTOBER 1991.