



Software Development for Automation of Space- and Time-Varying Pressurization on Small Caliber Gun Barrels

by Michael M. Chen and Joseph T. South

ARL-TR-4197

August 2007

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REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) August 2007		2. REPORT TYPE Final		3. DATES COVERED (From - To) January to June 2007	
4. TITLE AND SUBTITLE Software Development for Automation of Space- and Time-Varying Pressurization on Small Caliber Gun Barrels				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Michael M. Chen and Joseph T. South (both of ARL)				5d. PROJECT NUMBER 622618.H80	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory Weapons and Materials Research Directorate Aberdeen Proving Ground, MD 21005-5066				8. PERFORMING ORGANIZATION REPORT NUMBER ARL-TR-4197	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT A console application program was developed to automate the process, starting from triggering IBHVG2 (Interior Ballistics of High Velocity Guns, version 2) execution "on the fly" for pressure calculation, determining pressure gradient along down-bore distance, parsing the LS-DYNA ¹ key word file for element extraction, associating load curves with selected elements, and finally generating a complete LS-DYNA key word file for explicit dynamic analysis. This report presents the architecture and process flows of the software design using the unified modeling language. The software development integrated IBHVG2 code with LS-DYNA program, greatly streamlining pressure data computation, transformation and application.					
¹ LS-DYNA is a trademark of Livermore Software Technology Corp.					
15. SUBJECT TERMS console application; in-bore pressure; M855; small caliber gun; space-varying pressurization; time-varying pressurization					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 28	19a. NAME OF RESPONSIBLE PERSON Michael M. Chen
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include area code) 410-278-6146

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Acknowledgments

The authors wish to thank Dr. James DeSpirito of the U.S. Army Research Laboratory (ARL) for his efforts in validating gauge pressures from IBHVG2 (Interior Ballistics of High Velocity Guns, version 2) output with calculated results from Lagrange approximation. The validation has streamlined the explicit implementation of Lagrange formulation in the codes. In addition, the authors thank Mr. Paul Conroy of ARL for providing preliminary IBHVG2 input decks for code testing, Mr. Andrew Brant of ARL for offering the latest version of IBHVG2 executable file, and Mr. Robert Keppinger of ARL for providing the M855 bullet picture. This work was supported in the Lightweight Ordnance 07 mission program under the work area of ballistics technologies for small arms.

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1. Introduction

The mission program “Ballistic Technologies for Small Arms” was initiated to investigate small caliber ammunition and weapon functions. The objective of the mission program is to gain a better understanding of the events that occur during the firing of a small caliber round as well as the dynamic chain of weapon events including round insertion, primer strike, ignition, shot start, engraving, extraction, ejection, and launch dynamics. Over the past few years, significant research efforts have been conducted under the Small Arms program at the U.S. Army Research Laboratory, and numerous technical reports have been published (*1 through 12*). One of the work units concerning ballistic technologies is to develop a complete simulation capability including in-bore modeling, experimental validation of the projectile-weapon interactions, and ballistic analysis. The combined efforts are expected to provide an in-depth understanding of small caliber ammunition. This report aims to increase the fidelity of in-bore modeling that will facilitate the development of component and system models for small caliber weaponry. Specifically, space- and time-dependent in-bore pressures will be directly derived from Lagrange formulation without going through inaccurate linear interpolation. In addition, the pressures will be programmatically applied to the finite element model of the gun barrel, which will greatly streamline the modeling efforts.

Traditionally, when one dealt with gun tube pressurization using LS-DYNA¹, a number of pressure-time curves based on certain locations were obtained from interior ballistics codes, such as IBHVG2 (Interior Ballistics of High Velocity Guns, version 2). Subsequently, an interpolation on the derived pressure curves needed to be conducted for a number of small increments along the gun tube in order to account for spatial dependency. Typically, the entire set of the pressures would be imported to a preprocessor, such as HyperMesh², and then each pressure curve would be applied to the elements on the inner surface of the gun tube at the corresponding location. Finally, a LS-DYNA key word file that includes the spatially varying pressures can be written by a utility function within HyperMesh. These tasks have been a manual process since no explicit formulation can be specified for the space- and time-dependent pressurization in the command key word file of LS-DYNA. On the other hand, no direct linkage has been implemented between IBHVG2 and LS-DYNA so that the calculated in-bore pressures can be directly transferred to the finite element model of the gun system. Please note that, for instance, when 500 locations are selected along a gun barrel, i.e., 500 rings from a geometric perspective, the whole process to manually apply 500 pressure-time curves on the respective rings becomes too cumbersome and sometimes infeasible. In other words, one dedicated pressure-time curve needs to be associated with each ring to account for spatial variations. For clarification, an illustration of rings along the down-bore distance of a gun tube is given in figure 1. Because of the time-consuming and tedious steps, an initiative to

¹LS-DYNA is a trademark of Livermore Software Technology Corporation.

²HyperMesh is a registered trademark of Altair Engineering, Inc.

automate the pressurization was launched to eliminate the workloads. The development of the software is intended to embed IBHVG2 codes, i.e., triggering IBHVG2 execution “on the fly” for pressure calculations, to create load curves at desired time steps, to parse the LS-DYNA key word file for extracting element information, and to ultimately generate the final key word file for explicit dynamic analysis.

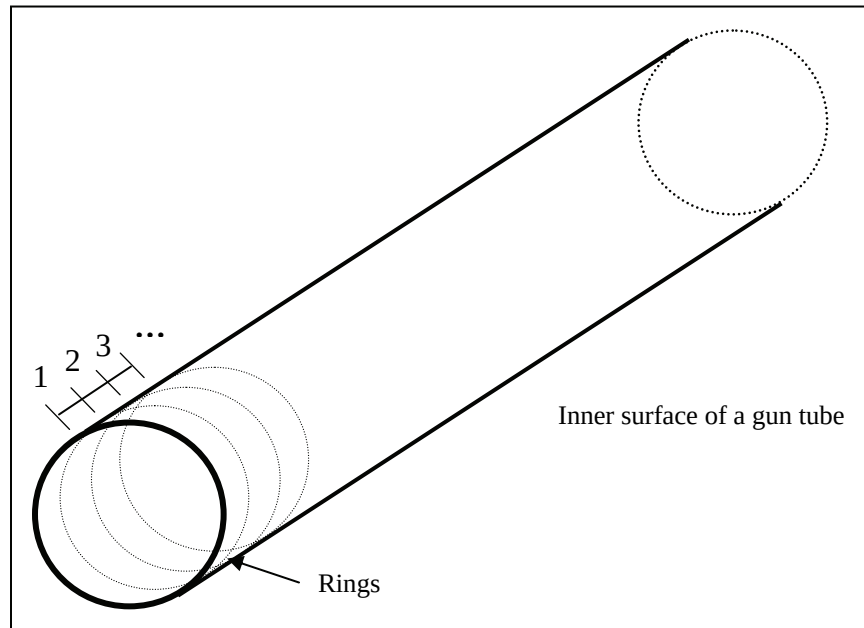


Figure 1. Illustration of rings in a gun tube.

2. Functional Requirements and Use Cases

Functional requirements capture the intended behavior of a software system. This behavior may be expressed as services, tasks, or functions that the system is required to perform. The name “Pressurizer” is adopted for the computer program that automates pressurization on a small caliber gun tube, and this name is used thereafter throughout the report. The baseline functionality necessary for the system is outlined below:

1. To increase the fidelity of the in-bore pressure gradient application, the spatially varying pressures should be calculated directly from IBHVG2 or from the Lagrange formulation instead of being linearly interpolated between base and chamber pressures.
2. A reasonable number of rings over the span of barrel length should be determined so that the spatial time pressure variations can be better reflected.
3. The associated elements with each ring location should be programmatically selected over the finite element model of a gun barrel.

4. The pressure curve at each ring location should be automatically assigned to the prescribed element set.
5. The interaction with a pre-processor tool, such as HyperMesh, should be eliminated in the pressurization process and a complete LS-DYNA key word file that contains the loading conditions should be created with Pressurizer.

A popular standard language named Unified Modeling Language³ (UML) for writing software blueprints is employed for the development. One of the fundamental diagrams in the UML for modeling the dynamics of a system is called a use case diagram. A use case defines a goal-oriented set of interactions between external actors and the system undergoing consideration. Actors are parties outside the system that interact with the system (13). The following use case diagram shown in figure 2 is created for modeling the behavior of the Pressurizer system. It illustrates a set of use cases and actors and their relationships.

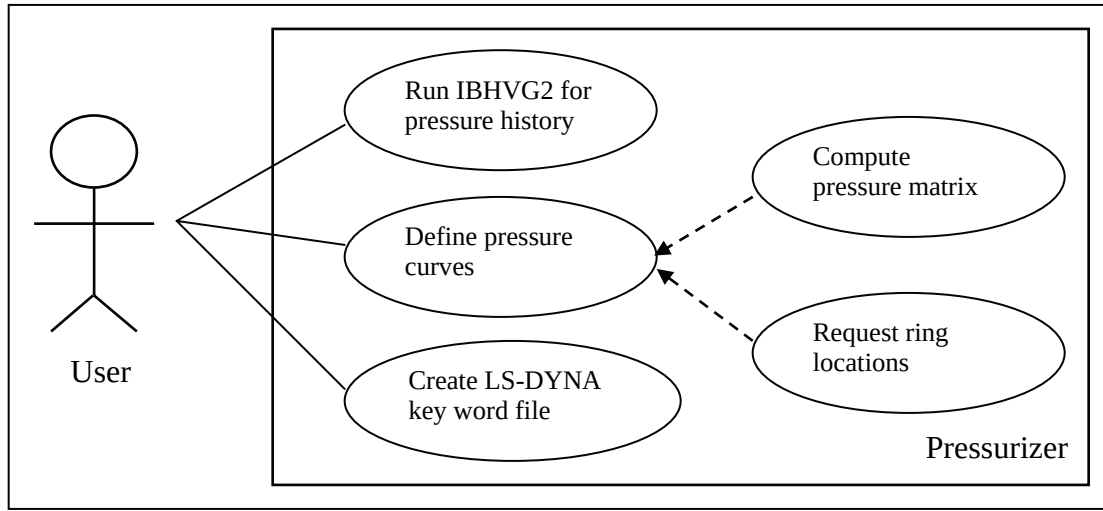


Figure 2. A use case diagram.

To fulfill the requirements on the calculation of the pressure gradient, the space- and time-dependent pressures derived from the Lagrange approximation (14) must be explicitly defined in the computer codes. The formulation can be expressed as

$$P(x,t) = P_{brech} - \frac{\Theta}{2} (P_{base} - P_{res} - P_{air}) \left(\frac{x}{x_p} \right)^2 \quad (1)$$

in which P_{brech} = pressure at the breach

P_{base} = pressure at the base

P_{res} = bore resistance

P_{air} = air resistance

Θ = charge-to-projectile-weight ratio

x_p = position of projectile base

³Unified Modeling Language and UML are trademarks of Object Management Group, Inc.

\$TDIS commands can be used to obtain the time history of breech pressure, base pressure, bore resistance, and air resistance from IBHVG2 execution (15). Each \$TDIS deck defines one variable, i.e., one of the trajectory-type output variables, to be printed. A revised input deck demonstrating the specification is given in appendix A. The ratio of charge to projectile weight is available in the IBHVG2 output file, which value can be parsed and directly used for the calculation. The weight ratio is a constant value, independent of time. The x variable refers to the axial direction of gun tube from ground reference system. The quadratic equation indicates that in-bore pressures from breech to base decay with the separation distance at the second order. To validate the equation used in IBHVG2, one can specify an array of gauge locations in \$GUN deck that is used to describe physical dimensions of the gun chamber and tube (15). As a result, the pressure history at the corresponding locations can be retrieved. Note that the gauge locations are based on the gun tube reference system and are offset by the effective chamber length when compared with the results from equation 1.

3. Design Architecture

When one is modeling the architecture of a software system, it is important to identify the views that are used to represent the architecture. Figure 3 illustrates a common modeling of a system architecture including logical elements and physical elements. The implementation view that primarily concentrates on system assembly and configuration management and the deployment view that mostly refers to distribution, delivery, and installation are fairly straightforward for the software development and are not addressed in detail in this report. The details for the design view and process view are outlined as follows.

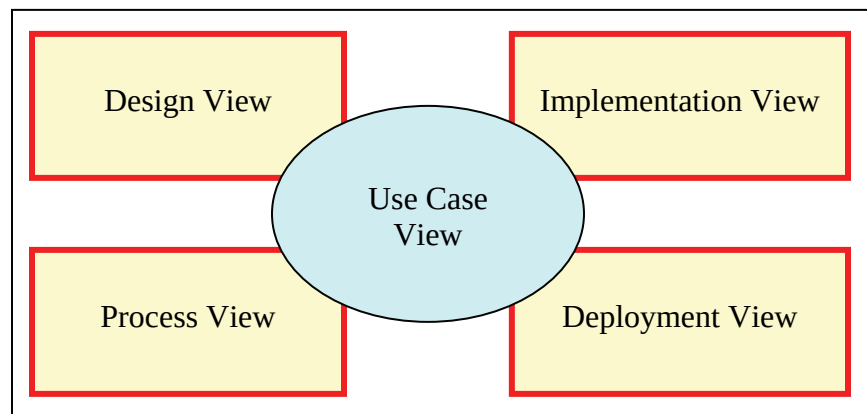


Figure 3. Typical software architecture modeling.

The Pressurizer system is divided into four components that can be developed independently. The set of distinct components can be plugged together and equipped with ease-of-change attributes. The modular design is adopted for the purposes of scalability and maintainability. The Pressurizer

system also provides simple interfaces that reduce the number of interactions when the intended functions are performed. The four function modules are described in detail in tables 1 through 4.

Table 1. Function module 1.

Objective: Obtain time history of pressure components needed for pressure gradient calculations.		
Input	Process	Output
Preliminary IBHVG2 input decks (INP1)	1. Parse input decks 2. Revise input decks. 3. Trigger IBHVG2 on the fly 4. Execute revised input decks 5. Generate a result file	Output file from IBHVG2 execution (OUT1)

Table 2. Function module 2.

Objective: Compute Lagrange pressure gradient and create *DEFINE_CURVE cards		
Input	Process	Output
1. OUT1 file 2. *DEFINE_CURVE card options	1. Parse OUT1 file 2. Perform unit conversion 3. Retrieve ring locations 4. Calculate pressure gradient 5. Write files	1. LS-DYNA *Define_Curve cards (OUT2) 2. Optional pressure matrix 3. Optional ring file.

Table 3. Function module 3.

Objective: Determine loading element faces and create *LOAD_SEGMENT cards		
Input	Process	Output
1. Preliminary LS-DYNA keyword file (INP2) 2. OUT2 file 3. *LOAD_SEGMENT card options	1. Parse INP2 file 2. Collect nodal and element data. 3. Determine order of nodes on the loading face of elements. 4. Associate nodes with pressure curves 5. Write a file	LS-DYNA *Load_Segment cards (OUT3)

Table 4. Function module 4.

Objective: Combine *DEFINE_CURVE and *LOAD_SEGMENT cards with preliminary LS-DYNA key word file.		
Input	Process	Output
1. INP2 file 2. OUT2 file 3. OUT3 file	Append OUT2 and OUT3 files into INP2	Enhanced LS-DYNA key word file

Note that the chamber pressure is always assigned to curve ID #1, the base pressure to curve ID #2, and the mean gas pressure in chamber to curve ID #3. The numbers are then increased by added rings in the chamber area and followed by calculated ring locations along the bore length. In addition, function module 4 is intended to append *DEFINE_CURVE and *LOAD_SEGMENT cards created from modules 2 and 3 to the end of the preliminary LS-DYNA key word file. Any pre-existing *DEFINE_CURVE and *LOAD_SEGMENT cards will not be removed and therefore remain valid in the key word file. A flowchart is a schematic representation of an algorithm or a process. It tends to provide people with a common language or reference point when dealing with

a project or process. In addition, it is an easy-to-understand diagram and therefore a useful tool for communicating how processes work and for clearly documenting how a particular job is done. Figure 4 demonstrates a high-level flowchart of the Pressurizer, where detailed data and document processing are ignored. Generally speaking, the elapsed time for the whole process was less than 3 minutes on an Intel Pentium⁴ M processor.

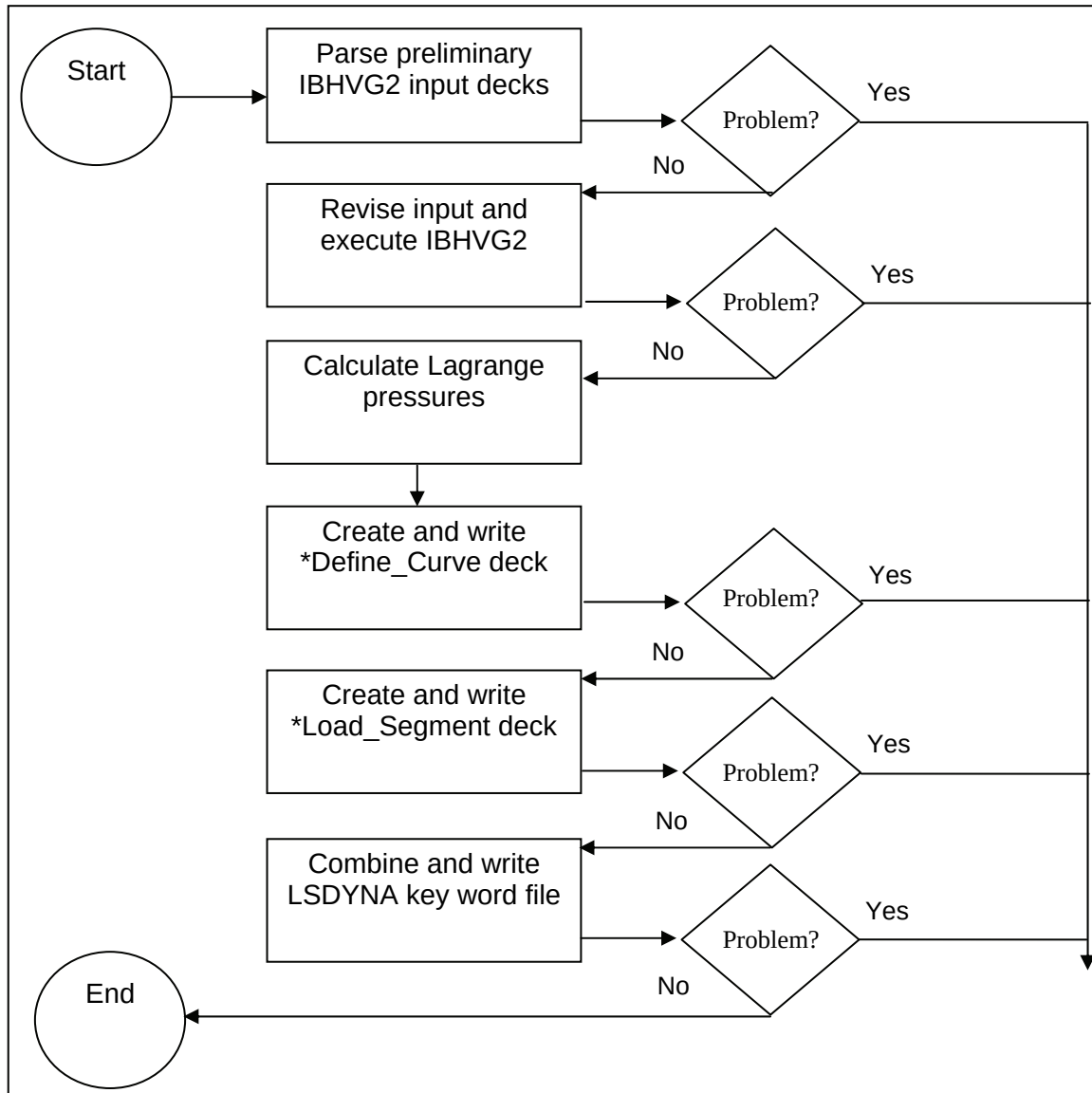


Figure 4. Flowchart of Pressurizer.

⁴Intel and Pentium are registered trademarks of Intel Corporation.

4. Command Specifications

The Pressurizer is a console application that can be executed in the Microsoft Disk Operating System (DOS) environment. It is a command-driven program written in C# language, a new object-oriented language for .NET environment developed by Microsoft. The DOS command to run the Pressurizer is “C:\> Pressurizer MyInputFile” in which MyInputFile is the input command file. Note that the Pressurizer.exe and the input file can reside in different folders as long as the whole path of the input file is specified.

In addition, because Pressurizer is designed to trigger IBHVG2 “on the fly,” both executable files must be in the same working directory. A log file named Pressurizer.log, which contains time stamps and any error message for the process, will be automatically created while the application is running. The log file and any associated output files will be generated in the working folder.

As prescribed, the Pressurizer consists of four different modules. Each module can be executed separately. Some cards are required and some are optional in a module. Required cards for each module are

Module 1: *RUN_IBHVG2
Module 2: *CREATE_LAGRANGE_PRESSURE_GRADIENT
Module 3: *CREATE_PRESSURE_LOAD; *SET_BORE_DIAMETER;
 *SET_PART_ID
Module 4: *CREATE_DYNA_FILE

Note that the order of input cards can be random in an input file. The Pressurizer reads through the input file before it starts processing any commands. For convenience, the input cards can be “commented out,” beginning with “\$\$” symbol so that they can be retained without going into effect. A sample input deck for the Pressurizer is given in appendix B.

Each input card consists of a number of fields separated by a comma. Detailed specifications for each field are provided in tables 5 through 8. The information include data type (text, integer or float), required (yes or no), I/O (input or output), description, and default value.

Table 5. Command specifications of module 1.

*RUN_IBHVG2

F1, F2, F3, F4, F5

Field Name	Data Type	Required	I/O	Description	Default
F1	Text	Yes	I	IBHVG2 executable file name	
F2	Text	Yes	I	IBHVG2 preliminary input file name	
F3	Text		O	IBHVG2 revised input file name	F2 + “_r”
F4	Text		O	IBHVG2 output file name based on revised input	F2 + “_r.out”

Table 6. Command specifications of module 2.

***CREATE_LAGRANGE_PRESSURE_GRADIENT**

F1, F2, F3, F4, F5, F6, F7, F8

Field Name	Data Type	Required	I/O	Description	Default	Note
F1	Text	Yes	I	IBHVG2 output file name based on revised input		
F2	Text		O	Pressure gradient file (i.e. *DEFINE_CURVE data)	PressureCurve	
F3	Integer		I	Pressure unit. (0 for metric and 1 for English) MPa in metric and psi in English	IBHVG2 input unit	
F4	Float		I	Ring threshold to apply pressure	0.0001	
F5	Integer		I	Request to create pressure matrix file(s). 0 for No and 1 for Yes The output file name is F1 input + "Matrix". If more than 250 columns, another separate file will be created with a number appended to the end of the file name.	0	Data are comma delimited importable to Excel
F6	Float		I	Scale factor to pressure	1.0	
F7	Integer		I	Request to create a ring file. 0 for No and 1 for Yes The output file name is F1 input + "Ring".	0	Data are comma delimited
F8	Float		I	Scale factor to ring file	1.0	

Note: Field F3 was developed to handle the situation when there is a discrepancy between the units used in IBHVG2 input decks and LS-DYNA key word file.

***ADD_RING_LOC**

F1, F2, F3, F4

(This is to add a ring in the chamber area. This command may be repeated as many as ten times. All rings will be reordered based on their X coordinates. The diameters among the rings are linearly interpolated.)

Field Name	Data Type	Required	I/O	Description	Default
F1	Float	Yes	I	X coordinate (gun tube longitudinal direction). Must be in a negative value.	
F2	Float	Yes	I	Diameter at the specified location.	
F3	Integer	Yes	I	Part ID used in LS-DYNA keyword for the ring location	
F4	Float		I	Bore diameter tolerance (used for selection of nodes)	0.01

***DEFINE_CURVE**

SIDR, SFA, SFO, OFFA, OFFO, DATTYP

Field Name	Data Type	Required	I/O	Description	Default
SIDR	Integer		I	Stress initialization by dynamic relaxation	0
SFA	Float		I	Scale factor for abscissa value	1.0
SFO	Float		I	Scale factor for ordinate value	1.0
OFFA	Float		I	Offset for abscissa values	0.0
OFFO	Float		I	Offset for ordinate values	0.0
DATTYP	Integer		I	Data type	0

This command is written in compliance with LS-DYNA *DEFINE_CURVE card so that the options of the card can be transferred to the Pressurizer output. More detail is available in LS-DYNA manual (15). Note that the input values apply to all *DEFINE_CURVE in the final key word file generated by the PRESSURIZER

Table 7. Command specifications of module 3.

***CREATE_PRESSURE_LOAD**

F1, F2, F3

Field Name	Data Type	Required	I/O	Description	Default
F1	Text	Yes	I	Preliminary LS-DYNA key word file	
F2	Text		I	Define curve file generated from *CREATE_LAGRANGE_PRESSURE_ GRADIENT	PressureCurve
F3	Text		O	Pressure loading output file (i.e. *LOAD_SEGMENT data)	PressureLoad

***SET_BORE_DIAMETER**

F1, F2, F3, F4, F5

Field Name	Data Type	Required	I/O	Description	Default
F1	Float	Yes	I	Bore starting coordinate	
F2	Float	Yes	I	Bore diameter	
F3	Integer	Yes	I	Part ID set (first field in *SET_PART_ID deck)	
F4	Float		I	Bore diameter tolerance (used for selection of nodes)	0.01
F5	Float		I	Element size When element size is specified, the bore diameter tolerance is overridden by 1% of the element size	0.0

***SET_PART_ID**

F1, F2, F3, F4, F5

Field Name	Data Type	Required	I/O	Description	Default
F1	Integer	Yes	I	Part ID set used in *SET_BORE_DIAMETER deck	
F2	Integer	Yes	I	Part ID in LS-DYNA keyword file	
F3	Integer		I	Second part ID	
F4 ...	Integer		I	Third part ID and so on (up to 8)	

***LOAD_SEGMENT**

SF, AT

Field Name	Data Type	Required	I/O	Description	Default
SF	Float		I	Load curve scale factor	-1.0
AT	Float		I	Arrival time for pressure or birth time of pressure	0.0

This command is written in compliance with LS-DYNA *LOAD_SEGMENT card so that the options of the card can be transferred to the Pressurizer output. More detail is available in LS-DYNA manual (15). Note that the input values apply to all *LOAD_SEGMENT in the final key word file generated by the PRESSURIZER.

Table 8. Command specifications of module 4

*CREATE_DYNA_FILE

F1, F2, F3

Field Name	Data Type	Required	I/O	Description	Default
F1	Text	Yes	O	Final LS-DYNA keyword file	
F2	Text	Yes	I	Preliminary LS-DYNA keyword file	
F3	Text		I	Define curve file generated from *CREATE_LAGRANGE_PRESSURE_GRADIENT	PressureCurve
F4	Text		I	Load segment file generated from *CREATE_PRESSURE_LOAD	PressureLoad

5. Results Demonstration

An M855 ball model of 5.56-mm ammunition shown in figure 5 is used to demonstrate the results of the software development. The M855 cartridge has a 62-grain, gilded metal-jacketed, lead alloy core bullet with a steel penetrator. The firing weapon M4 carbine, a compact version of a M16A2 rifle, is used for this study and is shown in figure 6. A finite element model was created for the gun barrel model of the M4 carbine. Figure 7 illustrates the barrel model, which has a length of 12.82 inches. The total in-bore travel time for the M855 bullet was 0.98 ms. No pre-processor was found to provide contour display capability of space- and time-dependent pressures over the finite element model of the gun barrel. Therefore, the spatially varying pressures along the down-bore distance from the rear face of the tube were calculated at some selected time instant. The pressures versus distance are displayed in figure 8, which align with the barrel model for easy side-by-side comparison. Since the bullet had no movement until 0.18 ms from ignition, a start time of 0.2 ms was chosen for the plot. An increment of 0.1 ms was adopted thereafter until the bullet reached the muzzle. As a result, the chart includes nine different pressure-distance curves. Because of very small magnitude of the displacement, i.e., 1.236×10^{-4} inch, the curve at time 0.2 ms is not visible. Understandably, no pressure should exist ahead of bullet location, which explains the abrupt drop on the curves. The pressure gradient along the distance appears to be high at peak pressure level and becomes more uniform as the bullet exits the barrel. On the other hand, figure 9 provides the relationships between pressure and time at selected in-bore bullet locations. Similarly, at certain down-bore distance, no pressure should exist until the time when the bullet travels to the location. For instance, at $X = 1.0$ inch, the pressure initially stays at zero and suddenly rises to 46,000 lb/in² at 0.51 ms. Note that when a sufficient number of curves are provided, an envelope that traces the spikes of the curves is equivalent to the pressure applied to the base of the projectile. For comparison, the time history of the base and breech pressures is given in figure 10.

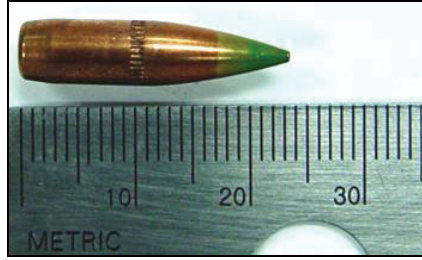


Figure 5. Display of M855 (5.56 mm) bullet.



Figure 6. Display of M4 carbine.

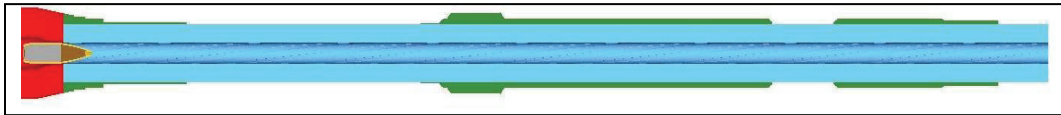


Figure 7. Gun barrel model of an M4 carbine.

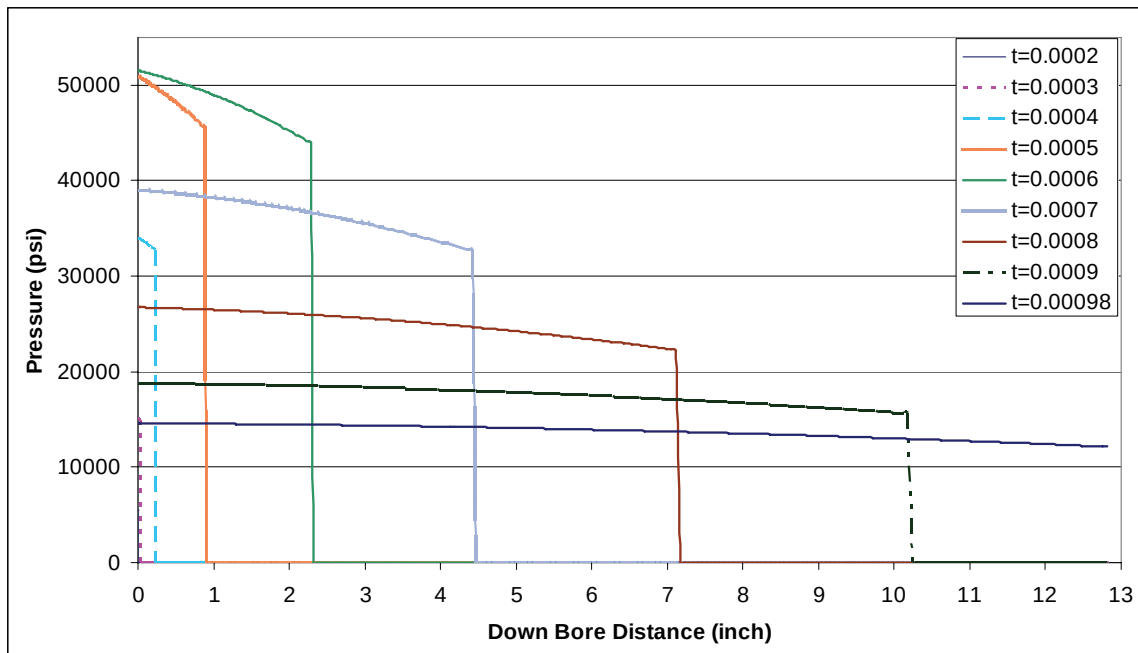


Figure 8. Plot of spatially varying pressure curves at selected time instant.

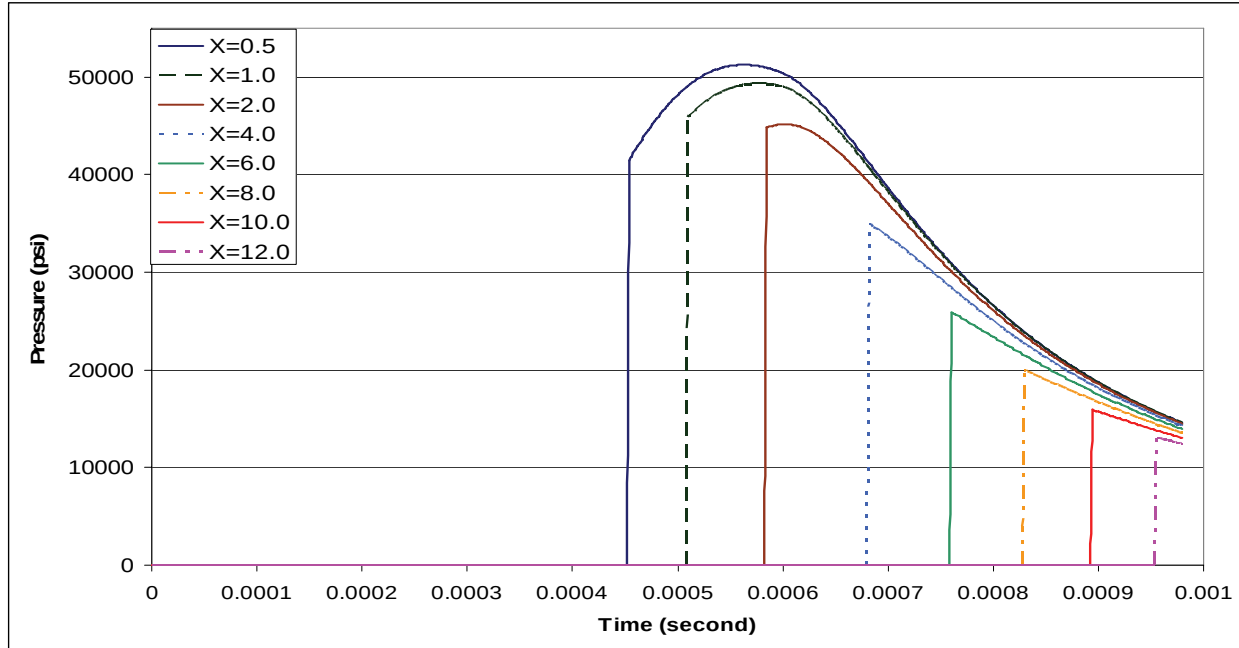


Figure 9. Plot of time-dependent pressure curves at selected locations (inch).

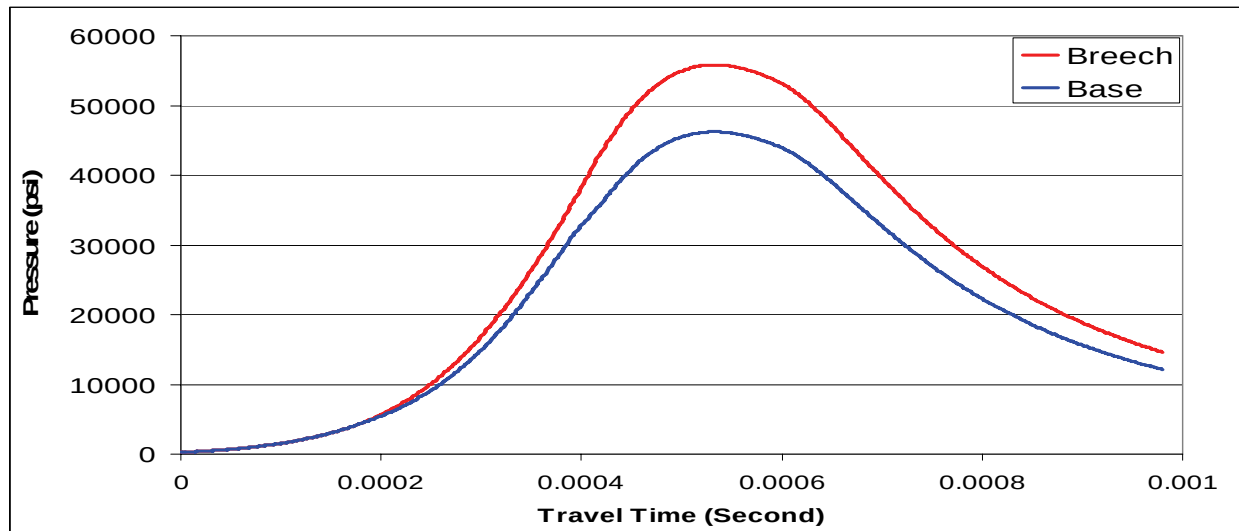


Figure 10. Computed breech and base pressure-time curves.

6. Summary

A console application program was implemented to eliminate tremendous manual efforts in defining and applying space- and time-varying pressures on finite element models of gun barrels. The computer program coupled with the IBHVG2 code was designed to employ some output from

IBHVG2 and to calculate in-bore pressures at any given location. Furthermore, the enhancement of LS-DYNA key word files by the incorporation of Lagrange pressure gradient for explicit dynamic analysis was greatly streamlined through the application program. Many parsing techniques were developed to accomplish the prescribed efforts.

Please note that the circular diameter between two selected rings in the chamber area is linearly interpolated. The value of the diameter is used to determine the elements on the chamber surface. Subsequently, the chamber pressure is applied on the elements. However, when the geometry of a curve shape exists in the chamber area, such as a forcing cone, the technique of linear interpolation is not sufficiently good to capture surface elements. In this case, mean gas pressure in the chamber, which is automatically populated and defined as ID#3, may be used and linked to the LOAD_SEGMENT key word for the chamber area as a “workaround”.

Although an M4 carbine was demonstrated as an example in the report, the algorithms are applicable to any size of gun barrels as long as the in-bore pressure variations are of concern. It is hoped that the software application will improve modeling of exact mechanisms that drive small caliber weaponry and will further allow for the development of weapons with increased performance and reliability.

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Appendix A. Revised IBHVG2 Input Deck

```
$COMM
    5.56MM BALL
$HEAT
    --- skipped ---
$GUN
    --- skipped ---
$PROJ
    --- skipped ---
$RESI
    --- skipped ---
$INFO
    --- skipped ---
$PRIM
    --- skipped ---
$PROP
    --- skipped ---
$TDIS
    SHOW = 'TIME'
$TDIS
    SHOW = 'TRAV'
$TDIS
    SHOW = 'BRCH'
$TDIS
    SHOW = 'BASE'
$TDIS
    SHOW = 'FRCR'
$TDIS
    SHOW = 'AIRR'
$TDIS
    SHOW = 'MEAN'
$END
```

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Appendix B. Sample Input Deck for Pressurizer

\$\$ The following is an example of pressurizer input deck

\$\$

\$\$ Module 1:

*RUN_IBHVG2

ib3.exe, M855ref51100.txt_r,

\$\$

\$\$ Module 2:

*CREATE_LAGRANGE_PRESSURE_GRADIENT

M855ref51100.txt_r.out, PressureCurve, 1, 0.1, 0,

\$\$

\$\$ Module 3:

*SET_BORE_DIAMETER

1.648, 0.22125, 1, 0.002

*SET_PART_ID

1, 1, 2,

*CREATE_PRESSURE_LOAD

preDyna.k,

\$\$

\$\$ Module 4:

*CREATE_DYNA_FILE

finalDyna.k, preDyna.k

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J NEWILL M CHEN (3 CYS)
J DESPIRITO J SAHU
B GUIDOS S SILTON
P WEINACHT
AMSRD ARL WM MB L BURTON
J SOUTH