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Lifetime expectancy test of RB 77 rocket engine.

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Rapportens title

Livslängdsprov RB 77 raketmotor

Sammanfattning (högst 200 ord)

Denna rapport redovisar livslängdsstatusen hos raketmotorn tillhörande RB 77 HAWK som vid denna provning uppnått en ålder av 24 år. Följande prover har genomförts: Glasomvandlingstemperaturmätning, mikrokalorimetrimätning, reometerprov och hårdhetsprovning av krutet. En röntgenundersökning har utförts för att säkerställa att inga sprickor eller släppningar har skett hos den tappade motorn. En invändig okulärkontroll med hjälp av ett endoskop och utvändigt med fotodokumentation har också genomförts.
Provbränning av motorn genomfördes vid en motortemperatur av ca 15 ^{o}C där dragkraften har registrerats.
Alla undersökningar och provningar visade ett för åldern normalt resultat.

Nyckelord

Glasomvandlingstemperatur, hårdhetsprov, mikrokalometrimätning, reometerprov.

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Report title (In translation) Lifetime expectancy test of RB 77 rocket engine		
Abstract (not more than 200 words) A lifetime expectancy test is reported for an engine belonging to RB77 HAWK that at the time of the test had reached an age of 24 years. The test included measurements of glass transition temperature, thermal stability, complex shear modulus and hardness. Furthermore, optical and radiographical investigations have been performed to ensure the integrity of the engine that prior to its arrival at FOI had been dropped. Finally, the engine was test fired at a temperature of 15 °C during which the thrust and the specific impulse were measured. All test and measurement results can be considered within normal ranges with respect to the engines age.		
Keywords Glass transition temperature, hardness, thermal stability, shear modulus		
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CONTENTS

Introduction.

The Defense Material Administration (FMV): Production group Weapons has commissioned a lifetime expectancy test of a RB77 rocket engine, order number 254441-LB612810.
The materials tested were an engine marked PART NO 10242870, MFG DATE November 1979, LOT NO AJT-3-125, MOTOR SERIAL NO 71981, CHAMBER SERIAL NO 10138, CLOSURE SERIAL NO TA0781 with an ignition system marked P/N 1C242896-F/T, S/N 16542, MFR LOT AJT-1-108, DATE MFG 10-81.
The tests consisted of:

- Visual inspection and photography of the engine
- Radiography in two perpendicular planes along the engine
- Dismantling of the nozzle for extraction of propellant samples
- Re-assembly of the engine
- Examinations of the propellant samples
- Test firing of the engine

Radiography.

The engine had been dropped prior to its arrival at FOI. To ensure safety during test firing it was optically and radiographicly investigated. The radiographs were taken in two perpendicular planes along the axis of the engine to ensure adhesion between insulation and case. Furthermore, the radiographs were examined in order to detect whether any cracks had been formed. The equipment used was an Andrex Smart 300 in conjunction with image enhancement plates. The latter were scanned using a Fuji FLA-5000 see (Figure 1).
The conclusion of the investigation was that no discernible defects were found in the engine see (Figure 2).

Figure 1. The Experimental setup for radiographic investigation.

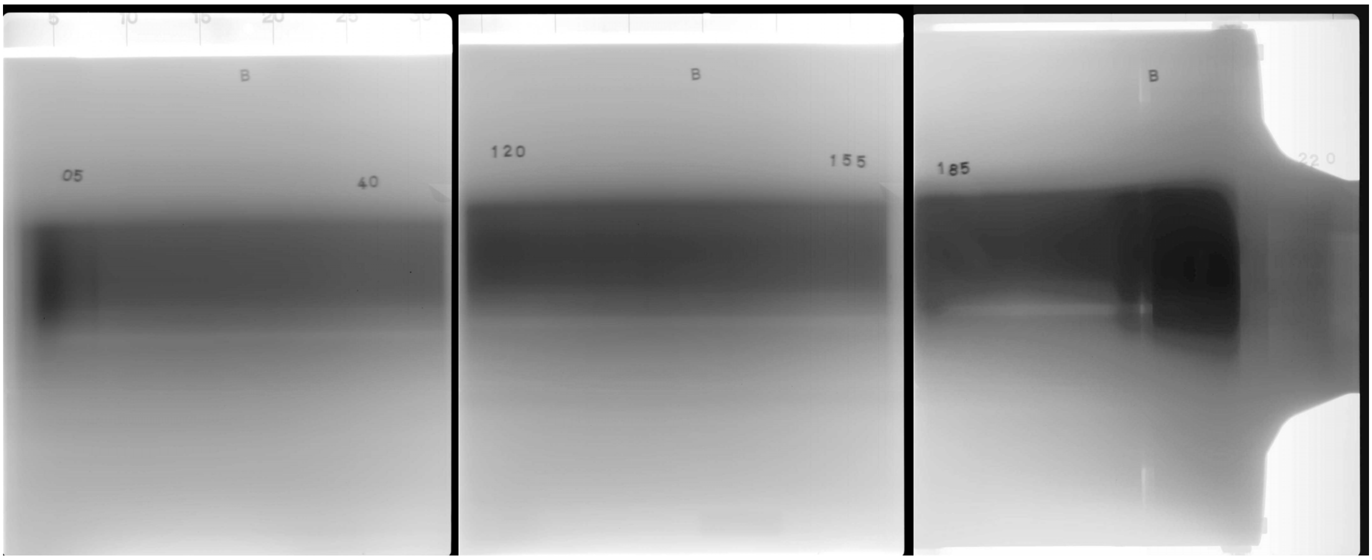


Figure 2. The resulting radiographs showing no discernible defects.

Extracting the test specimens for materials testing.

The engine was mounted in a jaw vice were the nozzle was demounted by pulling out the spring steel clamp ring with a pipe wrench and cutting the joint washer, see Figure 3.

Figure 3. Dismantling of the engine.

In order to perform all materials tests on the propellant at least ten discs were required. It was decided that three larger pieces were to be sawn of the rear end of the booster. Originally, the intention was to obtain such pieces from the front end as well, but the entrance at this end turned out to bee too narrow.
From the front-end ignition hole, approximately 2 g off propellant was extruded for thermal stability testing. In total 437 g of propellant was extracted from the engine where each of the larger pieces weighed approximately 145 g, see Figure 4 and Figure 5.

Figure 4.The extraction procedure of the three larger pieces.

Figure 5. Samples obtained as a result of the described method.

Re-assembling the engine.

With the help of a new joint washer and a greased spring steel clamp ring the nozzle was re-mounted to the engine, see Figure 6.

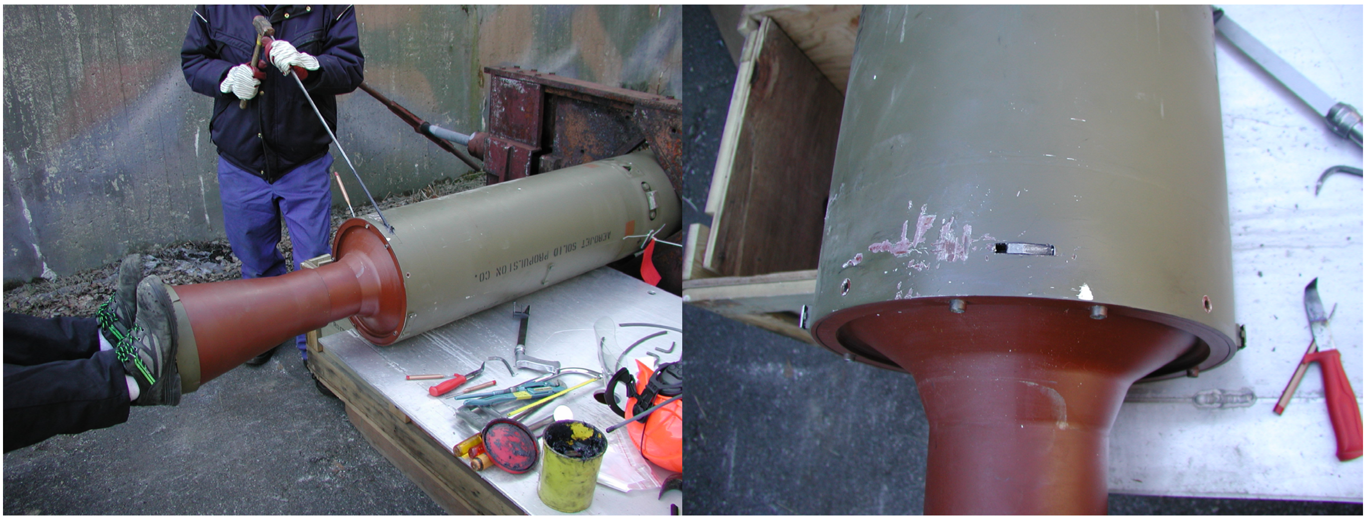


Figure 6. Re-assembling of the engine.

Test firing of the engine.

The engine was mounted on tresles, which in turn were mounted on rails, clamped with belt tightners which also prestressed the thrust gauge, see Figure 7

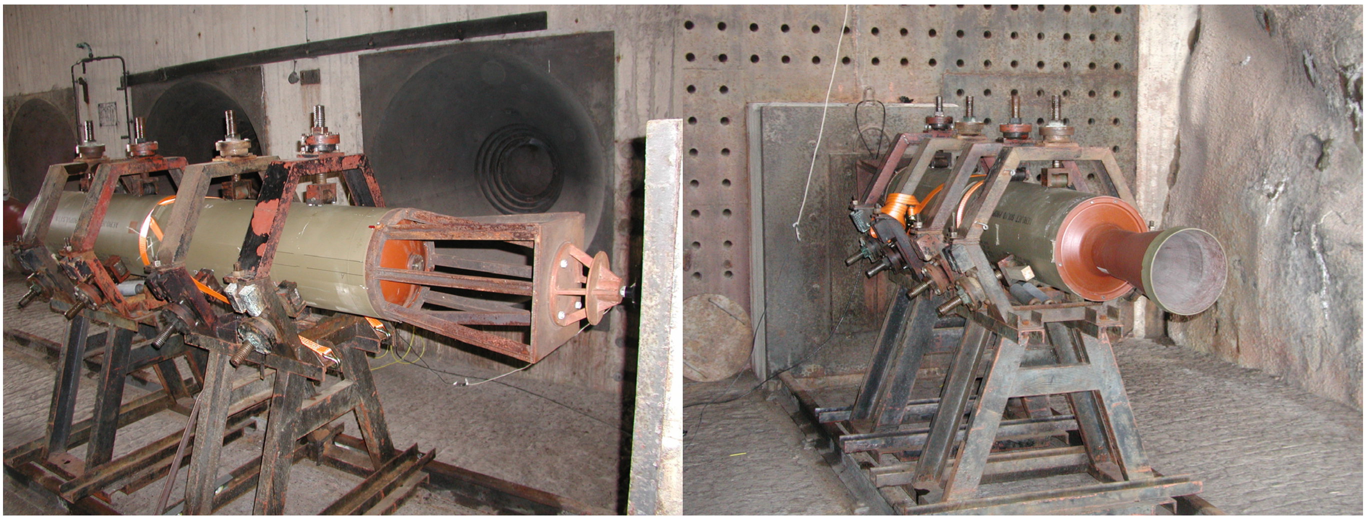
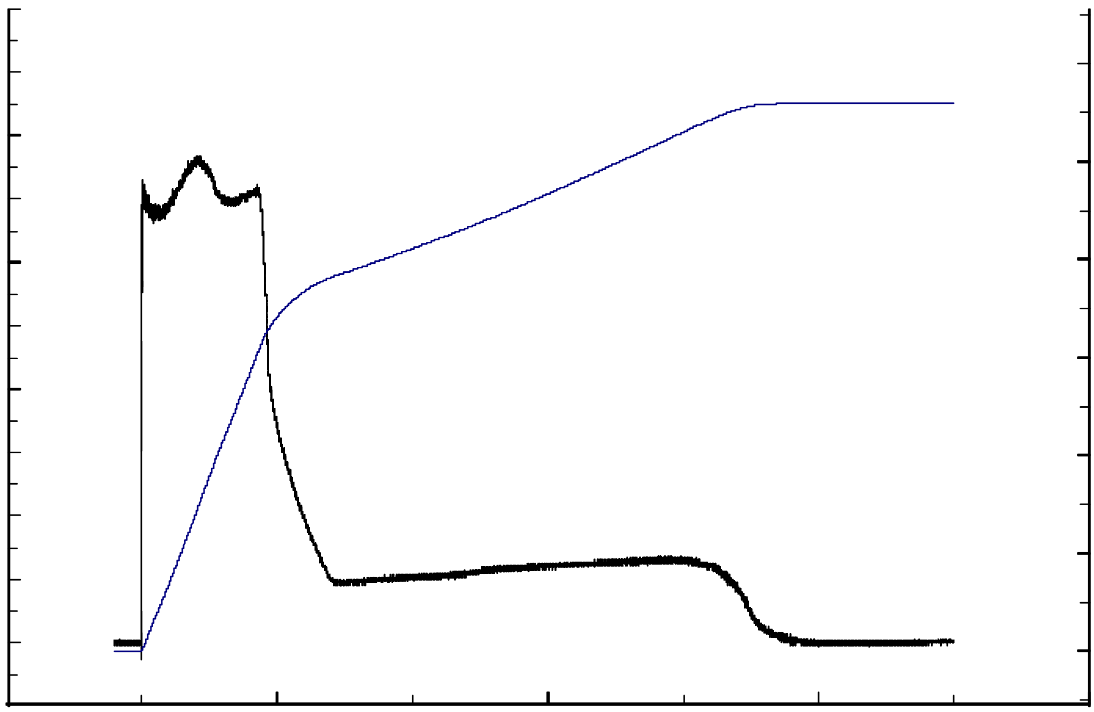


Figure 7. Mounting of the engine for test firing.

The registration equipment was a small digital camera mounted on the cave's back wall, pointing at the engine. It was connected to a computer placed indoors. The camera is started immediately prior to ignition and was set to collect data at a speed of 60 frames/s.
The signal from a surviellence camera, placed in the same building, was split between two monitors and a VCR. Two video cameras were placed in front of the cave, one zooming in on the engine and the other providing an overview of the cave. Furthermore, another overview of the whole set up was obtained from a video camera placed 500 m from the entrance to the cave. The thrust gauge used was a Bofors KSG-2 with sn 013, amplifier Endevco 4470/4476.2A. The signal was stored in parallell using Wavebook 512 sn 086706 on a laptop and on a PC with a so called DAP-card. Both systems worked with a sample rate of 10^3 s^{-1}.
The engine was ignited using a standard cranked apparatus.



Figur 8. Thrust and specific impulse registered during test firing.

Materials tests on the composite propellant of RB 77.

Determining hardness.

Hardness is measured by impressing an appropriate probe into the propellant surface. In this case, a durometer according to Shore A, of the brand Zwick & Co. KG, marked Prüfmaschinen Gummi Härteprüfgerät nach DIN 53505, ASTMD676. Werk nr 13494, was used. It was mounted to a stand from the same company marked Einsingen bei Ulm Mod Z223 No 12969/1960 to enhance the reproducibility. The load during a measurement according to Shore A is 1 kg.
Samples with parallel and smooth surfaces and a thickness of 10 mm were machined. The measurements were performed at a distance of at least 10 mm from the rim. The samples were preconditioned for minimum 3 days at 22 °C in a desiccator containing a saturated water solution of calcium acetate (23% RH).
A sample is placed on the bearing plate and the point of the durometer is placed against its surface and the test results are taken at 5, 10, 20, 40 and 80 s during the application of pressure at five distinct points. The room temperature at the time of the tests was 19 °C and RH 29%. The results of the tests are presented in Tables 1 through 4.
In order to obtain the initial hardness we used the following procedure. First we calculated the mean of the median values at the various times for the different tests. Then by plotting the hardness as a function of time, in a log-log diagram, we extrapolated the initial hardness at 1 s to be 61,9.

	5 s	10 s	20 s	40 s	80 s
1	54,0	53,5	52,5	49,6	47,8
2	55,2	53,8	52,5	50,8	49,0
3	59,0	58,0	56,2	54,3	52,3
4	53,0	52,1	50,8	49,3	48,2
5	56,5	55,0	53,5	52,5	50,7
Median	55,2	53,8	52,5	50,8	49,0

Table 1. The hardness at 5 different times and 5 different points and the median values for test nr 1. (RB77 sample1).

	5 s	10 s	20 s	40 s	80 s
1	55,8	54,0	52,3	50,3	48,8
2	57,0	55,0	53,8	52,2	50,2
3	60,0	58,0	56,5	54,3	52,3
4	61,2	59,5	58,0	56,3	54,2
5	58,0	56,5	55,7	53,0	51,0
Median	58,0	56,5	55,7	53,0	51,0

Table 2. The hardness at 5 different times and 5 different points and the median values for test nr 2. (RB77 sample1).

	5 s	10 s	20 s	40 s	80 s
1	62,2	60,5	58,5	56,2	54,3
2	60,3	58,2	56,5	55,3	53,4
3	59,0	57,5	56,5	54,4	52,3
4	58,5	56,5	54,7	53,0	51,3
5	60,2	58,2	56,5	54,3	52,5
Median	60,2	58,2	56,5	54,4	52,5

Table 3. The hardness at 5 different times and 5 different points and the median values for test nr 3. (RB77 sample2).

	5 s	10 s	20 s	40 s	80 s
1	60,2	58,1	56,1	54,0	52,4
2	56,5	55,0	53,5	51,5	49,8
3	56,5	54,5	53,0	52,0	50,0
4	58,5	57,2	55,0	53,8	52,0
5	63,0	61,5	59,3	57,3	55,2
Median	58,5	57,2	55,0	53,8	52,0

Table 4. The hardness at 5 different times and 5 different points and the median values for test nr 4. (RB77 sample2).

Measurement of the shear modulus.

A new test method for measuring the mechanical properties of the solid propellant has been evaluated. The method is a dynamic mechanical method where the (complex) shear modulus, G*, of the propellant was measured at three different temperatures, -40, +22 and +60°C. G* is equivalent to the stiffness of a solid material and is related to the elastic modulus or Young's modulus, E, measured by tensile testing. The advantage of this method is that only small samples (ø 20 mm, thickness 2 – 3 mm) are needed to analyses the mechanical properties. In tensile testing the required sample size is 125 × 25 (edges) × 12.5 mm (see Figure 9). Tensile testing also requires more samples, (6 samples for each combination of speed, 1, 10 and 33 mm/min and temperature (-20, +20 and +40°C) (ref. 1) whereas the rheometer method requires a minimum of 4 samples at each temperature. The advantage of the tensile measurement is that information about the breaking point of the propellant is obtained. This is not obtained during rheometer analysis.

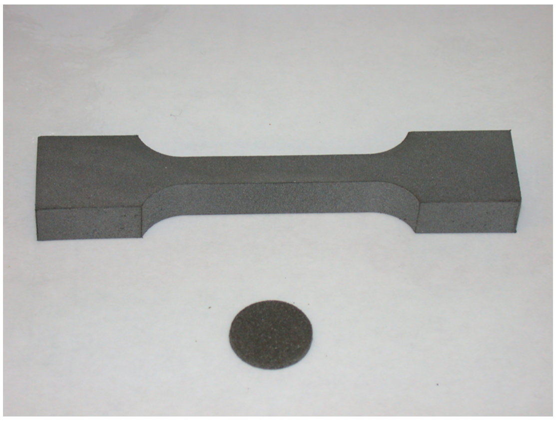


Figure 9**.** Comparison between samples for tensile testing (top, 125 × 25 (edges) × 12.5 mm) and rheometer (bottom, ø 20 mm, thickness 2 – 3 mm).

A sample is placed between two parallel plates that are serrated (rough surfaced) in order to hold the sample see Figure 10. The sample is then subjected to a sinusoidal deformation at one frequency (in this case 0.1 Hz). The sample response to this deformation gives information about the mechanical properties, such as shear modulus, G*, and the phase angle (the degree of elasticity). This operation is done at three different temperatures, -40°C, +22°C and +60°C in order to see how the mechanical properties of the sample differ. Poor mechanical properties at low temperatures might result in cracks, which may affect the burning behavior of the solid propellant engine.

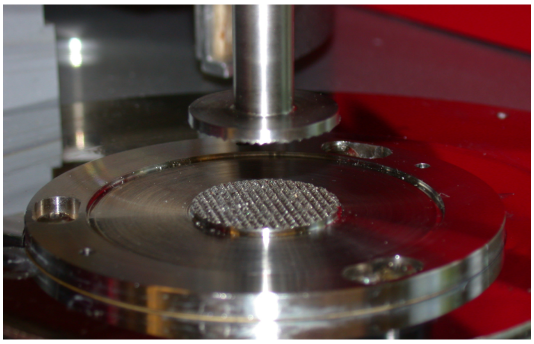


Figure 10**.** Serrated parallel plates used by measurement system.

This method is primarily used for distinguishing between samples of different characters and since this is the first time this method is used for solid propellant analysis at FOI, no values for comparison are available. The method may be developed to such extent that a value measured in the rheometer can be translated into values measured during tensile testing. No such comparable measurements have been done at this moment.
Dynamic mechanic measurements were done with a Stresstech Melt HR Rheometer. The samples were 20 mm in diameter and approx. 2 mm thick. The (complex) shear modulus, G*, were measured at -40, +22 and +60°C at 0.1 Hz and at a constant stress of 20 Pa. The position resolution was 1 mm and the measurement system was 20 mm serrated parallel plates. The samples were preconditioned for minimum 3 days at 22°C in a desiccator containing a saturated water solution of calcium acetate (23% RH).
The mechanical properties of RB77 solid propellant at 60°C and 22°C are similar. The shear modulus, G*, is in the range of 1 - 1.2 MPa. The modulus is insignificantly higher at 22°C compared to 60°C (1.2 MPa and 1-1.1 Mpa respectivly). The measurements at -40°C were very noisy and values of the modulus varied between 3.5 - 7MPa, which is a very broad range. Why the measurement did not work well at -40°C has not been evaluated at this stage.

Thermal stability tests.

The thermal stability of the solid propellant was determined by measuring the heat flow in a Thermal Activity Monitor, TAM 2277, heat flow calorimeter. The measurement was done isothermally at 65°C for 14 days. The accuracy of the calorimeter is better than 0.5 J/g, during one week. The samples where put in 3 ml sealed glass ampoules. The weight of each sample was 0.5 g. The total energy evolved by the sample, *E*, in the calorimeter, is calculated by integrating the heat flow with respect to time. If the energy evolution from a pure sample is low, then the sample is said to have a high thermal stability.
The Defense Material Administration has presented certain criterias when evaluating the thermal stability of solid propellants (ref. 1). These criterias are used for NC-, GGL-, DGL-, NIGU-FNH- and LOVA-propellants, but they will serve as guidelines for the evaluation of the RB77 composite solid rocket propellant as well.

The criteras:

1. The heat flow must not exceed 500 μW/g for single-base propellants and 700 μW/g for double-base- and triplebase propellants.
2. No signs of autocatalysis should appear when the initial heat flow has declined.
3. The heat flow must not exceed 27 μW/g for singlebase propellants or 45 μW/g for doublebase- and triplebase propellants when the initial heat flow has declined.

The thermal stability of the solid propellant was measured for 14 days at 65°C and there were no signs of autocatalysis. The maximum heat flow value was 22 μW/g and it is well below the criterias of the Defence Material Administration (max. 45 μW/g). The total energy produced during 14 days was 13 J/g which is considered low.

Glass Transition Temperature.

The thermal properties of the samples were determined using a Mettler DSC 30 working under a nitrogen atmosphere (50 ml/min). The samples were sealed in 40 µl aluminium pans equipped with holes. The sample weight was approximately 10 mg for glass transition temperature measurements. Calibration was made with indium (T_m = 156.6°C) and anhydrous n-octane (T_m = -57°C). All measurements were made at a heating rate of 10 °C/min. Duplicate measurements were done.

The glass transition temperature of the solid rocket propellant was calculated using the following eqution:

$$T_g = \frac{T_{onset} - T_{endset}}{2}$$

Solid propellants should be elastic and structurally stable within a temperature region ranging from -40 °C to +60°C. Table 5 shows the glass transition temperature of the RB77 solid propellant. This propellant has a glass transition temperature well below -40 °C and this ensure an elastic behavior at -40 °C. The glass transition region of this propellant is, however, not very distinct (see Appendix) and the glass transition temperature values might therefore differ by a few degrees depending on the evaluation of the actual heat flow curve. The shape of the transition region depends on the amount of binder (i.e. polymer) in the propellant. It is likely that the RB77 propellant contains only small amounts of binder (results in a flat transition region) and that is why the glass transitions values varies between -82 to -75 °C.

	T_{onset} (°C)	T_{endset} (°C)	T_g (°C)
RB77 #1	-92	-72	-82
RB77 #2	-85	-65	-75

Table 5. The onset, endset and midpoint of the glass transition temperature of two samples of RB77.

Conclusions

The composite solid propellant RB77 is thermally stable for 14 days at 65 °C.

The propellant has a glass transition temperature well below -40 °C and this ensure an elastic behavior at -40°C, which is the minimum service temperature in Sweden.

A new test method for measuring the mechanical properties of the solid propellant at temperatures between -40°C to +60°C has been evaluated. The advantage of this method is that only small samples are needed for the analysis of mechanical properties compared to those used in tensile testing. This method is primarily used for distinguishing between samples of different characters and since this is the first time this method is used for solid propellant analysis, no values for comparison are available.

The mechanical properties of RB77 solid propellant at 60 °C and 22 °C are similar. The shear modulus, G*, is in the range of 1 - 1.2 MPa. The measurements at -40 °C did not work well and the reason for that has not been evaluated at this stage. This method should, however, be further evaluated before it might be considered as a replacement for tensile testing. Especially comparable measurements between dynamic and tensile testing should be done to relate the shear modulus, G*, to the elastic modulus, E.

The investigations conclusion was that no discernible defects were found in the engine nor were any found in the ocular inspection.

The disassembly, extraction of propellant samples and subsequent re-assembly occurred without incidences. The non-measurement equipment used was supplied by ESRANGE. The test firing revealed nothing significant regarding neither burn time, thrust nor specific impulse.

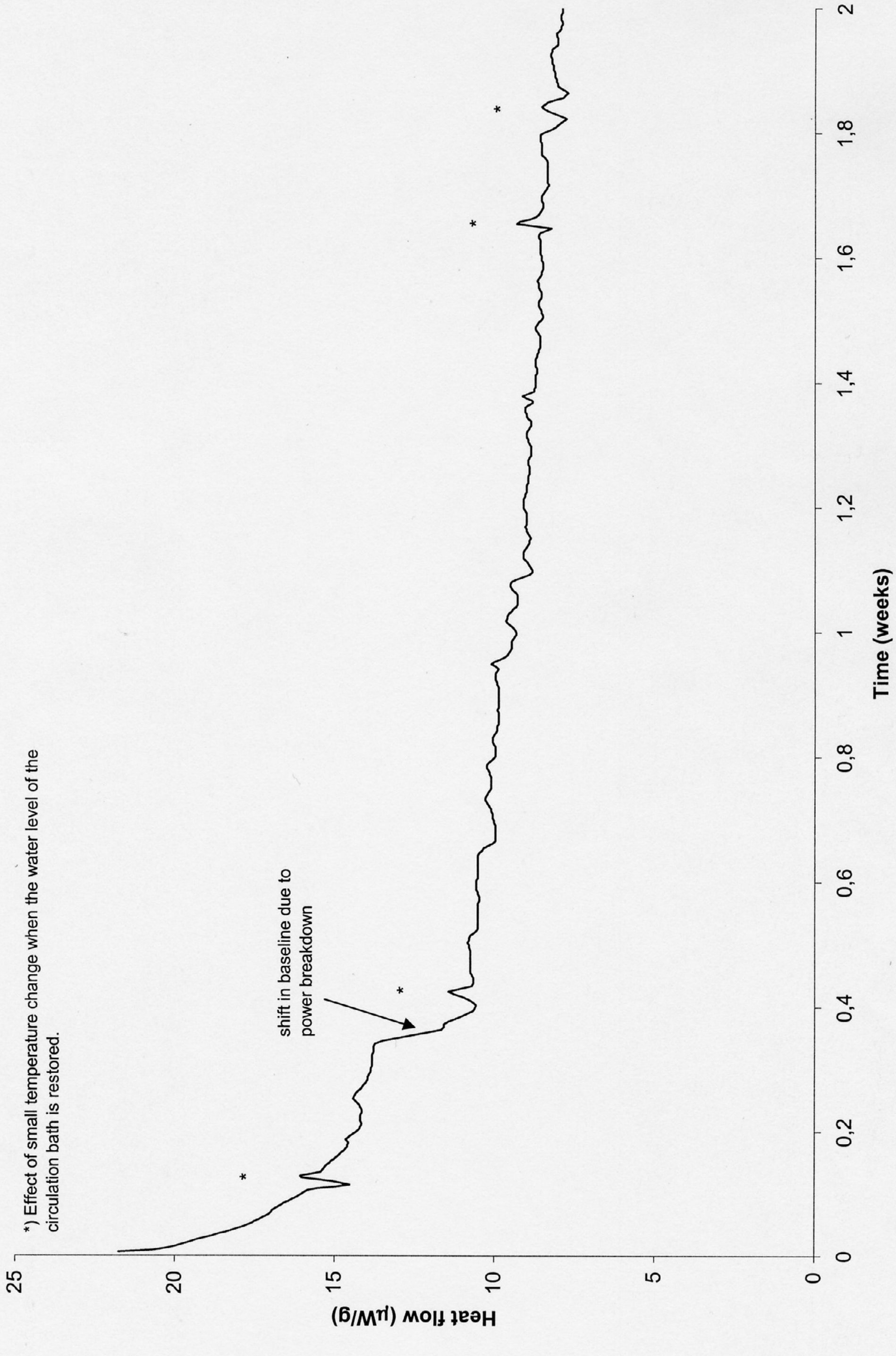
A renewed test series within three to five years, particularly regarding the material properties, is recommended by FOI.

A CD featuring a filmsequence of the test firing is enclosed to the report.

References

1. Schwartz, A., Metoder för provning av raketkrut. II. Kompositkrut. (Methods for testing of rocket propellant. II. Composite propellants.), Stockholm, FOA 1979, 31 p. FOA A20031-D1 (A-report).
2. Handbok ammunitionsövervakning, (Handbook in surveillance of ammunition.), M7762-000220, Defence Material Administration (FMV), 1997.

Appendices


*) Effect of small temperature change when the water level of the circulation bath is restored.
shift in baseline due to power breakdown
*
Heat flow (µW/g)
0
5
10
15
20
25
Time (weeks)
0
0,2
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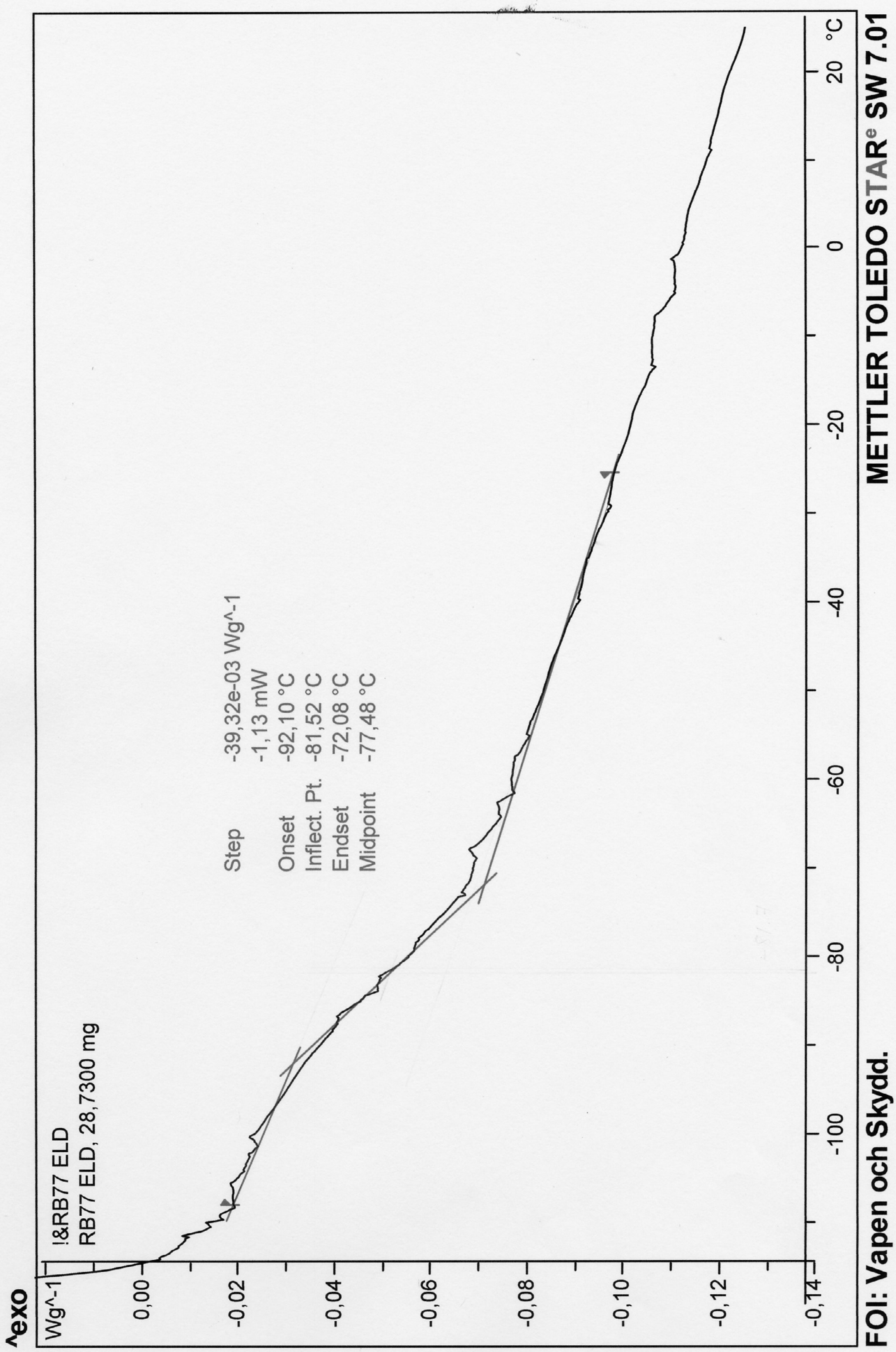
0,6
0,8
1
1,2
1,4
1,6
1,8
2


^exo
Wg^-1
!&RB77 ELD
RB77 ELD, 28,7300 mg
Step -39,32e-03 Wg^-1
-1,13 mW
Onset -92,10 °C
Inflect. Pt. -81,52 °C
Endset -72,08 °C
Midpoint -77,48 °C
0,00
-0,02
-0,04
-0,06
-0,08
-0,10
-0,12
-0,14
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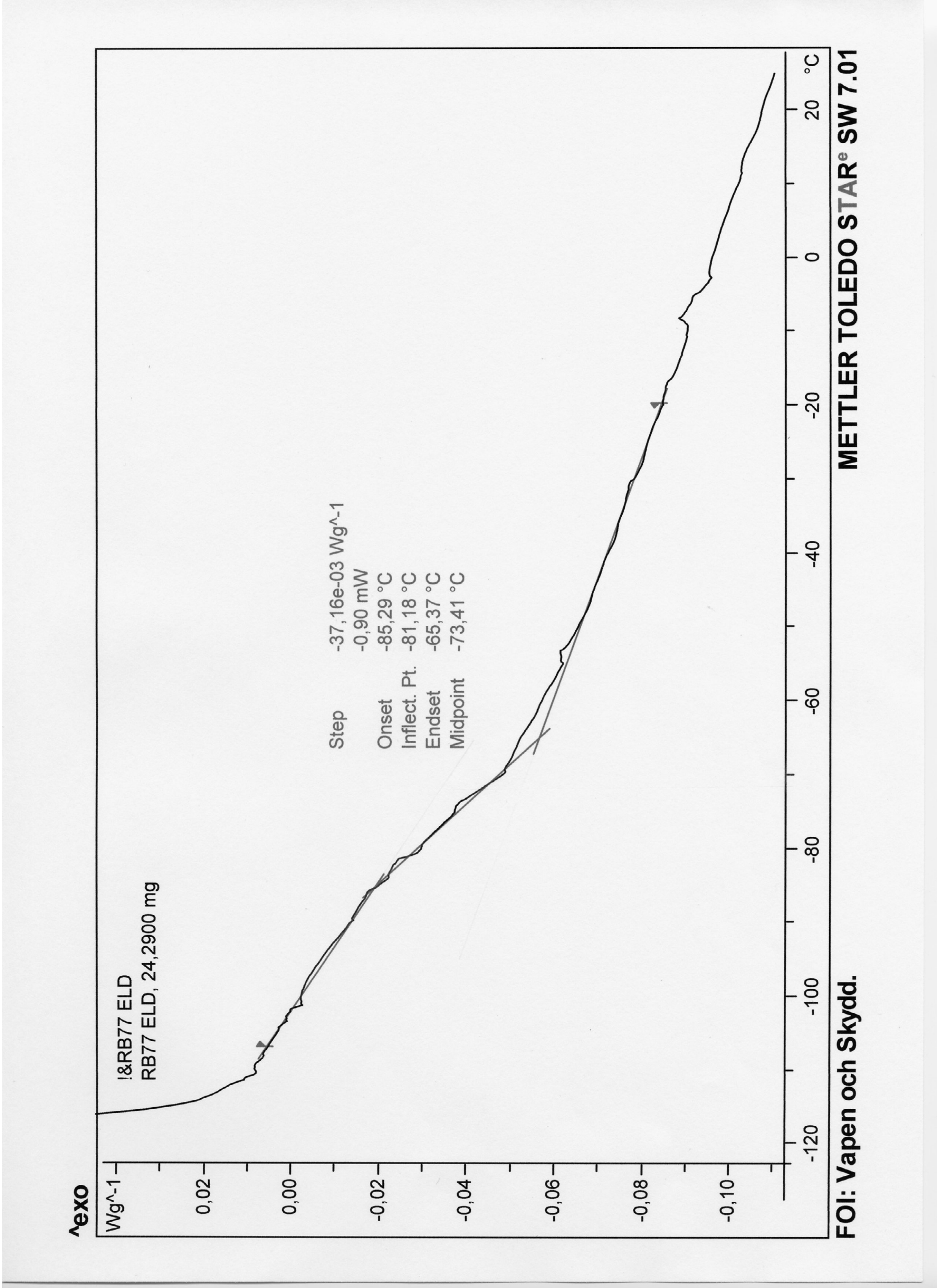
°C
FOI: Vapen och Skydd.
METTLER TOLEDO STARe SW 7.01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Wg^-1
0,02
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!&RB77 ELD
RB77 ELD, 24,2900 mg
Step -37,16e-03 Wg^-1
-0,90 mW
Onset -85,29 °C
Inflect. Pt. -81,18 °C
Endset -65,37 °C
Midpoint -73,41 °C
-120
-100
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FOI: Vapen och Skydd.
METTLER TOLEDO STARe SW 7.01