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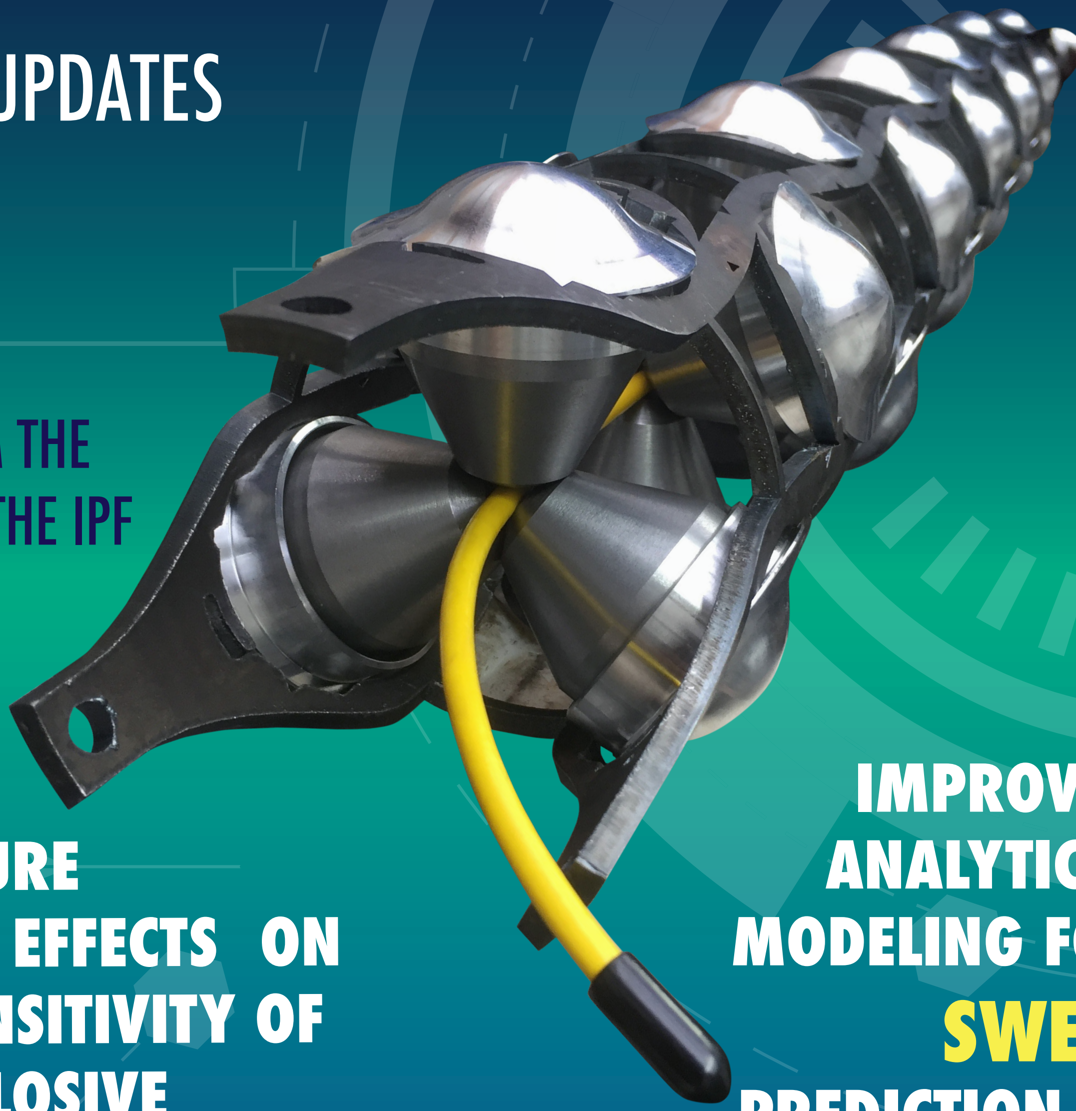
JOURNAL OF THE IPF

A Journal For The International Perforating Industry



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MESSAGE FROM THE PRESIDENT OF THE IPF

Welcome to the very first edition of the Journal of the International Perforating Forum (JIPF). When writing this short introduction to the JIPF, my thoughts turned back to when this all began. Operators were waking up to the fact that all was not rosy in perforator land and there was a lot to be achieved that was not being addressed at our short API meetings and SPE conferences. Perforating was no longer about punching a few holes and waiting for the black stuff to gush. It was becoming complex and varied, requiring a more in depth understanding of the performance of gun systems and we needed new technologies to deliver in our ever more challenging operating environments.

There was general agreement amongst the Operators that we needed to move forward, so at the API meeting on May 8th 2008 at Shell Bellaire I, with Kent Folse who was then with Marathon Oil, proposed that we set up a committee to run a perforating conference in the Fall of 2008. With amazing cooperation and efficiency, less than 5 months later a small committee delivered the first fully sponsored International Perforating Symposium (IPS) in the Woodlands at the end of September.

Since then, there has been global interest and cooperation, with IPS Committees set up in Europe, the Far East, South America, the Middle East, China and now in Russia. Even in this intense and prolonged downturn, we are planning symposiums in Buenos Aires and Muscat this fall and Tyumen in the early spring next year.

This industry clearly needed to have its own focal point and the IPF and all the committee members, sponsors, speakers and delegates at the many symposiums held over the last eight years have made it possible.

After years of remaining an informal group of individuals with a common goal, it became obvious that we needed to become a formal organisation. We became incorporated in the State of Texas in 2015 and quickly followed incorporation by launching a completely new website to make the IPF far more user friendly.

It is now time to take it to the next level, with the inauguration of a full peer reviewed journal for our industry, the JIPF. The SPE and other journals have been great vehicles for case studies, but a highly complex technologically focused industry like perforating needs the ability to publish more technically focused works that are less interesting to a wider audience, while leaving case studies for other journals.

The JIPF is not designed to replace petroleum engineering journals and conference papers, but rather to explore in depth the technical, scientific and engineering intricacies of perforating technology.

The IPF is all about the people in our industry and the JIPF is exemplary in that respect. Two Executive Editors were selected to take on this big job, continuing the tradition of having two Co-Chairs at IPF conferences and mirroring the finest traditions of Ancient Rome. Over thirty Technical Editors were selected to review the wide variety of technical material that will be published.

On behalf of the Board of Directors of the IPF, it is with great pleasure that I hand you over to the Executive Editors of the JIPF for this First Edition.

On behalf of James Barker and John Segura, Directors, IPF
Mark Brinsden, President, IPF

June 25, 2016

EDITORS' MESSAGE

Welcome to the inaugural issue of the Journal of the International Perforating Forum (JIPF). A technical publication has been the vision of the IPF for some time. Historically, technical papers and articles which might be of interest to the perforating community have been scattered amongst numerous societies and publications. This Journal offers a single venue for such research to be published, for the betterment of the oilfield perforating community

John Carminati

Brenden Grove

The Journal consists of three sections: *Regional Updates, News and Articles*. The *Regional Updates* section is where you can find the latest information on IPS events, in particular recent and upcoming symposia. The *News* section will highlight general items of interest to the perforation community at large, including Continuing Education and Young Professionals. The *Articles* section will contain peer-reviewed technical papers on a wide range of topics. The Journal has an excellent technical editor staff which will ensure the highest technical standards are met for publication.

We are pleased to feature in this inaugural issue two technical articles related to the science of perforating. The first relates to impact sensitivity of HMX explosive powders, as affected by temperature and time exposure. This article documents an experimental study, and may be relevant to the handling of explosive products which have been exposed to downhole conditions, then POOH without firing. The second article presents an analytical model which has been developed to estimate swell and the likelihood of catastrophic splitting for hollow carrier gun bodies. This topic is relevant to risk mitigation during perforating operations, as split/ruptured gun carriers can result in significant NPT or other operational issues.

The executive editors thank all who made this issue possible; in particular the authors, technical editors, reviewers, regional chairs, news contributors, and the IPF board for their support.

We hope you will find the Journal of value. If you wish to contribute to any section of the future Journal issues, please visit our article submission webpage here

We value your feedback on the Journal content. Please send any comments to journal@perforators.org.

Sincerely,

John Carminati & Brenden Grove
Executive Editors, JIPF

"We felt that creating awareness of new technology or application is an essential feature of the Journal."

REGIONAL UPDATES. NORTH AMERICA

On May 9-11, 2016 we held the 5th biennial International Perforating Symposium (IPS) at Moody Gardens in Galveston TX.

We received over 50 submissions for presentations, higher than any prior IPS. We extended the program from the normal 2 days to 2-1/2 days.

Lifetime Achievement Awards were presented to John Dees, Dr. John Schatz and Dr. Phil Halleck. Industry Awards were presented to Dave Leidel and Dr. Jim Brooks. Our thanks go to out to all the members of the 2016 IPS Organizing Committee for their dedication and efforts to make the recent IPS an unparalleled success!

We hosted the Executive Committee of the IPFC and several important decisions were made during that meeting.

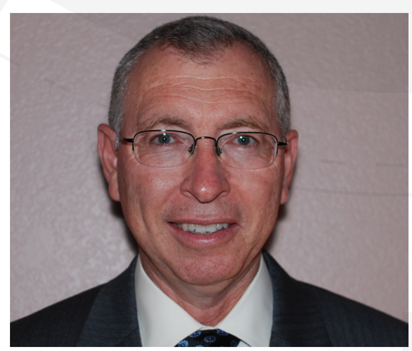
Please take some time to review the presentations and posters from the 2016 IPS via www.perforators.org!

Sincerely,

David Ayre, Co-Chair, IPS 2016
James Barker, Co-Chair, IPS 2016

"It was arguably one of the best IPS events we have held. Despite the global industry downturn, we had 213 attendees. "

David Ayre



James Barker

LATIN AMERICA

SLAP 2016 will be held this OCTOBER at the Sheraton Liberator in Buenos Aires, ARGENTINA. Sessions on modeling, productivity improvement, new technology and safety are planned. Registration and presentation submission are now available on perforators.org.

Dario Lattanzio

OCTOBER 18-20, 2016
BUENOS AIRES, ARGENTINA

MENAPS started in 2011 in Abu Dhabi with 22 technical presentations. MENAPS 2013 was held in Muscat, Oman with 100 attendees, 26 presentations and 11 technical posters. MENAPS 2016 will be held in Muscat 12-14 November 2016 in Bar Al-Jessah Resort. Our expectation is that 120 attendees will be in MENAPS 2016.

Hanaey Ibrahim

ASIA PACIFIC

Perforation strategies in SE Asia remain split between deep penetration perforating, dynamic underbalance and reactive liner techniques. The utilization of rock specific charges has been growing in acceptance.

Wireline continues to outnumber TCP footage deployment in the area but innovation in the slickline depth control technologies may be a factor in the near future.

As our inaugural issue of the Journal of the International Perforating Forum is released, we've seen a complete churn of the Asia Pacific Region Committee since initially being staffed.

Initial discussions among the former APPS 2011 and 2013 committee members as well as new volunteers concluded the risks of low delegate and presenter attendance due to staff reductions and travel bans may be too great for a 2016 symposium. We are optimistic for a more positive and stable environment in 2017.

We welcome any volunteers who would like to join the committee as a chair or advisor. Now, more than ever, the benefits of perforating technology can support our industry to improve the return on investment for development and intervention programs.

The last forum held within Asia Pacific in 2014 was in China. We look forward to staffing our team and selecting a venue for our next event expected to be held in 2017.

Clint Quattlebaum

RUSSIA

"The symposium is planned to be bilingual and presentations are to be held over a course of two days. The Vice-Governor of the Tyumen region is happy to act as patron for the event. "

I am happy to announce that we are presently starting the organization of the first Russian International Perforating Symposium.

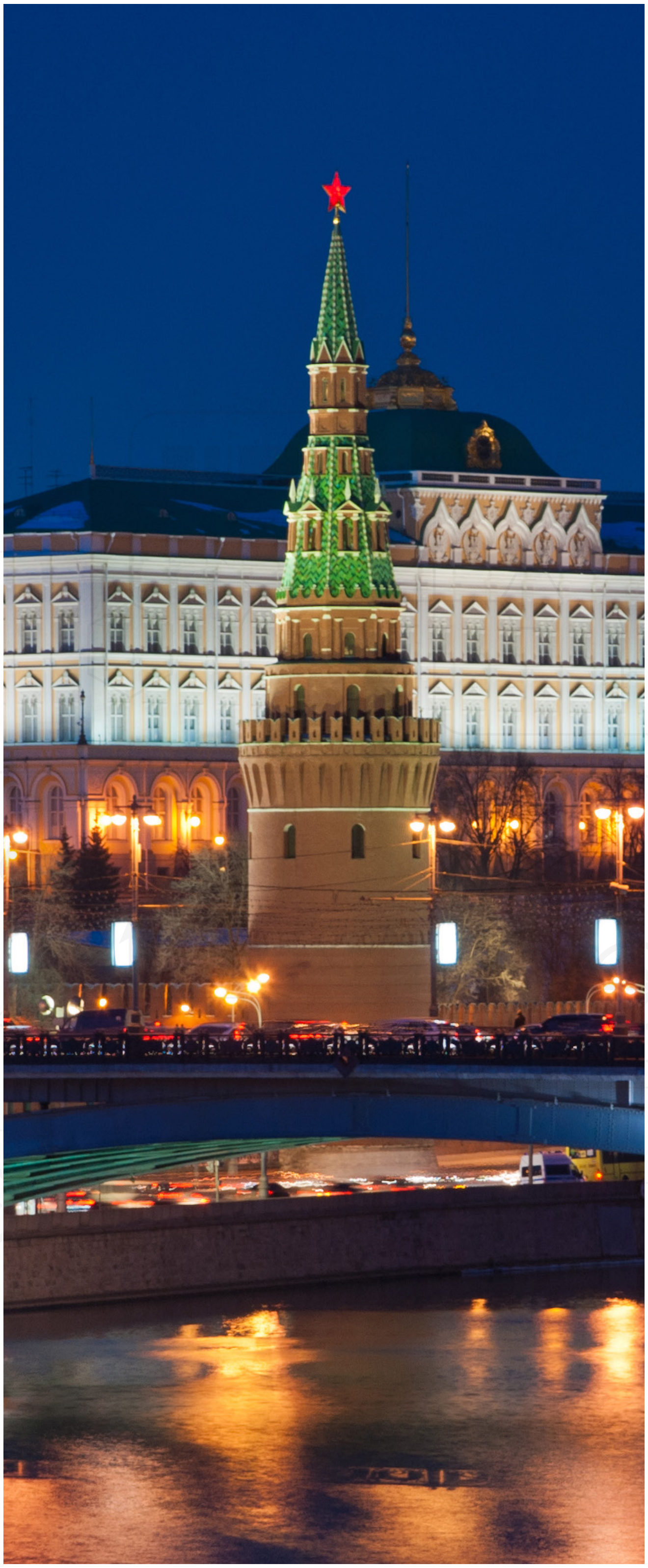
The idea is to hold the symposium towards the end of Q1 2017 in Tyumen, the first settlement of Siberia and the Russian oil and gas capitol.

The symposium is planned to be bilingual and presentations are to be held over a course of two days. The Vice-Governor of the Tyumen region is happy to act as patron for the event.

We hope to excite all of the local operators, service companies and manufacturers to participate in big numbers and are looking forward to also welcoming the international perforating community.

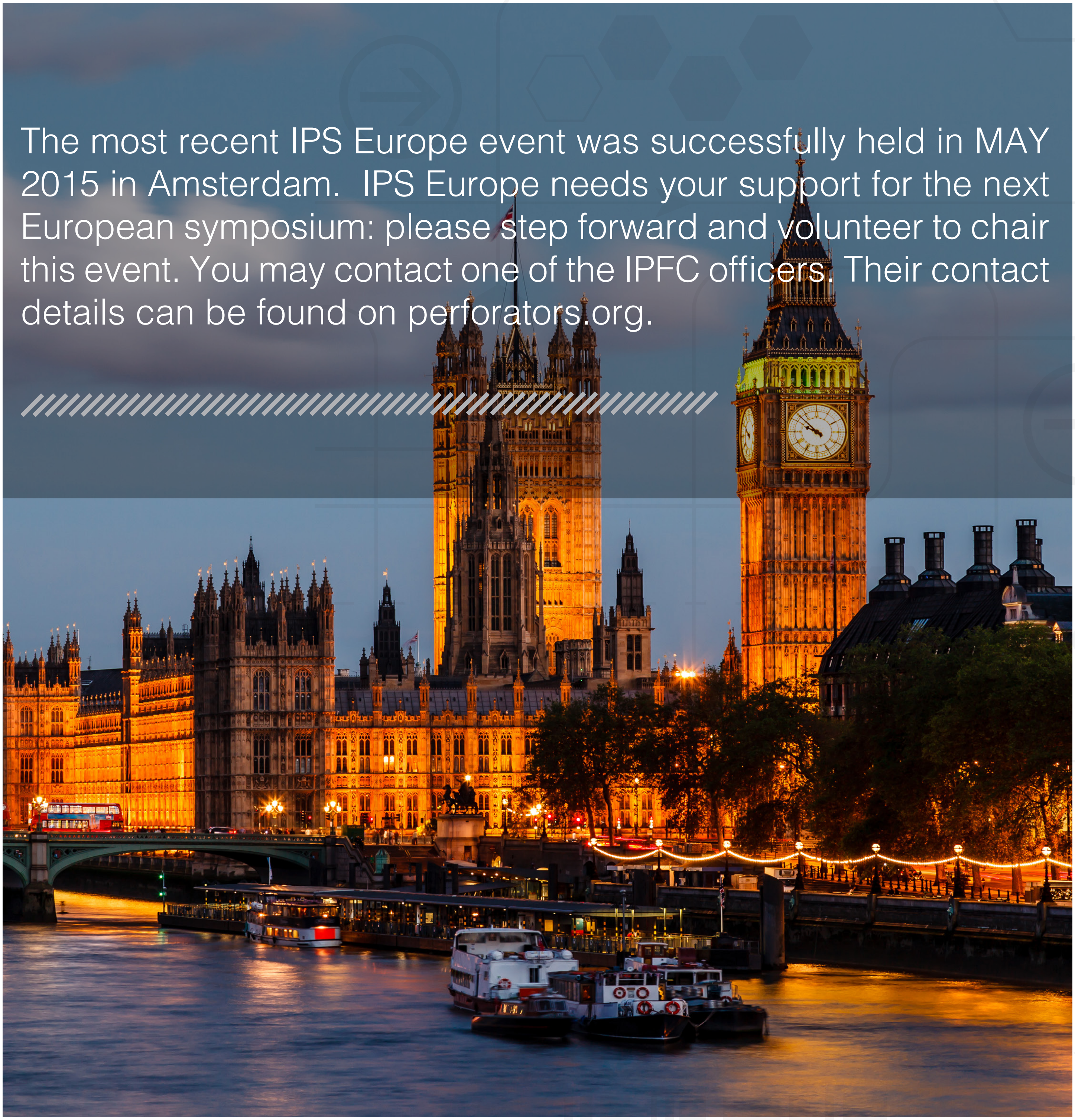
More details will be posted in June on perforators.org, the website of the International Perforating Forum Company. In case of any advance questions or if you want to participate in the organization please contact me at frank.preiss@dynaenergetics.com.

Frank Preiss



EUROPE

The most recent IPS Europe event was successfully held in MAY 2015 in Amsterdam. IPS Europe needs your support for the next European symposium: please step forward and volunteer to chair this event. You may contact one of the IPFC officers. Their contact details can be found on perforators.org.



CONTINUING EDUCATION

The Continuing Education committee has prepared a listing of publications to establish a baseline of knowledge for the community. The committee is also planning an RP67 webinar.

Alfredo Fayard

YOUNG PROFESSIONALS

The Executive Committee of the IPFC, has appointed **Shaun Geerts** to take on the Young Professionals (YP) leadership for the IPFC. The IPF Young Professionals mission is to engage a network of young professionals working in the perforating industry. All individuals within the perforating industry, 35 years of age and under, are invited to join the Young Professionals Committee in order to make this a successful and beneficial endeavor for all involved. Please feel free to contact Shaun at yp@perforators.org with any questions you may have regarding this opportunity.

IPFC

2016 OPERATORS MEETING

At the recent IPS 2016 Operator's Meeting, attendees discussed the opportunity to hold topical forums on overbalance, high temperature and plug and abandonment technology. If you are in the operator community and can support one of these forums, please contact one of the IPFC officers. Contact details are available on perforators.org.

ARTICLE I

Time and Temperature Exposure Effects on Impact Sensitivity of HMX Explosive Powders

Shaun Geerts, Owen Oil Tools

Shaun Geerts

Shaun has been affiliated with Owen Oil Tools, a Core Lab Division, for over 4 years. His experience has been primarily with perforating systems and other ballistic products. Previously he worked with the Energetic Materials Research and Testing Center for 3.5 years, conducting a variety of tests using a multitude of explosive compounds.

He studied at the New Mexico Institute of Mining and Technology earning a Bachelor of Science in Mechanical Engineering, continuing on to earn his Master of Science in Mechanical Engineering with Specialization in Explosives Engineering from NMT where his research focused on characterizing improvised explosive compounds.

While working at Owen he obtained a Master of Engineering Management, where his research focused on the valuation of exclusivity contracts based on portfolio optimization. He currently serves on numerous API subcommittees, on the organizing committee for the IPF, and as a technical expert for the JIPF.

TIME AND TEMPERATURE EXPOSURE EFFECTS ON IMPACT SENSITIVITY OF HMX EXPLOSIVE POWDERS

Shaun Geerts, Owen Oil Tools

SUMMARY

The focus of the research conducted was to examine the impact sensitivity of HMX explosive powders after being exposed to elevated temperatures at which the polymorph phase changes occur. The testing exposed HMX at varying temperatures of 280°F, 300°F, 320°F, and 340°F for durations of 1-48 hours. In addition to testing the powders after immediate exposure to temperature, testing was also conducted after letting the powder cool to ambient conditions from 8-120 hours. All tests utilized an Explosive Research Laboratory Type 12 Impact Sensitivity Test Apparatus to determine the impact sensitivity of the explosive. The testing proved that the HMX showed increasing levels of sensitivity as both time and temperature increased while the HMX was transitioning into the delta polymorph.

INTRODUCTION

The use of energetic materials in oilfield perforating systems is a common practice due to the relatively high amount of energy for the size of the product; explosives accomplish a large amount of work with high reliability for a relatively low price. One of the largest factors when using explosive products is safety. Explosives can be very dangerous if handled improperly, and the demand for safety in the oil & gas industry is very high.

The explosive known as HMX (octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrzocine)is commonly used in oilfield products due to its high energy output and increased temperature rating. HMX has four crystalline polymorphs: beta(β), alpha(α), gamma(γ), and delta(δ). Most commonly it is a very stable compound in the beta phase for its chemical structure. However, after elevated temperature exposure the HMX can undergo a phase change which forces a molecular structure change into the sensitive delta phase. Once in the delta phase the HMX can become extremely sensitive to initiation and should be handled with great care. There has been significant research addressing the sensitivity of HMX and the transition from Beta to elta, but generally there is no information on the transition in between those two phases. HMX will transition through the polymorphs with increasing sensitivity in the following order: $\beta < \alpha < \gamma < \delta$ (Liu, et al., 2012). Additionally, the HMX can exist in multiple polymorphs, where only a portion has transitioned from beta into one of the following polymorphs. This means there can be various stages of sensitivity, based on the composition of the polymorphs in the powder sample.

ARTICLE I

TIME AND TEMPERATURE EXPOSURE EFFECTS ON IMPACT SENSITIVITY OF HMX EXPLOSIVE POWDERS

The focus of this paper is to examine the specific changes in sensitivity of HMX powders based on the level and duration of temperature exposure. The test series used HMX of two different booster grade materials that had different particle sizes and a mainload HMX material that contained wax and graphite. A majority of previous research discusses the sensitivity of HMX once it is in the delta phase, but does not address the potential elevated sensitivity issues in the alpha or gamma phases of polymorph.

THEORY

This phenomenon of HMX undergoing a phase change is not a new concept to the explosives or the oil & gas industry. Current information in API RP67 has precautionary information and details regarding this phase change in HMX. The current recommended practice advises that any explosive device containing HMX that has been exposed to elevated wellbore temperatures above 300°F needs to be handled with special attention due to the increased sensitivity to impact (API, 2007).

A common issue in the oil & gas industry is how to determine if a device has been exposed to a temperature for a substantial time period to force the delta polymorph. There have been several publications on the topic by LLNL and in the Journal of Energtic Materials, and there is substantial evidence that there is no instantaneous moment for the change in sensitivity due to the polymorph change. Often manufacturers give a recommendation of 300°F, but there is still a lacking time component that discusses when this temperature affects the HMX sensitivity. The research conducted intends to serve as evidence that the sensitivity changes are based on both time and temperature. Additionally it serves to demonstrate that the sensitivity changes even before the powder has transitioned to the full delta polymorph and may exist in beta, alpha, or gamma.

Test Method

The test method used in this research was developed in order to test the explosive powder under a wide variety of temperatures and time durations. An ERL Type 12 Impact Sensitivity Test Apparatus was used for the measurement. The device utilized a 5kg falling steel weight that impacts a striker placed directly above the HMX sample. The explosive sample was placed on a small square of 150 grit sandpaper; typically for this type of device testing companies will use 120-180 grit sandpaper. Fig. 1 depicts a typical design of the ERL Type 12 device. The device has an extremely large steel base plate and is bolted into a concrete foundation in order to eliminate any recoil effects from the falling weight. This also ensures the total energy from the falling mass is transferred efficiently into the energetic sample being tested.

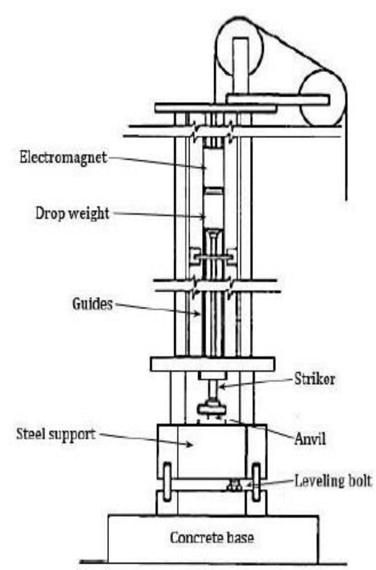


Fig. 1: ERL Type 12 Impact Test Apparatus (Phillips, 2010)

Table 1: Explosive Granulation Classes (Meyer, Kohler, & Homburg, 2007)

Class 1	Through 420 and 297 micron sieve, retained on 74 micron sieve
Class 2	Through 297 micron sieve
Class 3	Through 149 micron sieve
Class 4	50 to 70 % through 210 micron sieve
Class 5	Through 297 micron sieve, retained a 105 micron sieve
Class 6	89 to 97 % through 297 micron sieve
Class 7	45 to 65 % through 420 micron sieve

Table 2: Test Sample Exposure Conditions

Temperature, °F	Time Exposed to Temp, hrs				Time Cooled at 70F After Temp, hrs			
	1	8	24	48	8	24	48	120
280	X	X	X	X	X	X	X	X
300	X	X	X	X	X	X	X	X
320	X	X	X	X	X	X	X	X
340	X	X	X	-	X	X	X	X

The baseline conditions were set by testing each powder at ambient conditions of ~70°F. The first HMX sample tested was a booster grade material with a relatively fine particle size, classed as a medium fine powder or near to a Class 5 powder. The various Class sizes are defined fully in Table 1. This powder was tested in sample sizes of 35±3mg. The reduced sample size was done to limit the inconsistences found due to a cushioning effect of the powder. This cushioning effect is the larger volume of powder being able to absorb the impact energy and compact on itself instead of being compacted between the steel surfaces. The next material tested was a Class 1 booster grade HMX, meaning it consists of substantially larger particles. This material was tested in 50±5mg samples sizes. Both of the booster grade materials were HMX that was 99.9% pure HMX and free from other materials and binder. The last material tested was a mainload HMX that consisted of 98.3% HMX, 1.1% wax and 0.6% graphite. The HMX in this mixture must have a purity of 99.8%, but the addition of binders and dry lubricants is done for manufacturability of perforators. This powder was also tested in a larger 50±5mg sample size.

Each powder was taken in 10g sample sizes and tested to make sure the powder was below a level of 0.100% moisture content in the explosive. The 10g samples were then placed in smaller trays for each test series, respectively and were broken down into five 1g samples, and one 5g sample. All samples were placed in an Espec BTL-433 humidity chamber and exposed to elevated temperatures for various durations with a maximum humidity level of 50%. Table 2 provides a visualization of when test samples were taken. Red squares indicate the samples were pulled and tested immediately after temperature exposure, and blue squares indicate that the sample were allowed to cool back down to ambient 70°F and tested at the described time intervals. Due to the time/temp ratings of HMX and in order to maintain safe operating conditions, the powders were not tested at 340°F for 48 hours. For every red square a 1g sample was pulled, tested, and discarded. For every blue square the 5g sample was pulled, tested, and placed back in the controlled humidity chamber until the next interval test. From each of these samples the test specimens were weighed out individually in their respective 35 or 50 mg sizes.

The test heights were determined by the operator and then entered into the software package Neyer to determine the H50 and standard deviations. The H50 is the relative height at which the explosive has a 50/50 chance of initiating; below that height it commonly will not initiate, and above that height it will. In order to maintain adequate data, minimum test series of 20 drops were taken for each test conducted. To reduce the number of tests conducted, a Neyer approach was used instead of a Bruceton single step approach and did not prove to show any negative effects on the test data.

Additionally, to control the variables of testing and to maximize consistency of results, several precautions were taken. All testing was conducted by the same two operators to reduce any potential human error. All three explosive powders had a large 1,000g sample pulled and then the subsequent individual samples were pulled from that to eliminate any manufacturing lot date issues of HMX powder. Between every test, the surfaces of the anvil and striker were checked and cleaned as necessary, followed by a thorough cleaning before testing the next powder sample. Between every temperature test series, the tooling was removed from the fixture and was recut to ensure flat, smooth, and parallel test surfaces. All sandpaper samples were cut from the same single box of sandpaper to reduce variation of the sample paper.

Results and Discussion

The tests conducted showed several interesting results for each powder, which is primarily believed to be a result of their unique physical properties. The detailed test results are included in Appendix A, and summarized data is seen in the tables and figures. With limited equipment it was not possible to fully confirm if the powder had completely transitioned to the delta polymorph, but the level of sensitivity change in conjunction with existing research helps to determine if the powder had transitioned.

The first powder examined was the booster grade powder that was considered to be primarily fine particles. This powder demonstrated a rather inconsistent set of results during the cooled down test scenarios, but showed consistent sensitivity changes at the elevated temperatures, demonstrating that it was becoming inherently more sensitive. This fine powder never initiated lower than a ~20cm drop height, which is more than twice as sensitive from its ambient level of ~55cm. However, since it never became as sensitive as the other powder samples, which were lows of 5-8cm, it may not have fully transitioned to the delta polymorph. Based on the findings from a paper published by Lawrence Livermore National Laboratories, finer HMX particles take a substantially higher heat to transition through the various polymorphs. Their findings showed that a fine HMX particle can take 338°F-374°F to transition, whereas, a coarse particle can transition from 320°F to 338°F (Saw, 2002).

Due to the extremely fine particle size of this HMX sample it is also substantially more hygroscopic. After being kept in the elevated temperature for long durations a large amount of the moisture is removed from the powder. Once the powder returns to ambient conditions it will start to absorb moisture from the ambient air, which is observed in the data as a trend of decreased sensitivity and an increase in the standard deviation in the test samples, as seen in the Appendix A data. The chamber was kept at minimal humidity and desiccants were placed in the powder during the cooled down testing to try to reduce the effect of moisture absorption.

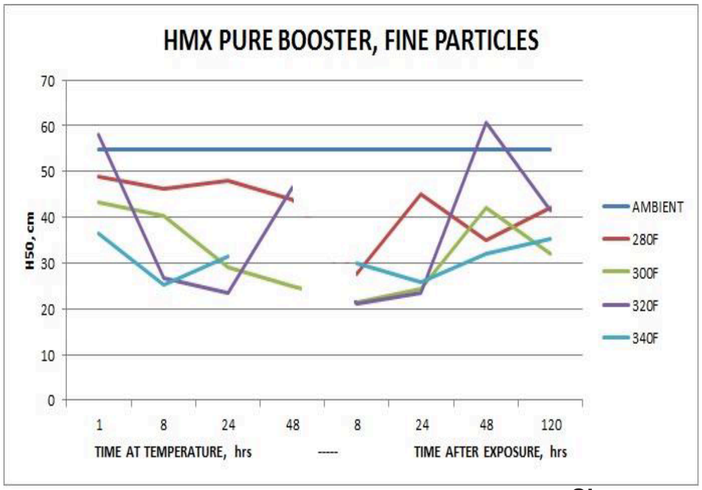


Fig. 2: Impact Sensitivity of HMX Booster, Fine Particle Size

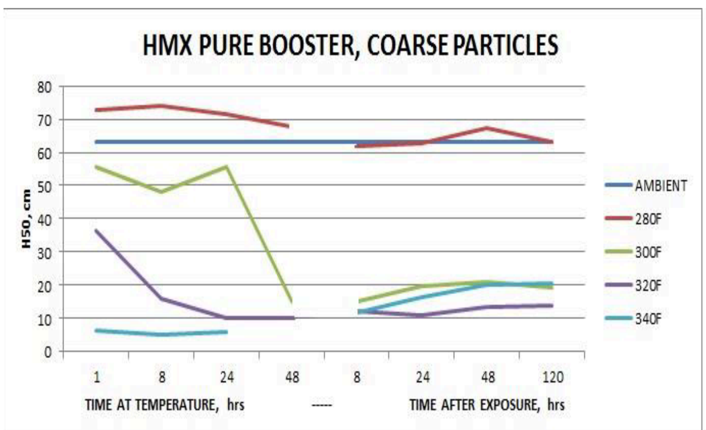


Fig. 3: Impact Sensitivity of HMX Booster, Coarse Particle Size

The coarse booster showed the most consistent and reproducible results of the powders tested during this research. The coarse powder results seen in Fig. 2 show strong support for the effect of time as a driving factor for phase change at each of the various temperatures tested. As the temperature increased, the time duration it took to witness the sensitivity change decreased. This supports the current research showing that the phase change can occur at a range of temperatures, and it is time exposure that drives the polymorph change.

The last powder tested was the mainload powder, containing binders such as wax and graphite. Due to this powder containing wax and graphite, several issues became apparent during testing. The wax led to large inconsistencies in the powder sensitivity under all test conditions due to its ability to act as a shock absorber under impact. At 280°F and 300°F, it was visually apparent in the samples that the wax had started to soften, melt, and agglomerate/coat the HMX crystals. The wax coating is believed to have contributed to the result of a decreased sensitivity at higher temperatures than at ambient conditions.

At 320°F, the powder became very sensitive, but upon cooling it returned back to an insensitive state. It is believed that this change in sensitivity is caused by the wax forming around the crystals and cooling, providing a larger cushion of wax around the individual particles. However, at 340°F the sensitivity of the mainload powder dramatically increased, down to the same level as the coarse booster. The results show that once the sample became this sensitive it remained at this level of sensitivity and the wax did not offer any level of protection to impact.

Upon examination of the test results, it was determined that all the powders saw a substantial change in sensitivity at some stage in the test series. It is important to recognize that the mainload and the coarse booster HMX both saw sensitivity levels where detonation was achieved from a height of less than 10 cm, which is a drastic change from ambient conditions. This is equivalent to the sensitivity of lead azide, a primary explosive powder known for its sensitivity to impact initiation (Gessel & Zollner, 1994).

ARTICLE I

TIME AND TEMPERATURE EXPOSURE EFFECTS ON IMPACT SENSITIVITY OF HMX EXPLOSIVE POWDERS

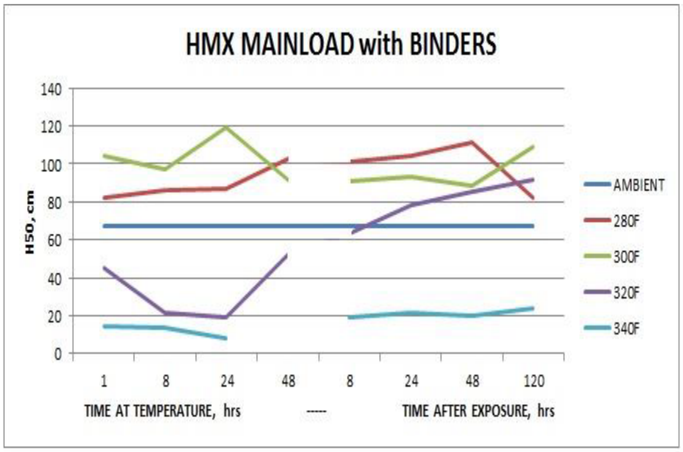


Fig. 4: Impact Sensitivity of HMX Mainload with Binders

Table 3: HMX Powder Impact Sensitivity Change

HMX Boost, Fine Particles			
Temperature, °F	Ambient Sensitivity, cm	Highest Sensitivity, cm	% Change
280	54.83	27.51	66%
300	54.83	21.30	88%
320	54.83	21.00	89%
340	54.83	25.27	74%
HMX Boost, Coarse Particles			
Temperature, °F	Ambient Sensitivity, cm	Highest Sensitivity, cm	% Change
280	63.14	61.73	2%
300	63.14	15.18	122%
320	63.14	10.00	145%
340	63.14	5.05	170%
HMX Mainload with Binders			
Temperature, °F	Ambient Sensitivity, cm	Highest Sensitivity, cm	% Change
280	68.20	81.91	-18%
300	68.20	88.10	-25%
320	68.20	19.33	112%
340	68.20	8.18	157%

For each of the three HMX powders tested, photomicrographs were taken of the particle shapes at ambient conditions and after cooling down from temperature exposure of 340°F for 24 hours. The micrographs show that after temperature exposure, the explosive particles will begin to cluster and form very sharp and jagged edges. The individual particles will form very sharp needle-like fingers protruding from the surface, leading to the increased level of sensitivity of the HMX powders.

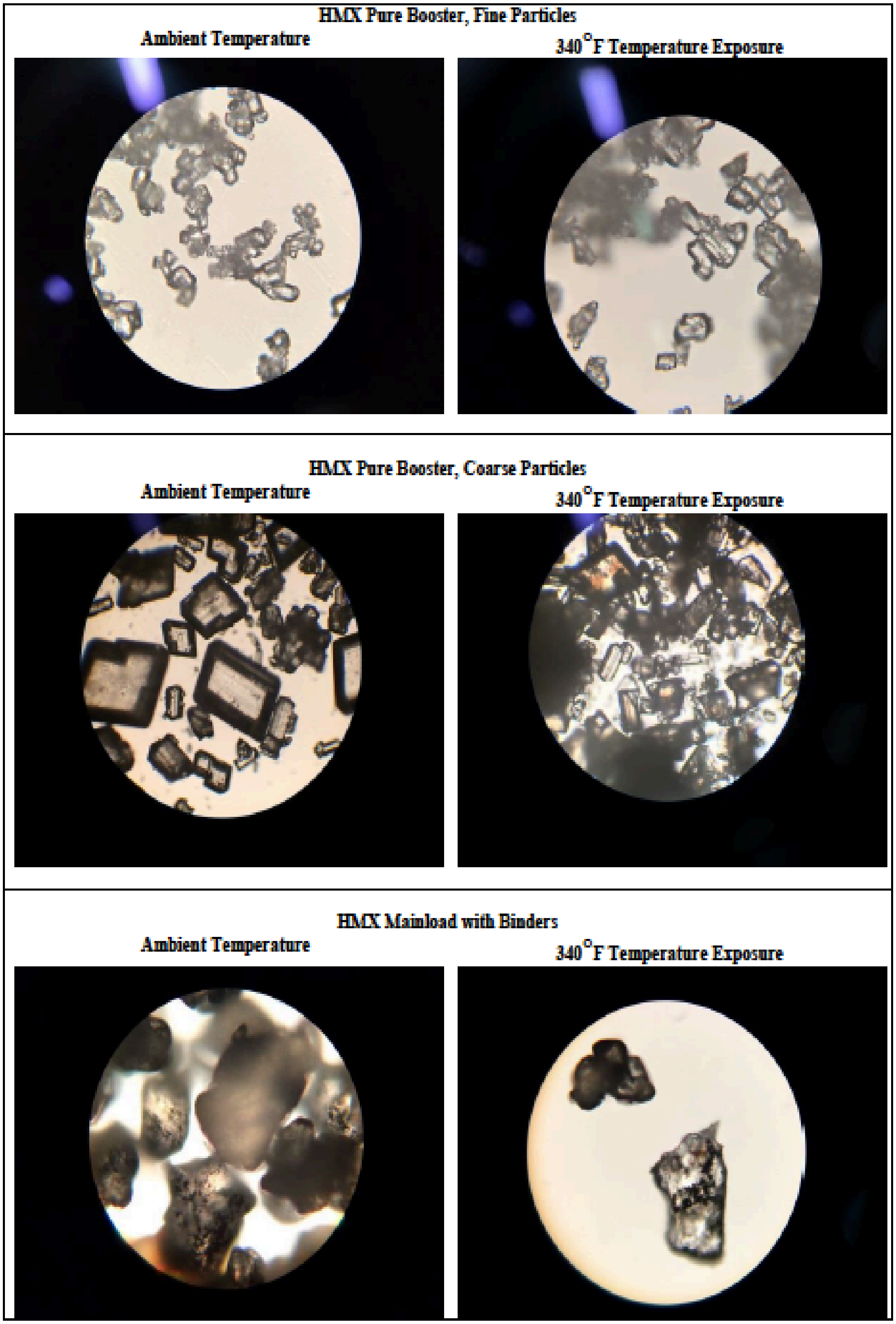


Figure 5: 40x Magnification of HMX Powders

ARTICLE I

TIME AND TEMPERATURE EXPOSURE EFFECTS ON IMPACT SENSITIVITY OF HMX EXPLOSIVE POWDERS

CONCLUSION

From the testing conducted, it was determined that the sensitivity of the powder did change based on the time of exposure. The coarse booster material showed the most prominent display of sensitivity change as a factor of time. At 280°F there was not a significant change; at 300°F the transition occurred between 24-48 hours; at 320°F the transition occurred between 1-8 hours; and at 340°F it occurred in less than one hour.

This powder also showed a continual increase in sensitivity, and eventually all samples plateaued to the same point. This provides evidence that HMX sees increased sensitivity based on time as it transitions from the beta to delta polymorph due to elevated temperatures above 300°F. Based on the test results, there is no evidence that once the powder has completely transitioned to the delta polymorph it returns back to a less sensitive state.

In conclusion, this research proves that HMX powder does in fact undergo a phase change that results in an increase in initiation sensitivity due to impact. The primary scope of the research was to determine what effect time had on the transition, and it did appear that regardless of the temperature there were drastic step changes in the sensitivity at varying times. An increase in temperature required a decrease in time for the sensitivity transition to occur.

This further emphasizes the need to handle HMX products with great care after being exposed to elevated temperatures for any time interval. Since many explosive products used in the oil & gas industry use combinations of booster and mainload explosive, as well as different particle sizes, it is good practice to handle all products with care due to the uncertainty of the sensitivity levels. The sensitivity can change in under an hour, or take as long as 48 hours, based on the testing seen here. Additionally, it was seen that even when the powder did not appear to transition entirely to the delta polymorph there was still substantial sensitivity increases. Future work would need to examine how the sensitivity of the final product was affected by temperature exposure, not just the explosive component as a loose powder.

References

API. (2007, May). Recommended Practice for Oilfield Explosives Safety. *API Recommended Practice 67.* Washington DC: API.

Gessel, U., & Zollner, H. (1994). *Sensitivity of secondary explosives after exposure to pressure and temperature.* DynaWell/ Dynamit Nobel.

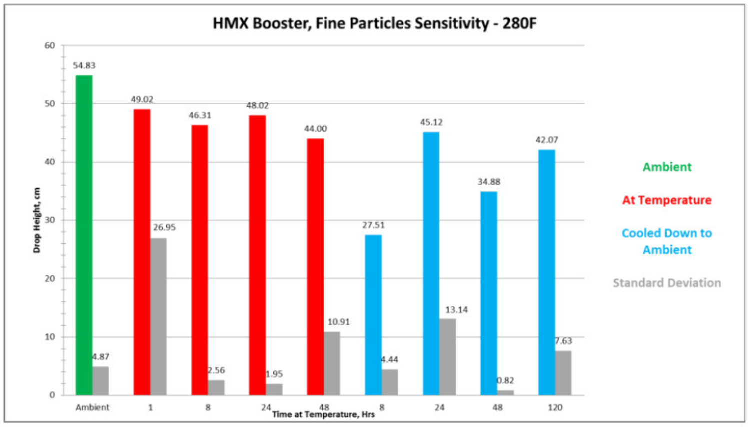
Liu, S., Chang, J., Wei, D.-Q., Chen, X.-R., Zhang, Q.-M., Gong, Z.-Z., et al. (2012). *Properties and phase transitions of the solid Beta-HMX: different force fields. Journal of Atomic and Molecular Sciences*, 41-48.

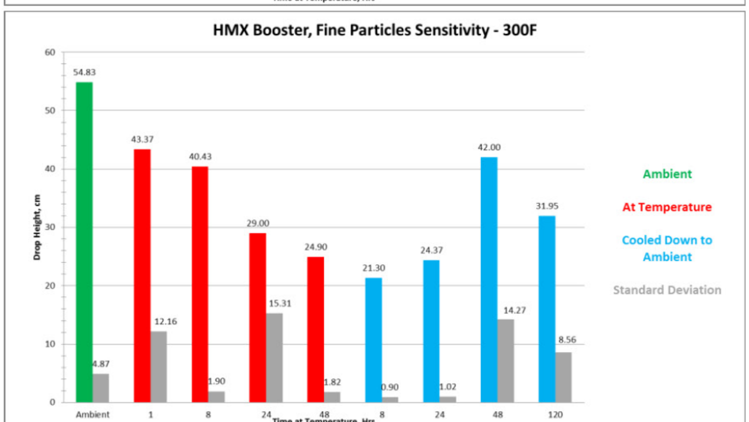
Meyer, R., Kohler, J., & Homburg, A. (2007). Explosives. Germany: Wiley- VCH.

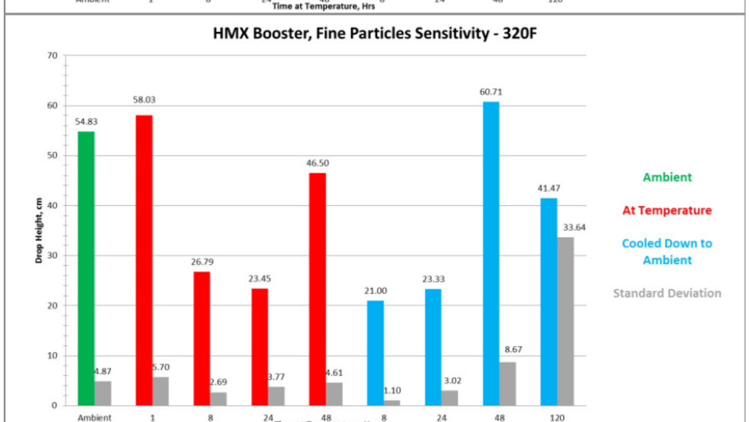
Phillips, J. J. (2010, September). AN INVESTIGATION OF MODIFICATIONS TO THE TYPE-12 IMPACT SENSITIVITY TEST APPARATUS FOR EXPLOSIVES. Socorro, New Mexico: New Mexico Tech.

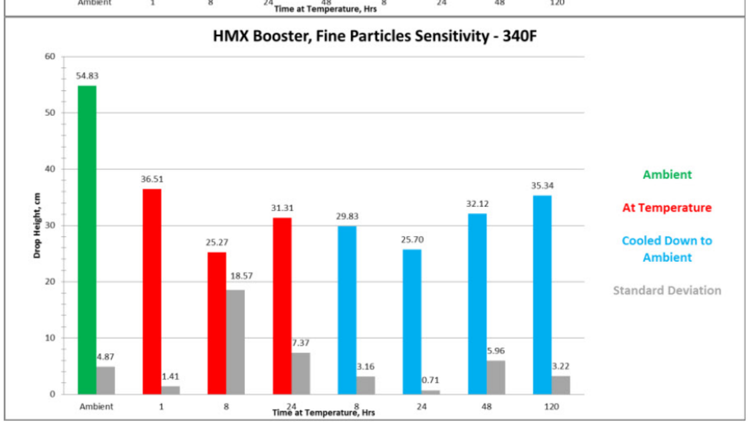
Saw, C. (2002). Kinetics of HMX and Phase Transitions: Effects of Grain Size at Elevated Temperatures. *12th International Detonation Symposium*. San Diego.

Appendix 1: Impact Sensitivity Results

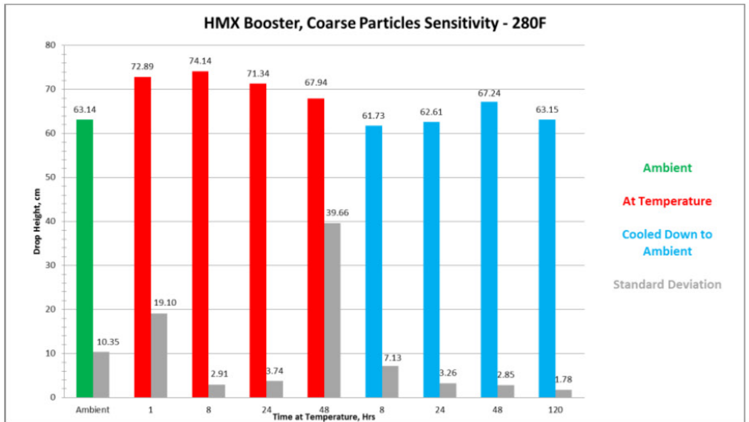








ARTICLE I


HMX Booster, Coarse Particles Sensitivity - 280F
Drop Height, cm
Time at Temperature, Hrs
Ambient
1
8
24
48
8
24
48
120
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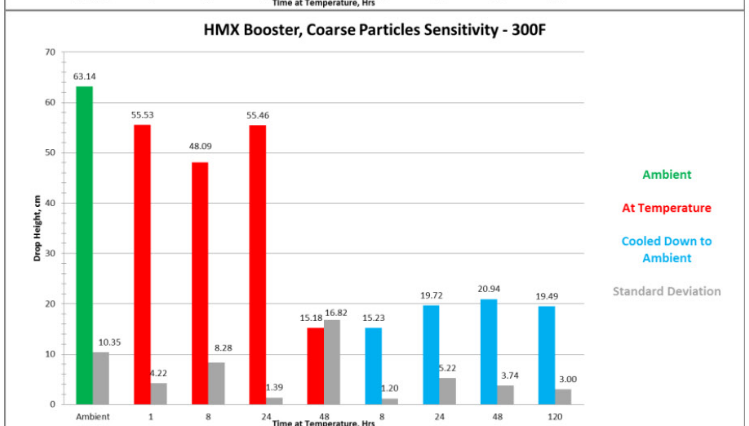
10.35
72.89
19.10
74.14
2.91
71.34
3.74
67.94
39.66
61.73
7.13
62.61
3.26
67.24
2.85
63.15
1.78
Ambient
At Temperature
Cooled Down to Ambient
Standard Deviation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8
24
48
8
24
48
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10.35
55.53
4.22
48.09
8.28
55.46
1.39
15.18
16.82
15.23
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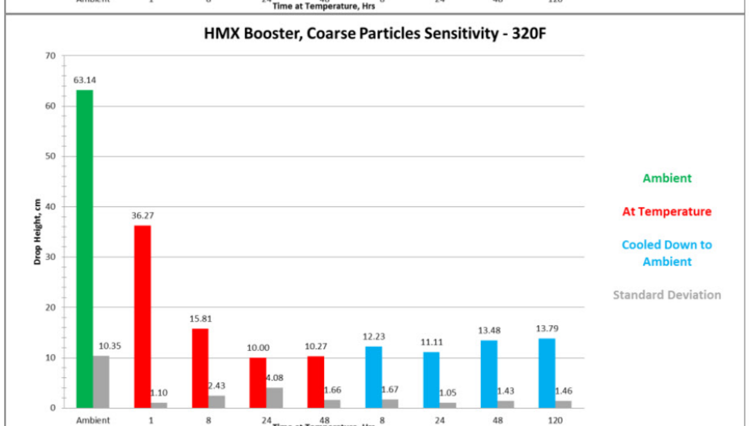
5.22
20.94
3.74
19.49
3.00
Ambient
At Temperature
Cooled Down to Ambient
Standard Deviation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Time at Temperature, Hrs
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8
24
48
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36.27
1.10
15.81
2.43
10.00
4.08
10.27
1.66
12.23
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1.05
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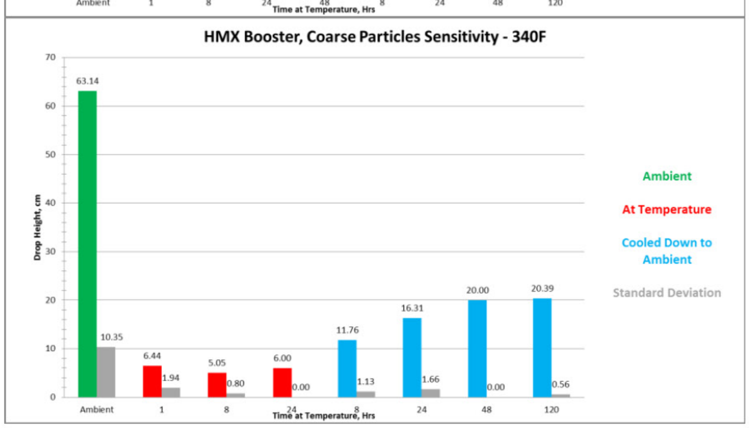
1.43
13.79
1.46
Ambient
At Temperature
Cooled Down to Ambient
Standard Deviation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24
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24
48
120
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10.35
6.44
1.94
5.05
0.80
6.00
0.00
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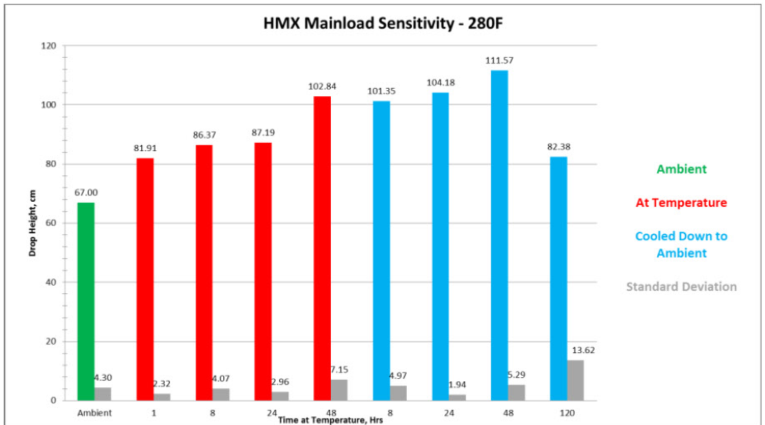
20.00
0.00
20.39
0.56
Ambient
At Temperature
Cooled Down to Ambient
Standard Deviation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Time at Temperature, Hrs
Ambient
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24
48
8
24
48
120
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87.19
102.84
101.35
104.18
111.57
82.38
4.30
2.32
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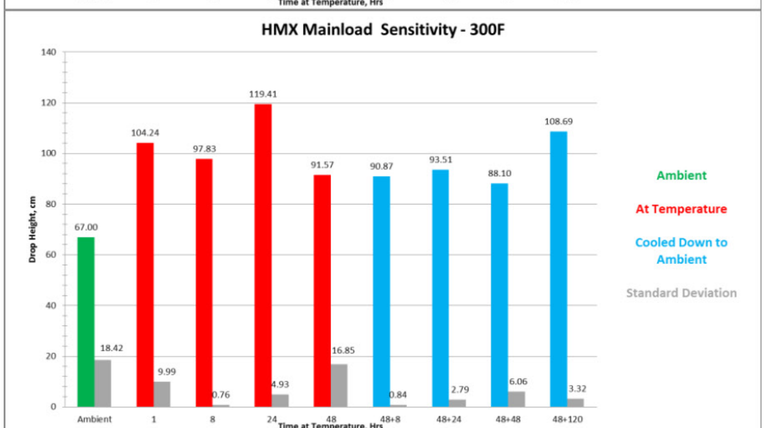
7.15
4.97
1.94
5.29
13.62
Ambient
At Temperature
Cooled Down to Ambient
Standard Deviation


HMX Mainload Sensitivity - 300F
Drop Height, cm
Time at Temperature, Hrs
Ambient
1
8
24
48
48+8
48+24
48+48
48+120
67.00
104.24
97.83
119.41
91.57
90.87
93.51
88.10
108.69
18.42
9.99
0.76
4.93
16.85
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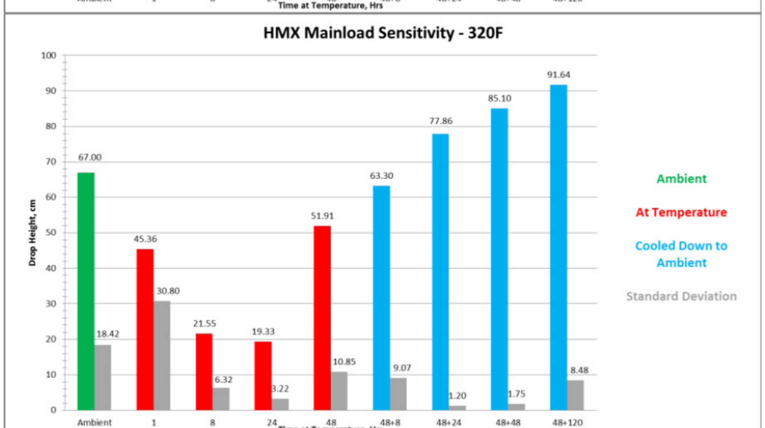
2.79
6.06
3.32
Ambient
At Temperature
Cooled Down to Ambient
Standard Deviation


HMX Mainload Sensitivity - 320F
Drop Height, cm
Time at Temperature, Hrs
Ambient
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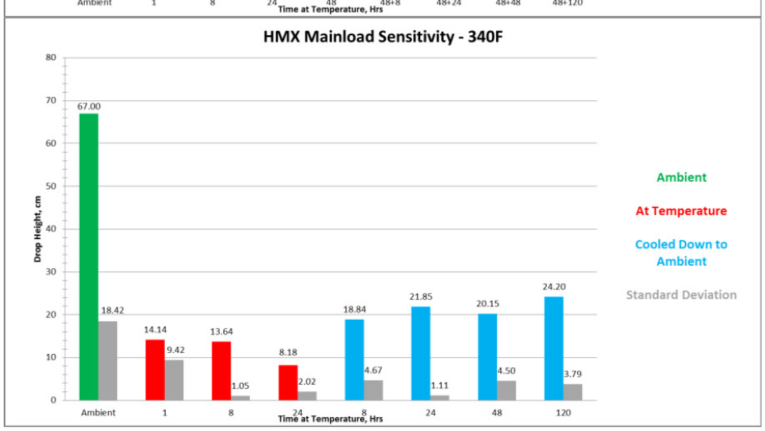
8
24
48
48+8
48+24
48+48
48+120
67.00
45.36
21.55
19.33
51.91
63.30
77.86
85.10
91.64
18.42
30.80
6.32
3.22
10.85
9.07
1.20
1.75
8.48
Ambient
At Temperature
Cooled Down to Ambient
Standard Deviation


HMX Mainload Sensitivity - 340F
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Time at Temperature, Hrs
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24
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120
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13.64
8.18
18.84
21.85
20.15
24.20
18.42
9.42
1.05
2.02
4.67
1.11
4.50
3.79
Ambient
At Temperature
Cooled Down to Ambient
Standard Deviation

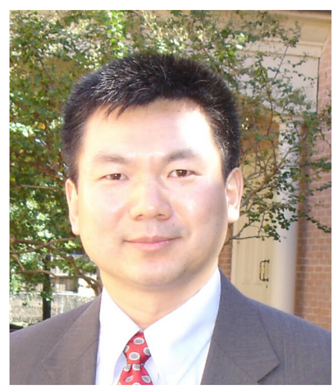
ARTICLE II

Improved Analytical Modeling for Swell Prediction of Perforating Guns

Michael H. Du, Schlumberger
C. (Oliver) Han, Hunting Titan

Michael H. Du, Schlumberger

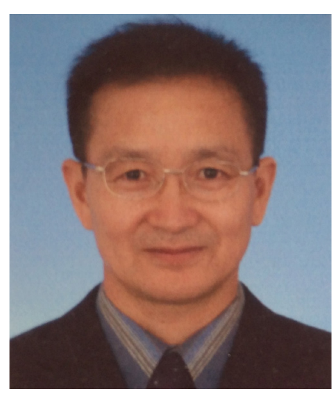
Michael Du is a PE and principal engineer, who has been working with Schlumberger for 19 years and is experienced in a wide range of downhole tools used for artificial lift, testing, completions and productions.



Michael H. Du

C. (Oliver) Han, Hunting Titan

Oliver Han is a principal engineer, who worked for Schlumberger for 16 years and is experienced in perforating, specially shaped charges, perforating guns and propellant tools, API RP 19B tests, and explosive safety.



Oliver Han

IMPROVED ANALYTICAL MODELING FOR SWELL PREDICTION OF PERFORATING GUNS

Michael H. Du, Schlumberger
C. (Oliver) Han, Hunting Titan

SUMMARY

In oil and gas field services, a perforating gun is used to perforate the casing and formation with shaped charges to open a communication channel from a petroleum reservoir to the well. However, the perforating process may cause swelling or even splitting of the gun. An excessively swollen or split gun can result in the gun being stuck in the well and therefore, a serious operational failure. In this paper, an improved analytical model is developed to predict the swelling of two types of perforating guns. The outcome from the analytical model was compared with test data, and it showed that the improved model could predict the swelling for not only the deep-penetrator perforating guns, but also for big-hole perforating guns.

INTRODUCTION

A perforating gun consists of shaped charges, jackets (charge holders), loading tube, tubular carrier, and adapters (upper and lower). The shaped charges are packaged inside the loading tube and arranged in certain patterns for different perforating objectives. The carrier and adapters work together to isolate the shaped charges from the downhole environment. A detonating cord connects the shaped charges and fires them sequentially as the detonation wave propagates down the cord. The jet formed by the charge will perforate through the carrier, wellbore, casing and formation. Fig. 1 is a cross-sectional view of a regular deep penetrator perforating gun system.

The big-hole perforating gun is designed to perforate casing and generate larger entrance holes. Consequently, this type of gun also makes larger exit holes in the perforating gun carrier. The shaped charge in a big-hole perforating gun has the same fundamentals as that of a regular deep penetrator perforating gun. However, the arrangement of shaped charges in a big-hole perforating gun system is different. Instead of having one charge at a given axial position along the gun, the big-hole gun has multiple charges at the same axial position. Fig. 2 shows a typical bighole perforating gun configuration with “three-charges-in-plane”.

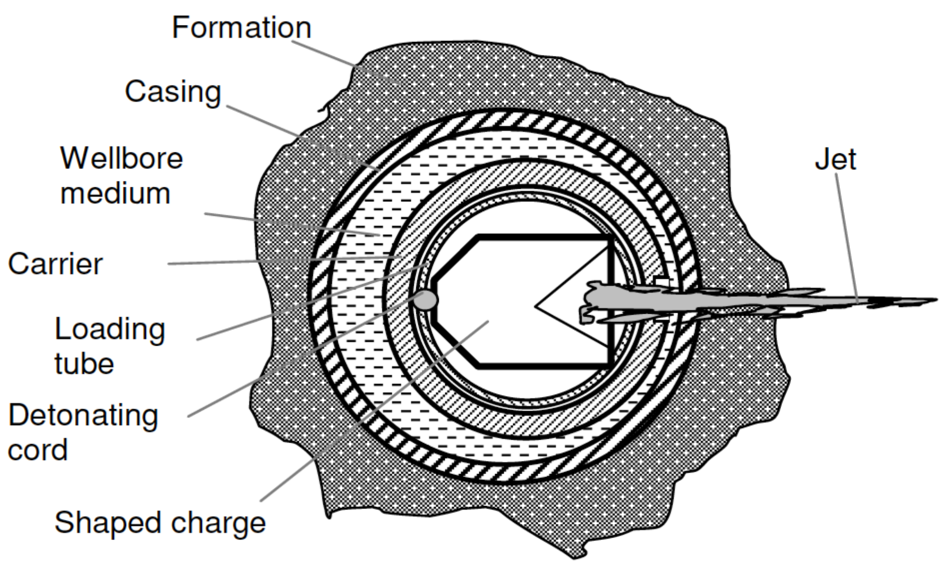


Fig. 1. Schematic of a deep penetrator perforating gun used in downhole.

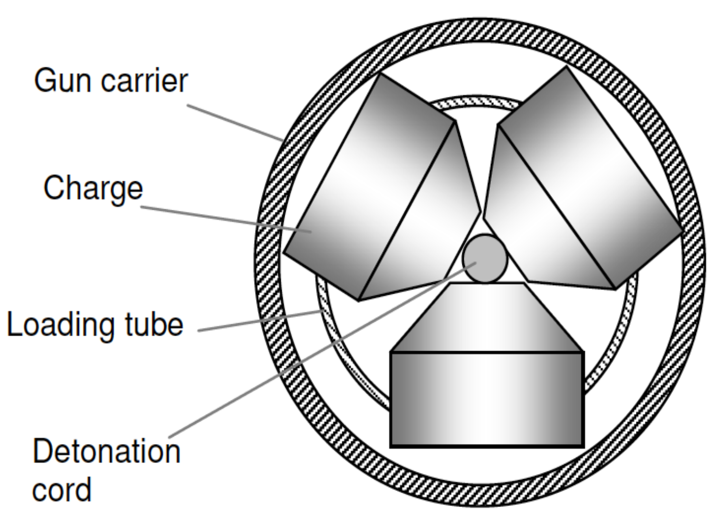


Fig. 2. Sectional view of a big-hole perforating gun with three-charge-in-plane configuration.

The detonation cord simultaneously detonates multiple shaped charges in a common plane. When the in-plane shaped charges are detonated, metallic jets will be generated along with a higher detonation pressure inside the carrier. Like the deep penetrator perforating gun, these jets will perforate the casing and the formation to create passages for oil or gas to flow from the reservoir into the well. As is the case for deep penetrator guns, this same perforating process can cause splitting or swelling of the carrier with big-hole guns. A split or excessively swollen carrier can result in the gun becoming stuck which can be detrimental to well operations. Therefore, it is important to have a reliable method to accurately predict the postdetonation condition of the carrier when either deep penetrator or the big-hole perforating guns are to be used.

Han and Du [2] developed an energy based model to simulate the swelling of deep-penetrator perforating guns used for gas wells only, and proposed a serviceability or failure criterion which was ver fied by both computational and experimental results. They took the total expendable energy from the explosives into account, related it to the energy consumed by the functional and non-functional processes, and described the relationship of the energy distribution among them. Han, Du and Walton [3] further expanded the model to cover continuously phased perforators for both gas well and oil-well applications. Application of the model to risk management in the perforating jobs was also discussed by the authors. However, these studies done by Han and Du [2] and Han, Du and Walton [3] were limited to regular, continuously-phased deep penetrator perforating gun families. How to deal with the big-hole perforating guns in terms of gun swell still remained unanswered.

In this paper, differences between a regular, continuously phased, perforating gun and a big-hole perforating gun are studied. An improved analytical model is developed which can be used to predict the swelling of both gun families.

Existing Modeling

According the models established by Han, Du and Walton, it is assumed that detonation and interaction of different components inside the perforators are axisymmetric, adiabatic and instantaneous; deformation of a perforator carrier is uniform in both radial and hoop directions; interference and the effect of the exit hole made by the jet are negligible, and boundary effects from casing or adjacent shaped charges is negligible.

The gun can be fired in either gas or liquid. Typically, the gas is air and the liquid is water. After being perforated by the jet from the shaped charge, the carrier will sustain impacts from all internal components including the shaped charge case, loading tube, and liner debris. The carrier will also be subject to detonation shock. The shaped charges can be made of several kinds of high explosives, of which the most common ones are RDX, HMX, and HNS. The study described in this paper is limited to HMX. Readers can easily follow the same methodology to adapt the model to fit other high explosives such as RDX and HNS.

The model is based on the fundamental principle of energy conservation. The total energy Q created by the detonated explosives can be separated into the following categories:

- Kinetic Energy, W_k
- Deformation Energy, W_d
- Work Done by Gas Expansion, or Thermal Work W_T
- Shock Energy, W_s

Plugging the above energy terms into the energy conservation equation yields:

$$Q = Wk + Wd + WT + Ws \qquad (1)$$

ARTICLE II

IMPROVED ANALYTICAL MODELING FOR SWELL PREDICTION OF PERFORATING GUNS

The kinetic energy is distributed to the liner jet, charge case, loading tube, and carrier, as well as the explosive product. For simplification without losing significance of the physics, the kinetic energy is treated as two parts,

$$W_k = W_{k,l} + W_{k,\Sigma} \tag{2}$$

where $W_{k,l}$, is kinetic energy of the liner jet; and $W_{k,\Sigma}$ is combined kinetic energy of the charge case, loading tube, carrier and explosive product. With the Gurney formula, Eq. 2 can be written as

$$W_k = \frac{1}{2}k_{v,l}m_l G^2\left(\frac{1}{m_l/m_e+f}\right) + \frac{1}{2}k_{v,\Sigma}\left(m_c+m_t+m_g+\frac{1}{2}m_e\right)G^2\frac{1}{(m_c+m_t+m_g)/m_e+f'} \tag{3}$$

where G is Gurney energy; $k_{v,l}$ and $k_{v,\Sigma}$ are constants for a given explosive; m_e is the mass of explosive per charge; m_l is the mass of the liner; f is a geometrical constant for liner; m_c is the mass of case; m_t is the mass of loading tube per charge; m_g is the mass of carrier per charge; f' is a geometric constant for the case, loading tube and gun carrier.

Both the elastic and plastic deformation energies of the case, loading tube and gun carrier are taken into account, but the energy to collapse the liner into jet is neglected. Assuming that the charge case, loading tube and carrier are made from elastic-perfectly plastic materials, the deformation energy W_d can be written as

$$W_d = \frac{1}{2}\left(\frac{m_c\sigma_{Y,c}^2}{E_c\rho_c} + \frac{m_t\sigma_{Y,t}^2}{E_t\rho_t} + \frac{m_g\sigma_{Y,g}^2}{E_g\rho_g}\right) + \frac{2}{\sqrt{3}}\left[\frac{m_c\sigma_{Y,c}}{\rho_c}\ln\left(\frac{R_c}{R_{c,0}}\right) + \frac{m_t\sigma_{Y,t}}{\rho_t}\ln\left(\frac{R_t}{R_{t,0}}\right) + \frac{m_g\sigma_{Y,g}}{\rho_g}\ln\left(\frac{R_g}{R_{g,0}}\right)\right] \tag{4}$$

where m is mass; σY is yield strength; E is Young's modulus; ρ is density, and R is radius. Subscript "c" represents the shaped charge case; subscript "t" represents the loading tube; subscript "g" represents the gun carrier; and subscript "0" represents the initial state. $R_c/R_{c,0}$ is assumed to equal to 1.1 (10% of expansion rate); R_g minus R_t is equal to the carrier tubing thickness.

The gaseous product from the detonation expands and consumes a portion of energy from the explosives. Assuming that the gaseous product behaves as an ideal gas, and knowing that the post-detonation pressure is much higher than the pre-detonation pressure, the work done by gas expansion becomes W_T as shown in Eq. (5) [3],

$$W_T = m_e\left(\frac{r_0}{r}\right)^{2(\gamma-1)} q \tag{5}$$

where r_0 is the radius of the initial explosive load, assuming it is solid and in spherical shape; r is the radius of area swept over by the particles of the explosion product; in this case, r equals to R_g minus

wall thickness of carrier; q is unit detonation energy, known for a given explosive [4, 5, 6]; γ is specific heat of gaseous product of the explosive.
Shock wave energy is calculated differently in different media. In air, we have shock energy expressed as

$$W_s = \pi\rho l \frac{\alpha R_g^2 - R_{g,0}^2}{\alpha - 1} G^2 \left(\frac{1}{(m_c + m_t + m_g + m_e)/m_e + f'} \right) \quad (6)$$

where l is the unit section length of carrier per unit shot (3 shots per unit for big-hole guns) or per charge, which is related to the shot density of the perforators; $\alpha = \frac{\gamma'+1}{\gamma'-1}$;

and specific heat $\gamma' = 1.4$ for air [2].

In water, the shock wave energy is

$$W_s = k_a \pi l \rho_{a,0} v_a^2 \left(\frac{1}{2} + \frac{1}{(\gamma'-1)\left(\frac{v_a^2 \rho_0}{B} + 1\right)^{\frac{1}{\gamma'}}} \right) \frac{\left(\frac{v_a^2 \rho_0}{B} + 1\right)^{\frac{1}{\gamma'}} \left(R_g^2 - R_{g,0}^2\right)}{\left(\frac{v_a^2 \rho_0}{B} + 1\right)^{\frac{1}{\gamma'}} - 1} \quad (7)$$

where B is constant , equal to 299 MPa; γ' is the ratio of the specific heats of water, equal to 7.15; k_a is a modifier to account for air/gas content in water, ranging 0.01~0.2 [3].

Rewriting Eq. (1), we have

$$f(R_g) = Q - (W_k + W_d + W_T + W_s) = 0 \quad (8)$$

where W_k can be found from Eq. (2) and is independent of R_g; W_d and W_T can be found from Eq. (4) and (5). Depending on the application of a perforator, Eq. (6) is used for gas wells and Eq. (7) for oil wells to take account of energy taken away by detonation shocks, W_s. R_g, implicitly included in Eq. (8), is the only unknown, and therefore can be solved from Eq. (8).

The above methodology was shown to be successful in predicting the swelling of regular continuously phased deep penetrator perforating guns[3]. However, when dealing with big-hole guns, the predicted results are not in agreement with the experimental data. Therefore, an improved model is necessary.

Improved Modeling

In the previous work done by Han, Du and Walton [3], they assumed that the detonation and interaction of different components inside perforators are axisymmetric, which is a reasonable approximation for the regular deep-penetrator perforating gun. However, a big-hole perforating gun is also scalloped, and it usually has a higher shot density. The charge arrangements inside the carrier are more uniformly distributed in the hoop direction in a given cross-sectional plane. Therefore, the deformation of the gun carrier is relatively uniform in both the hoop and axial direction due to the higher shot density. Because of the tighter packaging of charges and axial symmetry, damage or swelling resulting from the impact of charge case fragments is less pronounced than that from the detonation pressures. Therefore, big-hole gun carriers have a greater chance of being split rather than cracked. Splitting occurs when a fissure in the longitudinal direction connects two adjacent scallops. Cracking can either initiate from an exit hole or any other location but it stops before reaching any adjacent exit holes in a carrier. It is a common understanding that cracking is due to fragment impact. Splitting is more dramatic if it happens, and it results from a high internal pressure inside the gun carrier in combination with stress concentrations at the scallop and the exit hole.

A big-hole shaped charge has a relatively larger in OD (caliber) with a shallower and wider-angled liner. The jet (or self-forged projectile) formed by the charge is relatively thicker in diameter and shorter in length than a deep-penetrator charge. It is assumed that the in-gun pressure induced by this type of shaped charges will be higher.

The same physics and process previously described for deep-penetrating guns also applies to a big-hole perforating gun, but the energy distributions can be different. Hence, the geometric coefficients used in the Gurney formula and the coefficient used in the thermal dynamics equations are different and should be adjusted accordingly.

Kinetic and deformation energies given by Eq. (3) and (4) are modified due to the configuration of big-hole perforating guns. For kinetic energy, we have the following:

$$W_k = \sum_{i=1}^{n} \frac{1}{2} k_{v,l} m_{l,i} G^2 \left(\frac{1}{m_{l,i} / m_{e,i} + f} \right) + \sum_{i=1}^{n} \frac{1}{2} k_{v,\Sigma} \left(m_{c,i} + \frac{m_t + m_g}{n} + \frac{1}{2} m_{e,i} \right) G^2 \frac{1}{\left(m_{c,i} + \frac{m_t + m_g}{n} \right) / (m_{e,i}) + f'} \quad (9)$$

where n is number of charges within one shooting unit of the gun (3 for the gun shown in Fig. 2), $m_{l,i}$ is liner mass of the ith charge in the unit, $m_{e,i}$ is explosive mass of the ith charge; $m_{c,i}$ is case mass of the ith charge; the rest is the same as given above.

For thermal work done due to expansion of the detonation gaseous product, and the characteristics of big-hole charge arrangement, Eq. (5) can be expanded as follows:

$$W_T = \sum_{i=1}^{n} m_{e,i} \left(\frac{1}{3} \left(\frac{r_{0,i}}{r_g} \right)^2 \right)^{(\gamma-1)} Q \qquad (10)$$

where $r_{0,i}$ is the initial radius of the explosive load assumed in spherical shape and solid state for each charge.

For shock energy in air,

$$W_s = \pi \rho l \frac{\alpha R_g^2 - R_{g,0}^2}{\alpha - 1} G^2 \left(\frac{1}{\left(\frac{\sum_i^n m_{c,i}}{n} + m_t + m_g + \frac{\sum_{i=1}^n m_{e,i}}{n} \right) / \sum_{i=1}^n m_{e,i} + f'} \right) \qquad (11)$$

In water, shock energy given by Eq. (7) is still valid. By substituting Eqs. 9, 10, 11 and 4 into Eq. 8, and solving for R_g the perforating gun swell OD can be readily obtained.

Modeling Results and Validation

Two typical big-hole gun systems (6-5/8" and 7") were simulated under the conditions in both air and water environments. Table 1 shows the results of the swell OD of the two big-hole gun systems from both testing and prediction. For convenience of the following discussion, the OD swell rate (ΔOD/OD) was also computed and listed in the table.

Table 1: Swell OD, Testing vs Modelling for Big-Hole Gun Systems

No.	Size of Gun	Medium	Swell OD, Tested (in)	Swell OD Modeled (in)	Difference (%)	ΔOD/OD
1	6.625", 18 spf	Water	6.73	6.73	0	1.59%
2	6.625", 18 spf	Air	Split	6.87	NA	3.27%
3	7.000", 18 spf	Water	7.13	7.14	0.1	1.97%
4	7.000", 18 spf	Air	Split	7.47	NA	6.77%

For both guns shot in water, the simulated OD swell is 1.59% of the original OD for the 6-5/8" gun and 1.79% for the 7" gun. The simulated final swell OD for each gun is very close to the tested swell OD if not precisely that.

For the guns shot in air, it was known that both the gun systems would not survive, so the "Swell OD, Test" column test were noted as "split" in Table 1. The simulated OD swell is 3.27% for the 6-5/8" gun and 6.77% for the 7" gun. Based on the study by Han, Du and Watson [3], the gun will split if the expansion of the gun OD is greater than 20%. However, as shown in Table 1, for big-hole perforating guns, an expansion of less than 2% seems to indicate the gun will survive. Expansion rate larger than 3% seems to indicate that the gun will fail.

The above results seem to deviate from the previous study [3], in which the authors reported the failure criterion is 16% ~18% of the expansion rate for deep penetrator perforating guns. This confirms the discussion in the "Modelling" section of this paper, which indicates that the failure modes for big-hole and deep-penetration perforating guns are drastically different. The deep-penetration perforating guns' failure mode is characterized by internal fragment impacts on the gun carrier, characterized by "bumps", while big-hole perforating guns' failure mode is characterized by internal swelling due to extremely high detonation pressure. Consequently, different failure criteria are indicated for big-hole and deep-penetrator perforating guns in practice, respectively.

So far, the big-hole guns used for validating the model were "three charges on a plane" systems of high shot density and large size in diameter. Further work can be done to apply this model for more variable gun configurations and gun sizes with the same principles

CONCLUSION

An improved analytical model to simulate perforating gun swelling has been derived to address both deep penetrator and big-hole perforating guns. The model was verified with big-hole experimental data, yielding results with a similar accuracy as for the deep penetrator model reported previously. Due to differences in failure modes between the two different gun types, a failure criterion (<3% OD expansion) is proposed for the big-hole perforating gun.

Although this analytical model was derived and validated based on a specific group of perforators, the approach and principles taken by the authors would be applicable to different perforating guns with variable configurations and sizes developed by other manufacturers. The model can be used as an effective tool for both product development and job design in field operations.

References

[1] Grove, B.,A. Werner and C. Han, "Explosive-induced damage to oilwell perforating perforator carriers," Structures under Shock and Impact IX, ed. by N. Jones and C. Brebbia, 165-176 (2006).

[2] Han, C., and Du, M. H., 2006, "Modelling Air Perforators for Serviceability," Proceedings of the 23rd International Symposium on Ballistics, Tarragona, Spain, 16-20 April 2007.

[3] Han, C., Du, M. H. and I. Walton, 2009 "Modeling Air and Water Perforator Swell for Better Risk Management," SPE Journal of Drilling & Completion, Vol. 24, No. 3, pp. 424-429.

Nomenclature

B	Constant, equal to 299MPa
E	Young's modulus
f	Geometrical factor, equal to 0.33
f'	Geometric constant, equal to 0.5
G	Gurney energy
k_a	Coefficient to account air/gas content in water (0.01~0.1)
$k_{v,l}$	Constant for a given explosive (1 to 1.8).
$k_{v,\Sigma}$	Constant for a given explosive (0.9 to 1.0).
l	Length of carrier per shot or per charge
m	Mass
p	Pressure
p_a	Medium pressure after being shocked or shock pressure
Q	Total detonation energy
q	Unit detonation energy
R	Radius
r	Radius of area swept over by particles of explosion
W_d	Deformation Energy
W_k	Kinetic Energy
$W_{k,l}$	Kinetic energy of liner
$W_{k,\Sigma}$	Combined kinetic energy of case, loading tube, carrier and explosive product
W_s	Shock Energy
W_T	Thermal Work
v_a	Velocity of carrier, loading tube, case and water particle behind shock
v_l	Velocity of liner
γ	Ratio of specific heats of the gaseous product
γ'	Ratio of specific heats of medium
ρ	Density
σ_Y	Yield strength

Subscripts

a	Medium undergone with shock;
c	Shaped charge case
e	Explosive
l	Liner
t	Loading tube
g	Perforator carrier
0	Initial state
Σ	Sum of Case, loading tube, carrier and explosive product

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